INTEGRAL MONITORING OF THE BLACK HOLE CANDIDATE 1E 1740.7-2942

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ABSTRACT

The brightest persistent Galactic black hole candidate close to the Galactic Centre, 1E 1740.7-2942, has long been observed with INTEGRAL. In this paper, we report on the long-term hard X-ray monitoring obtained during the first year of observations as part of the Galactic Centre Deep Exposure. We discuss the temporal and spectral behaviours in different energy bands up to 250 keV, as well as the hardness-flux correlations.

Key words: Gamma-ray astronomy – INTEGRAL – X-ray binaries – Black hole candidates – 1E 1740.7-2942.

1. INTRODUCTION

The black hole candidate (BHC) 1E 1740.7-2942 was first observed with the EINSTEIN observatory by Hertz & Grindlay (1984). It lies 50′ away from the centre of the Galaxy and it is the brightest persistent source within a few degrees of the Galactic Centre (GC) above \( \sim 40 \) keV [Sunyaev et al. 1991]. The source usually shows a hard X-ray spectrum characteristic of BHCs in their low/hard state; the X-ray emission is strongly attenuated by a high hydrogen column density \( N_H = 1 \times 10^{23} \text{ cm}^{-2} \) [Sakano et al. 1999]. Interest in this source increased when Mirabel et al. (1992) discovered double-side jets in radio emission that classified the source as microquasar. It has also been suggested as a possible positron-electron annihilation source due to a SIGMA (French instrument on-board of the GRANAT satellite) observation of the 511 keV line [Bouchet et al. 1991] from 1E 1740.7-2942. Actually, a definitive confirmation has not been reported so far.

We present some results collected during the first year of INTEGRAL guaranteed time observations. This paper is structured as follows: in section 2 we describe the data set we have used and the performed analysis. In section 3, we report on imaging, temporal, and spectral analysis results obtained with the imager IBIS. We focus on the temporal behaviour and spectral variability of a data sub-set, that is when the instrument achieves its best performances.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. The INTEGRAL monitoring

The GC region has been frequently pointed by the INTEGRAL satellite [Winkler et al. 2003] during its guaranteed time observations (Core Programme).
The Core Programme consists of a deep exposure of the Galactic Centre (GCDE) and regular scans of the Galactic plane (GPS), plus some pointed observations. During the first year the GCDE observing time was 4.8 Ms; as part of these observations, the region including 1E 1740.7-2942 has been pointed for $\sim 1.4$ Ms.

In this paper we present results of the first year of monitoring obtained with IBIS (Ubertini et al. 2003), the imager on board INTEGRAL satellite.

IBIS is a coded mask telescope consisting of two detector layers, ISGRI (Lebrun et al. 2003) and PICsIT (Labanti et al. 2003); herein we refer only to the data collected by the ISGRI detector. The IBIS Partially Coded Field Of View (PCFOV) is $29^\circ \times 29^\circ$ at zero response, but the full instrument sensitivity is achieved in the $9^\circ \times 9^\circ$ Fully Coded Field of View (FCFOV).

By considering the coding effect of the instrument, during the first year of Core Programme the effective exposure time for 1E 1740.7-2942 was $\sim 790$ ks. Basically, such a value (corrected for the dead-time) is calculated by multiplying the pointing exposure time by a vignetting map which is equal to 1 in the FCFOV and decreases to zero at the borders of the PCFOV.

The total number of pointings, or science windows (SCWs), is 782, covering a period of 7 months between March 2003, revolution (rev.) 50, and October 2003, rev. 122 (the INTEGRAL Julian Date interval corresponds to 1166.39 $\pm$ 1382.77). Raw data have been pre-processed and distributed by the Integral Science Data Center (Courvoisier et al. 2003). The IBIS scientific data analysis has been performed by using the INTEGRAL off-line analysis software (OSA) release 3.0 (Goldwurm et al. 2003), Ftools 5.2 adapted to the INTEGRAL fits files format by the HEASARC software team. The energy ranges selected for the imaging and temporal analysis are: 20-40 keV, 40-80 keV, 80-120 keV, and 120-250 keV. The light curves have been extracted from the images of each SCW: they have a binning time of $\sim 1800$ s that is the mean duration of each GCDE pointing.

A logarithmic binning table with 16 energy channels has been chosen for spectral extraction. Note that the response matrix for partially coded sources is not available yet, therefore we performed the spectral analysis of a sub-set of the whole data set: 66 pointings with the source in the FCFOV for a total exposure time of $\sim 120$ ks.

We used a renormalized effective area, in the sense that some systematics may be partially taken into account by introducing post facto corrections using the Crab as a standard candle (Ubertini et al. 2004); in spite of this, we still need to assume a 2% systematic error in order to obtain good fits.

Spectral fitting have been performed with the standard XSPEC v.11.2 tools and all parameters errors have been calculated at 90% of confidence level.

3. RESULTS

3.1. The RXTE campaign

The Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA) has been periodically monitoring 1E 1740.7-2942 since the first week of spacecraft science operations in 1996. These began as monthly pointings of 1000-1500 s and have increased over the years until they take place twice a week. This frequency has been found to sample some of the more rapid state changes, and the data quality is sufficient to look for small spectral changes within the standard so called low/hard state, and to measure the approximate level of fast variability, for each pointing.

Nearby sources are excluded by placing the centre of the $1^\circ$ field of view about $0.5^\circ$ away from 1E 1740.7-2942, and the strong Galactic diffuse background is subtracted with the help of pointings to an empty field symmetrically positioned across the GC. This monitoring campaign has been used to discover an unexpected temporal relation between spectral shape and luminosity in this source, very different from Cyg X-1 (Smith et al. 2002a); to identify state changes promptly (Smith et al. 2002b); and to find the orbital period of the 1E 1740.7-2942 system, estimated as 12.73$\pm$0.05 days (Smith et al. 2002c).

3.2. Imaging analysis

In the FCFOV of individual maps (corresponding to a single SCW), 1E 1740.7-2942 is detected in the

1http://isdcul3.unige.ch/~ebisawa/ftools.html
range 20-40 keV at a level of confidence of 10σ and at a level of 3σ at 14° from the centre of the FOV. In the energy range 40-80 keV, it is detectable up to offset angles of ~12°; on the contrary, between 80 and 120 keV it has been detected in only a few pointings (less than 200 SCWs). The 20-40 keV mosaic of 370 significance maps ($6.15 \times 10^5$ s) is shown in Figure 1; numerous sources are detected by IBIS/ISGRI around 1E 1740.7-2942, which is in the centre of the map at a detection level of 112σ.

In Figure 2 two mosaics for two different energy bands built with 66 maps when 1E 1740.7-2942 was in the FCFOV are shown. In the GC zone, the only two sources detected up to 250 keV are two BHCs: 1E 1740.7-2942 and the transient source IGR J1746-3213 (Capitanio et al. 2004).

Figure 2. Significance maps in the 20-40 keV (left) and 120-250 keV (right) bands of 66 pointings when 1E 1740.7-2942 was in the IBIS FCFOV.

3.3. Light curves

Light curves corresponding to the first 3 selected energy ranges are shown in Figure 3. At low energy we detected 1E 1740.7-2942 in 460 SCWs. We decided to reject all the SCWs with statistical errors not determined by the software. On the first plot (top) the RXTE/PCA light curve in the energy range 8-25 keV is superimposed. As can be seen, the two temporal profiles look consistent during the simultaneous observations. In the two energy ranges 40-80 keV (middle) and 80-120 keV (bottom), the number of good SCWs we found is 371 and 180 respectively. Some systematic errors could still affect the count rate evaluation, because the instrumental off-axis response has not been fully evaluated yet. Because of that, we also extracted light curves considering only SCWs with the source in the FCFOV. These observations cover three time intervals: rev. 53-62, rev. 103, and rev. 119-120. As it is shown in Figure 4, there is no evidence of

Figure 3. Light curves extracted from the whole data set for 3 ISGRI bands. On top, the rhomboidal points superimposed are the RXTE/PCA data per detector from 8-25 keV.
Figure 4. Light curves of the FCFOV observations in two different energy bands: the flux clearly increased comparing the first (rev. 53-62, left) and the second (right) part of the observation.

flux variation within each of the two periods, while on a longer time scale there is a clear indication of a 30% increase. The mean value of the count rate and the variance have been calculated in the energy range 20-40 keV: with OSA 3 software we obtain 4.7 ± 0.3 ct/s and 6.9 ± 0.2 ct/s as mean rates within the first and second period respectively.

Considering mCrab, such increase comes from 41 mCrab up to 61 mCrab. On the contrary, during the third period the source decreased above 30 mCrab. The later (more recent) INTEGRAL observations (Grebenev et al. 2004) showed that the source flux declined below the ISGRI sensitivity limit (∼1.7 mCrab, 3 σ) by March 2004.

Hereafter we refer to the spectral analysis performed by using the first and the second period data set.

3.4. Hardness ratio and spectral behaviour

In order to search for spectral variations, we evaluated the hardness ratio defined as:

\[ HR = \frac{(h - s)}{(h + s)} \]  

with \( h \) and \( s \) being the count rate in the 40-80 keV and 20-40 keV energy ranges respectively.

Performing a \( \chi^2 \) test, no spectral variations have been found within each of the two periods. In Figure 5, the hardness ratios and the models employed for the fit have been plotted: both fits are consistent with a constant model with roughly the same value.

In addition, all spectra (in the range 20-80 keV) extracted from each SCW have been fitted by a single power law. In a single GCDE pointing, the source intensity and low counting statistics do not allow us to constrain the cut-off. The aim of this analysis was to investigate a possible correlation between the photon index and the flux: no relation has been found, as is clearly visible in Figure 6.

Since a simple power law does not allow a good fit (\( \chi^2/(9) = 7 \)), the averaged spectrum corresponding to the first period (57 spectra) has been fitted by a cut-off power law (Figure 7). A fit with a \( \chi^2/(9) = 1.4 \) has been obtained with a photon index \( \Gamma = 0.84^{+0.22}_{-0.24} \) and a high energy cut-off \( E_c = 36 \pm 6 \) keV.

We also fitted the averaged spectrum from the second data set, consisting of 9 spectra at the higher flux level, both using the empirical cut-off power law model and the physical thermal Comptonization (Hua & Titarchuk 1995) model (compTT in XSPEC).

The empirical model gives \( \Gamma = 0.84^{+0.22}_{-0.24} \) and \( E_c = 36^{+14}_{-10} \) keV with a \( \chi^2/(9) = 1.1 \).

In the two fluxes state, even though the parameters are a little bit different, they are consistent within the errors, confirming the hardness ratio result. A good fit (\( \chi^2/(9) = 1.2 \)) on the second data set has been also obtained by using the compTT model (Figure 8). Following, the Comptonization parameters that we have found: a plasma temperature (kT) of 22 ± 2 keV and a Thompson optical depth \( \tau = 2.5 \pm 0.3 \). The flux estimated between 20 and 250 keV was \( 1.2 \times 10^{-9} \) erg cm\(^{-2}\) s\(^{-1}\).

The compTT model does not allow a good fit to the first data set because the low statistic does not permit to constrain the fit parameters.

\footnote{The Crab gives 114 ct s\(^{-1}\) in ISGRI from 20-40 keV.}
4. CONCLUSION

The BHC 1E 1740.7-2942 has been detected by IBIS/ISGRI up to 250 keV in \( \sim 120 \) ks. During the seven months of INTEGRAL monitoring, we measured for this source a flux variation up to 50% on a time scale of months, but without any change in spectral shape. The source 20-40 keV flux increased from 40 mCrab up to 60 mCrab and then decreased to roughly 30 mCrab during October 2003. In the IBIS/ISGRI energy range, the 1E 1740.7-2942 spectral shape is typical of the BHCs in their low/hard state.

The empirical model achieves an energy cut-off of about 40 keV, while a 22 keV Comptonization temperature and an optical depth \( \tau = 2.5 \pm 0.3 \) have been found by using the thermal Comptonization fit. Such a result is consistent with the BeppoSAX Galactic Centre observations performed with the source at the same flux level (Sidoli et al. 1999).

In order to study the source behaviour by using a broad band spectrum, we plan to continue with analysis of the JEM-X and SPI data as well. In conclusion, we underline the IBIS fine imaging capabilities, especially in crowded field like the Galactic Centre.

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Figure 8. Averaged spectrum during the period with higher flux fitted with the \textit{compTT} model.

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