

# IGR J17098-3628: AN X-RAY NOVA DISCOVERED BY INTEGRAL

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## ABSTRACT

We report the discovery with INTEGRAL on March 24, 2005, and follow-up observations of the distant Galactic X-ray nova IGR J17098-3628.

Key words: X-ray nova; transient; outburst; black hole.

## 1. INTRODUCTION

X-ray novae are bright transients flared up on the sky for several months due to unsteady accretion of matter from a low mass companion onto a compact object. Doppler spectroscopy of optical lines from such systems performed after their switching off in X-rays allowed their mass functions to be measured and indicates that the compact objects in these systems are black holes. The canonical X-ray novae have very soft black body spectra near their brightness maximum (the reason to call them sometimes as soft X-ray transients) and very hard (extended to  $\sim 200$  keV) Comptonized spectra at the short initial and long decaying phases of the outburst. It is obvious that the spectral evolution of X-ray novae should trace changes in regimes of disc accretion onto a black hole in these sources connected with changes in the accretion rate. This opportunity for studying the accretion regimes and the unique opportunity for finding new black holes and measuring their mass make X-ray novae very interesting targets for observers and astrophysicists.

Long term X-ray observations by GINGA, MIR/KVANT, GRANAT, CGRO and RXTE indicate that X-ray novae flare up approximately once a year that allowed us to believe that the *International Gamma-Ray Astrophysics Laboratory* (INTEGRAL) [16] with its wide fields of view of main telescopes, high sensitivity in the hard X-ray band and excellent capabilities for broad band spectroscopy will be able to detect and investigate many X-ray novae and provide us with new discoveries related to their peculiar X-ray properties. However, two years of the INTEGRAL nominal operation have passed, more than one hundred of new hard X-ray sources have been discovered, several recurrent transients containing a black hole (XTE J1550-564, 4U 1630-472, H 1743-322/IGR J17464-3213, SLX 1746-331, GX 339-4) have

flared up and been investigated but no one really new X-ray nova has been observed. In this paper we report the discovery with INTEGRAL probably the first source of this type, IGR J17098-3628, describe its X-ray properties and some results from the follow-up observations.

## 2. DISCOVERY AND X-RAY OBSERVATIONS

The new transient source IGR J17098-3628 was discovered by Grebenev et al. [3] with the IBIS/ISGRI telescope [9] on board INTEGRAL on March 24.33-25.58, 2005 (UT), during deep Open Program observations of the Galactic center field. The signal-to-noise (S/N) ratio for the source in the mosaic image accumulated during this observation was  $\simeq 22$  in the 18–45 keV band and  $\simeq 15$  in the 45–70 keV band, the corresponding average fluxes were  $28.2 \pm 1.4$  and  $38.7 \pm 2.8$  mCrab. The source was variable on a time scale of hours reaching the maximum flux levels of 60 and 95 mCrab in these bands.

The S/N mosaic map obtained in 18–45 keV X-rays with ISGRI during this observation is presented in Fig. 1a. It shows that IGR J17098-3628 was located in the close vicinity ( $9.4'$  away) of the other strongly variable INTEGRAL source IGR J17091-3624 [8, 11, 5, 2]. The position of IGR J17098-3628 measured with ISGRI,  $R.A. = 17^{\text{h}}09^{\text{m}}48^{\text{s}}$ ,  $Decl. = -36^{\circ}28'12''$  (equinox 2000.0, error radius  $2'$ ), kept it however well outside the error circle for the position of the second source ( $R.A. = 17^{\text{h}}09^{\text{m}}06^{\text{s}}$ ,  $Decl. = -36^{\circ}24'07''$ , error radius  $0.8'$  [11]). To illustrate the capability of the telescope for distinguishing these sources we are giving in Fig. 1b the S/N map of the same region as in Fig. 1a but obtained with ISGRI on February 16.23-18.66, 2004, when IGR J17091-3624 was in the bright state.

Two next sets of our observations of the Galactic center field (on March 26.10-26.78 and 28.05-28.46 UT) showed that IGR J17098-3628 was strongly evolving in both brightness and spectral shape [4]. The spectra measured on March 24–25 and March 26 could be satisfactorily described by a simple power law in the broad 18–200 keV band without any signs of a high energy cut-off. The photon index was equal to  $1.81 \pm 0.09$  and  $2.20 \pm 0.06$ , respectively. The spectrum measured on March 28 was

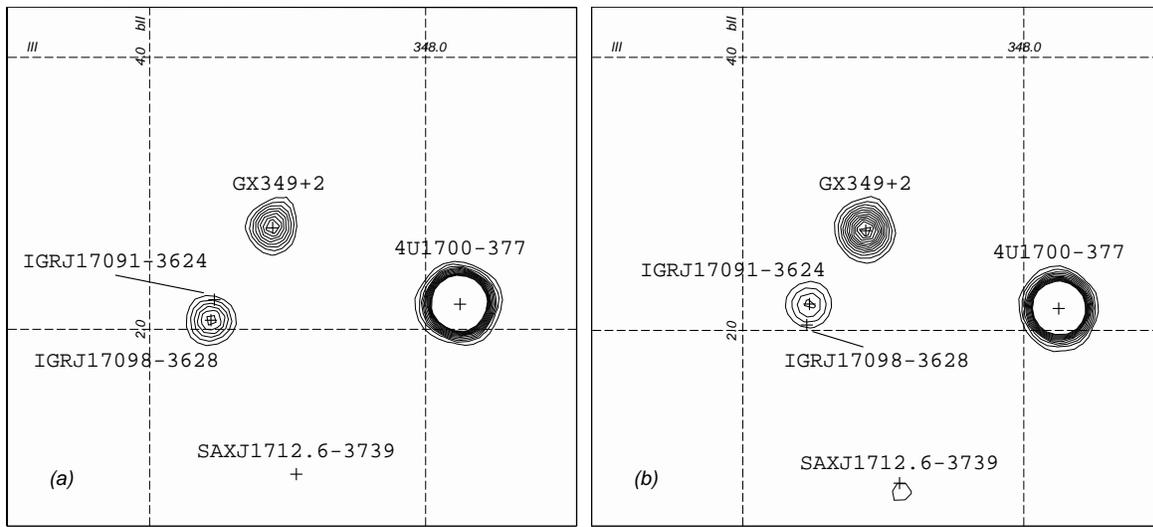


Figure 1. X-ray images (S/N maps) of the region near GX 349+2 obtained with IBIS/ISGRI in the 18–45 keV band: (a) on March 24.33-25.58, 2005 (UT) when the outburst of the new transient IGR J17098-3628 was discovered, and (b) on February 16.23-18.66, 2004 (UT) when IGR J17091-3624, the twin of IGR J17098-3628, was observed in its active state. Contours show regions of confident detection of sources at the S/N levels of 5, 8, 11, 14, ..., 44.

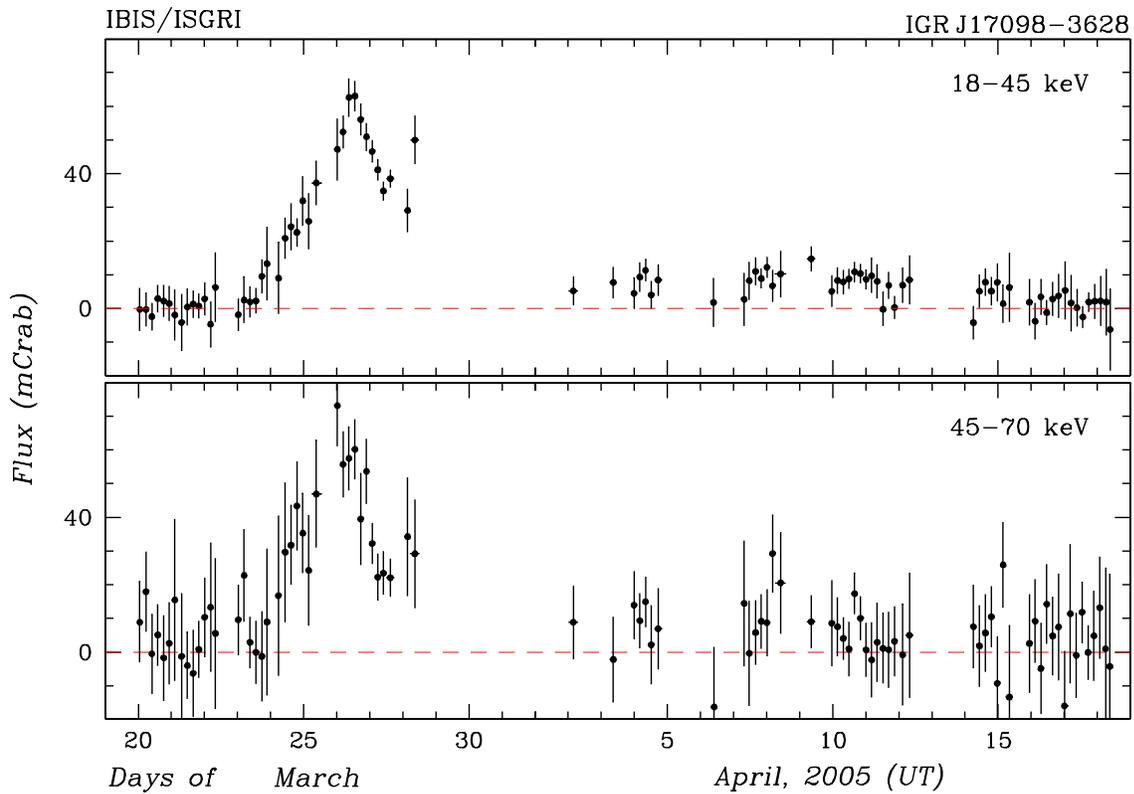


Figure 2. Light curve of IGR J17098-3628 measured with IBIS/ISGRI in two energy bands during the first month of its activity. Every point is the result of averaging the fluxes obtained in 7–8 subsequent individual pointings (covering together an interval of  $\sim 1600$  s in duration). Flux of 1 mCrab corresponds to  $1.1$  and  $0.5 \times 10^{-11}$  erg  $\text{cm}^{-2} \text{s}^{-1}$  in the 18–45 and 45–70 keV bands for the source with the Crab-like spectrum.

significant only below 70 keV. Its approximation with a power law led to the photon index  $3.00 \pm 0.25$ .

Figure 2 gives light curves of the source in two energy bands, 18–45 and 45–70 keV, measured with ISGRI during this and several subsequent weeks of observations. Data from the INTEGRAL Galactic Bulge monitoring program (partly presented in [10]) and several other Open Program observations (currently public) were added here to data of our deep view to the Galactic center field. Unfortunately there was a gap in the data between March 29 and April 2 because of calibration observations of the Crab nebula performed with INTEGRAL. The figure shows that the steady increase in the hard X-ray flux observed during the first days of the outburst stopped on March 26 when the level of  $\sim 65$  mCrab has been reached. The flux began to decrease, slowly in the 18–45 keV band and abruptly in the 45–70 keV band, but then stabilized and was detectable at the level of 5–10 mCrab during at least two next weeks.

The observed hard X-ray variability did not reflect changes in the rate of energy release in IGR J17098-3628. A bulk of the total luminosity was emitted in the softer ( $\lesssim 15$  keV) X-ray band. Measurements with the JEM-X monitor on board INTEGRAL could be useful but the source was usually outside the narrow field of view of JEM-X or at its very edge, in the region of low sensitivity. The RXTE observatory carried out a cross-scanning of this field on March 29.179-29.227 (UT) and detected the source with the 3–20 keV flux of  $\sim 80$  mCrab [4] (we thank the RXTE team for organizing such a prompt observation). Its best-fit position ( $R.A. = 17^{\text{h}}09^{\text{m}}38^{\text{s}}$ ,  $Decl. = -36^{\circ}27'41''$ , error radius 5') was generally consistent with that of ISGRI (being only 2.1 away). The broad-band spectrum  $E^2 dN/dE$  of IGR J17098-3628 measured with RXTE/PCA (on March 29) and IBIS/ISGRI (on March 28) is shown in Fig. 3 by open points. The spectrum is complex consisting of a soft black body component (we approximated it with the `diskbb` model of XSPEC) and a hard tail (approximated with the `cutoffpl` model of XSPEC). The inner temperature and radius of the disk were  $kT_{\text{in}} = 1.20 \pm 0.01$  keV and  $R_{\text{in}}(\cos i)^{1/2} = (6.6 \pm 0.1) d_{10}$  km, the photon index and cut-off energy of the hard tail were  $\alpha = 2.14 \pm 0.09$  and  $E_0 = 46 \pm 9$  keV. Here  $i$  is an inclination angle of the disk and  $d_{10}$  is a distance to the source in units of 10 kpc. To improve the fit an absorption with the column density  $N_{\text{H}} = 8 \times 10^{21} \text{ cm}^{-2}$ , consistent with the Galactic value, and a narrow ( $\sigma = 0.1$  keV) Gaussian line at  $6.63 \pm 0.08$  keV with the flux  $(9.6 \pm 2.6) \times 10^{-4} \text{ phot cm}^{-2} \text{ s}^{-1}$  have been included. The ISGRI spectrum was normalized to the PCA spectrum by a factor  $A = 1.19 \pm 0.14$  derived from the fit. The luminosity was  $\simeq 2.4 \times 10^{37} d_{10}^2$  and  $5.0 \times 10^{36} d_{10}^2 \text{ erg s}^{-1}$  in the 3–20 and 20–200 keV bands. Note that the hard component contributed significantly  $\sim 55\%$  to the 3–20 keV luminosity. The luminosity of the `diskbb` component  $L_{\text{dbb}} = 4\pi R_{\text{in}}^2 \sigma T_{\text{in}}^4 \simeq 1.2 \times 10^{37} d_{10}^2 (\cos i)^{-1} \text{ erg s}^{-1}$ .

Later RXTE carried our several pointed observations of the source (with a  $\sim 25'$  offset to discriminate possi-

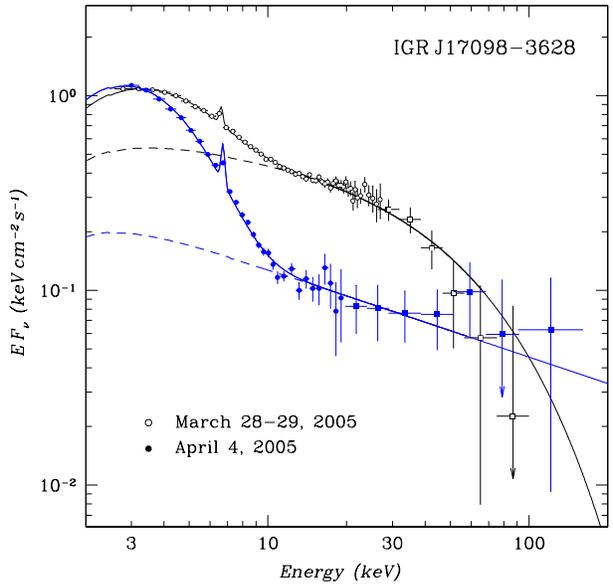


Figure 3. Spectral evolution of IGR J17098-3628 according to INTEGRAL/ISGRI (squares) and RXTE/PCA (circles) data. Best-fit models dominated by disk black-body spectra are shown by solid lines, hard power law components (with a cut-off for March 28) — by dashed lines.

ble contributions from IGR J17091-3624). The spectrum measured on April 4 with PCA and ISGRI is shown in Fig. 3 by filled points. The best-fit parameters were  $kT_{\text{in}} = 0.99 \pm 0.01$  keV,  $R_{\text{in}}(\cos i)^{1/2} = (12.7 \pm 0.2) d_{10}$  km,  $\alpha = 2.45 \pm 0.12$  and  $E_0 > 74$  keV,  $A = 0.71 \pm 0.12$ . The flux in the iron line was consistent with that measured on March 29 confirming its interstellar (Galactic) origin. The luminosity was  $\simeq 1.6 \times 10^{37} d_{10}^2$  (3–20 keV) and  $1.5 \times 10^{36} d_{10}^2 \text{ erg s}^{-1}$  (20–200 keV),  $L_{\text{dbb}} \simeq 1.9 \times 10^{37} d_{10}^2 (\cos i)^{-1} \text{ erg s}^{-1}$ .

### 3. RADIO AND OPTICAL IDENTIFICATION

To allow identification of IGR J17098-3628 in soft X-ray, optical and radio bands we initiated its TOO observation with the SWIFT/XRT telescope. The observation was carried out on May 1.68-1.76, 2005 (UT) with an exposure time of 2.8 ks. The analysis [6] of these data has revealed a bright X-ray source with the coordinates  $R.A. = 17^{\text{h}}09^{\text{m}}45^{\text{s}}.9$ ,  $Decl. = -36^{\circ}27'57''$  and the error radius of about 5'' (90% containment). This position is 30'' from the INTEGRAL position. The source's average 0.5–10 keV flux corresponded to the luminosity  $1.6 \times 10^{37} d_{10}^2 \text{ erg s}^{-1}$  (non-corrected for absorption). The flux dropped by  $\sim 8\%$  during the observation.

Following the SWIFT/XRT localization the possible optical/IR counterparts for IGR J17098-3628, associated with 2MASS J17094612-3627573, have been proposed [7] and nominally confirmed by new observations from the 6.5-m Magellan-Baade telescope [13] and SWIFT/UVOT [1]. However, because of the low Galac-

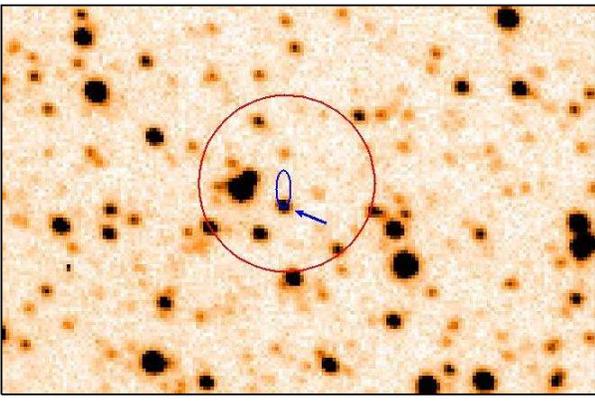


Figure 4. Magellan-IMACS I-band image of the field near IGR J17098-3628. Circle and ellipse denote the 90% error regions of the SWIFT and VLA localization, arrow — the variable optical counterpart. 2MASS J17094612-3627573 with  $V \simeq 19.3$  is  $3''$  to the left (from [14]).

tic latitude of IGR J17098-3628 (see Fig. 1), the stellar density in this field is high and the chance of finding a non-related star even within the narrow XRT error box was considerable. The long term VLA observations [12] have shown that 2MASS J17094612-3627573 did not relate to the X-ray source. These observations were carried out on March 31, April 5, April 12, and May 4, all at 4.86 GHz. The first data set showed the only significant radio source within the  $2'$  INTEGRAL error circle, located at  $R.A. = 17^{\text{h}}09^{\text{m}}45^{\text{s}}.934 \pm 0^{\text{s}}.011$ ,  $Decl. = -36^{\circ}27'57''.30 \pm 0''.55$ . Its flux density on March 31 was  $0.34 \pm 0.07$  mJy. The later observations gave nominal flux densities of  $0.06 \pm 0.07$ ,  $0.16 \pm 0.07$  and  $0.21 \pm 0.05$  mJy/beam; only the last was a detection. The radio transient lies  $0''.5$  from the SWIFT/XRT position and  $2''.8$  from that of 2MASS J17094612-3627573. Its fading from March 31 to April 5, and possible re-appearance around May 4, are consistent with the X-ray evolution [4, 6] and indicate that this is indeed the radio counterpart to the X-ray transient.

Steeghs et al. [14] re-investigated their Magellan-Baade I-band images obtained on April 9, 2005 [13] and found (see Fig. 4) a point source located at  $R.A. = 17^{\text{h}}09^{\text{m}}45^{\text{s}}.93$ ,  $Decl. = -36^{\circ}27'58''.2$  ( $0''.2$  uncertainty). This optical position is consistent within  $2\text{-}\sigma$  error with that derived from the radio observations. The additional I-band images taken with the telescope on May 13.388–13.394, 2005 (UT) indicated that the optical source has faded by  $0^{\text{m}}12 \pm 0^{\text{m}}02$  since April 9. The positional coincidence with the SWIFT and VLA detections and the photometric variability suggest that this source is indeed the optical counterpart to IGR J17098-3628.

#### 4. CONCLUSIONS

The observed behaviour of IGR J17098-3628 suggests that it was an X-ray nova at an initial stage of the outburst and thus — a new black hole candidate. Its spectra have

been successfully described with a sum of a disk black-body emission and a hard power law tail. Note that:

1). The temperature  $kT \sim 1$  keV of the soft spectral component of IGR J17098-3628 was much smaller than that typical of LMXBs containing neutron stars. The variable 2 keV component in such sources originates from a hot boundary layer at the neutron star's surface.

2). The value of  $R_{\text{in}}$  measured on April 4 can be compared with the radius  $R_0 = 6GM/c^2$  of the marginal stable orbit of a black hole. Assuming that the black hole's mass  $M \geq 3M_{\odot}$  we get the following restriction for the inclination and distance  $\cos i \leq 0.22d_{10}^2$  ( $i \geq 77^{\circ}$  for  $d = 10$  kpc, i.e. we see the disk in this system nearly from its edge). The diskbb luminosity  $L_{\text{dbb}} \gtrsim 5.3 \times 10^{37}$  and  $\gtrsim 8.7 \times 10^{37}$  erg s $^{-1}$  on March 29 and April 4. The small value of  $R_{\text{in}}$  and  $L_{\text{dbb}}$  measured on March 29 was probably connected with a notable contribution of the power law component to the soft  $\lesssim 15$  keV part of the spectrum that affected the disk parameters. In reality, the hard tail should be gradually formed from photons of the disk black body spectrum in result of Comptonization.

3). Optical emission of IGR J17098-3628 is likely due to X-ray heating of outer regions of the disk. Scaling the observed  $V \sim 20.8$  (see Fig. 4) to the average absolute magnitude of LMXBs  $M_V \simeq 1.2$  [15] and correcting for the extinction  $A_V \sim 4.5$  (derived from  $N_{\text{H}}$ ) we can estimate the distance to the source  $d \simeq 10.5$  kpc.

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