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1E 1740.7–2942: Temporal and spectral evolution from INTEGRAL and RXTE observations[*]

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Abstract. We present results of the monitoring of the black hole candidate 1E 1740.7–2942 with *INTEGRAL*, in combination with simultaneous observations by *RXTE*. We concentrate on broad-band spectra from *INTEGRAL*/IBIS and *RXTE*/PCA instruments. During our observations, the source spent most of its time in the canonical low/hard state with the measured flux variation within a factor of two. In 2003 September the flux started to decline and in 2004 February it was below the sensitivity level of the *INTEGRAL* and *RXTE* instruments. Notably, during the decline phase the spectrum changed, becoming soft and typical of black-hole binaries in the intermediate/soft state.

Key words. gamma rays: observations – radiation mechanisms: non-thermal – stars: individual: 1E 1740.7–2942 – X-rays: binaries – black hole physics

1. Introduction

The X-ray source 1E 1740.7–2942 was discovered in 1984 by the *EINSTEIN* observatory (Hertz & Grindlay 1984) and its hard X-ray emitting nature was firstly reported by Skinner et al. (1987). Based on the spectral shape of its soft γ-ray emission and on the similarities with Cyg X-1, it was classified as a black hole candidate (BHC) and reported as the strongest persistent source in the Galactic Centre region (Sunyaev et al. 1991a).

After the discovery of a double-sided radio-emitting jet, 1E 1740.7–2942 was classified as a microquasar near the Galactic Centre by Mirabel et al. (1992). In 1991, it was also suggested as a possible positron-electron annihilation source due to a *GRANAT*/SIGMA observation of a high energy feature (Bouchet et al. 1991; Sunyaev et al. 1991b) in the spectrum, although its definitive confirmation has not been reported so far.

A simultaneous observation by *CGRO*/OSSE (Jung et al. 1995) has severely constrained the suggested feature intensity with an upper limit substantially below the flux measured by SIGMA (Cordier et al. 1993).

Most of the time, the source is observed in the typical BHC low/hard state, characterised in the X-ray domain by an absorbed power law with the photon index of $\Gamma \sim 1.4$–1.5 (Gallo & Fender 2002) and a cutoff at high energies (Sidoli et al. 1999). The high hydrogen column density toward the source, recently estimated by *Chandra* as $N_{\rm H} \simeq 1.05 \times 10^{23}$ cm^{-2} (Gallo & Fender 2002), does not permit any identification of its optical counterpart.

During *RXTE* observations of 1E 1740.7–2942, an interesting correlation between the time derivative of the flux and the hardness was discovered; no such correlation was found in Cyg X-1 (Smith et al. 2002a). A periodic modulation with amplitude 3–4% at 12.73 ± 0.05 days has been measured and interpreted as the orbital period, suggesting that the object could have a red-giant companion (Smith et al. 2002b). On the contrary, Martí et al. (2000) reported an upper limit for an IR counterpart with *VLT* that seems to exclude a red-giant companion.

Table 1. *INTEGRAL* observations of 1E 1740.7–2942.

Data Set	Observation Period	*INTEGRAL* JD[a]	Revolutions	Exposure (ks)
GCDE 1\a	2003/02/28–2003/04/23	1166.4–1205.6	50–64	690
GCDE 1\b	2003/08/10–2003/10/14	1317.7–1382.2	100–122	720
XTE J1720–318 ToO	2003/02/28–2003/03/02	1154.2–1156.3	46	168
H1743–322 ToO	2003/04/06–2003/04/22	1191.6–1207.5	58, 61, 63	280
GCDE 2\a	2004/02/16–2004/04/20	1507.7–1571.5	164–185	930

[a] The *INTEGRAL* Julian Date (IJD) starts from 2000 January 1 and it corresponds to MJD = IJD + 51544.

Preliminary *INTEGRAL* results have been presented in Del Santo et al. (2004); they reported a flux variability of a factor of 2.5 and the absence of any correlation between photon index and 20–80 keV flux during the low/hard state period. No spectral variability was presented, since the analysis was not completed at that time.

In the present work, we report on one year of almost simultaneous *INTEGRAL* and *RXTE* observations and on the first period of *INTEGRAL* second year observations. Details of the data set and scientific analysis are presented in Sect. 2. Temporal and spectral behaviour are reported in Sect. 3 and are discussed in Sect. 4.

2. Observations and data analysis

We analyse here *INTEGRAL* observations of 1E 1740.7–2942 performed in the framework of the Core Programme. This includes roughly 800 science windows (ScWs) collected during the first year of the Galactic Centre Deep Exposure (GCDE). The total exposure of 1.4 Ms consists of two parts separated by ~4 months. The second year of the GCDE has not been completed yet; 930 ks have been obtained so far and they are included in this work.

We have also added some pointings of the Targets of Opportunity (ToO) observations of XTE J1720–318 (Cadolle Bel et al. 2004) and H1743–322 (Parmar et al. 2003), corresponding to the new *INTEGRAL* source IGR J17464–3213 (Revnivtsev et al. 2003), which included 1E 1740.7–2942 in the field of view. In Table 1, we give the log of the observations. The *INTEGRAL* Core Programme pointings have a duration of 1800 s each for the GCDE and 2200 s each for the ToOs (see Winkler at al. 1999 for Core Programme details).

RXTE has also monitored 1E 1740.7–2942 since its first week of science operations in 1996. The monitoring began as monthly pointings of ~1000–1500 s, the frequency of which has increased over the years to about twice per week now. The *RXTE* observations simultaneous with those by *INTEGRAL* cover three different periods: 2003 March 13–April 26 with the total exposure of ~19 ks; 2003 August 12–24 with an exposure of ~5 ks; and the third one, which consists of only two pointings at the beginning of 2003 October.

We use here data collected with the ISGRI (Lebrun et al. 2003) detector of the imager IBIS (Ubertini et al. 2003) on board *INTEGRAL* for the soft γ-ray range, and with the *RXTE*/PCA detector for the X-rays. The IBIS Partially Coded Field Of View (PCFOV) is 29° × 29° at the zero response, but the full instrument sensitivity is achieved in the 9° × 9° Fully Coded Field of View (FCFOV). For the temporal analysis, we took into account all the data, whereas for the spectral extraction, we selected only pointings with the source within the FCFOV, for which a reliable detector spectral response matrix is available.

Raw data corresponding to each pointing were preprocessed and organised in ScWs by the Integral Science Data Centre (Courvoisier et al. 2003) pipeline. The IBIS scientific data analysis software (Goldwurm et al. 2003) used is included in the *INTEGRAL* off-line analysis software (OSA) release 3.0. The lightcurves were extracted from the images in two energy bands: 30–50 keV and 50–80 keV. The ISGRI spectra were extracted in 16 logarithmic bins and fitted using the response matrix corrected and tested by the IBIS team, and now delivered with the OSA 4.0 release.

The PCA data were analysed with FTOOLS v. 5.2 of the NASA High Energy Astrophysics Science Archive Research Center. Due to the crowded field near the Galactic Centre, the pointing axis was offset by ≳0.5° to avoid nearby sources. To eliminate the spectral contribution from the Galactic diffuse emission as much as possible, a background field was taken at a position symmetrical about the Galactic Centre from the source field. A map of the source and background fields with nearby sources is given in Main et al. (1999).

Spectral fitting was done with XSPEC v. 11.3.1 and single parameter uncertainties calculated at the 90% confidence level, i.e., for $\Delta\chi^2 = 2.71$. Systematic errors of 2% for the ISGRI spectra (which approximately corresponds to the current accuracy of the calibration) and 1% for the PCA spectra have been added in quadrature.

3. Results

During the GCDE 1\a (see Table 1), the 30–50 keV ISGRI count rate increased by 50%. We measured the rate of 2.43 ± 0.04 s^{-1} at the beginning of 2003 March and 3.66 ± 0.33 s^{-1} after one month; these values correspond to ~37 and ~56 mCrab, respectively. After four months, we observed a further increase up to 70 mCrab in the rev. 103 (2003 August), in the same energy range. In 2003 September, the flux began to decline, and at the end of the GCDE 2003 it reached 25 mCrab.

In Fig. 1, we show the PCA lightcurve (8–25 keV) together with two ISGRI lightcurves in the 30–50 keV and 50–80 keV energy ranges. Similar temporal behaviour appears in all three energy bands.

In 2004, when *INTEGRAL* pointed again at the Galactic Centre, the 1E 1740.7–2942 flux was dramatically lower. The source was detected at ~10 mCrab during rev. 164 and
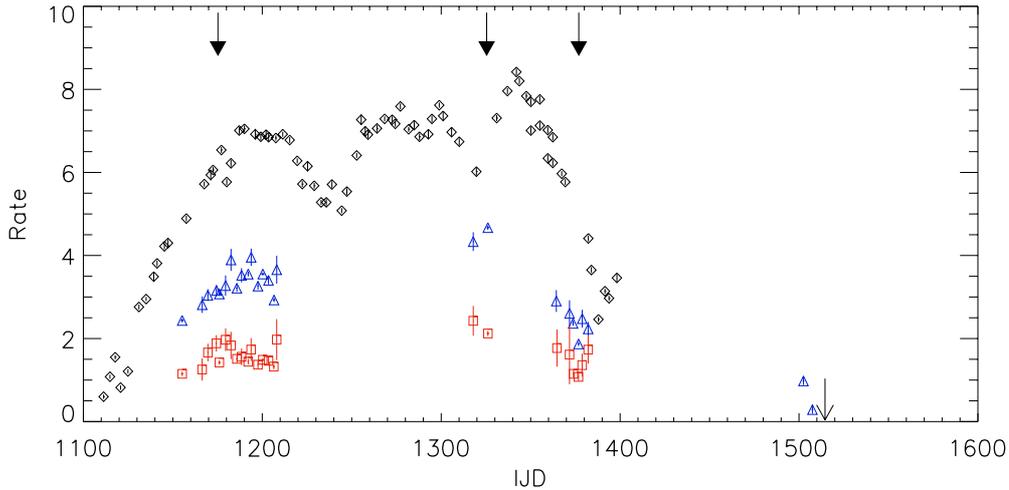
Fig. 1. Lightcurves from PCA (8–25 keV, black diamonds) and from IBIS/ISGRI in the two bands 30–50 keV (blue triangles) and 50–80 keV (red squares). Solid arrows indicate periods used for the spectral analysis. The differences in the sizes of the ISGRI error bars are due to the different exposure times. For clarity, the lightcurve for the 50–80 keV band has been multiplied by 0.6. Simple arrow indicates when the source was no longer visible by IBIS.

~3 mCrab during rev. 165 (2004 February, IJD ~ 1500). Soon after (simple arrow in Fig. 1) no detection was possible either with IBIS in γ-rays (also reported by Grebenev 2004) and with PCA in the X-ray domain (D. M. Smith, private communication). Such behaviour is not unusual, although rare; in spring 1991 the source flux went down to the *GRANAT*/SIGMA sensitivity level in the 40–150 keV range (Cordier et al. 1994).

To study the source spectral evolution, we have chosen three periods corresponding to different flux levels, namely rev. 53, 103 and 119–120, indicated by the solid arrows in Fig. 1. We initially fitted power law and an e-folded power law models. For rev. 53 and 103 we obtained the following best fit parameters with the N_H fixed at 1.05×10^{23} cm^{-2} (using the model `WABS` in XSPEC): the photon index $\Gamma = 1.59 \pm 0.03$ and the e-folding energy $E_c = 146^{+53}_{-32}$ keV with $\chi^2_\nu = 63/54$ for the first period, and $\Gamma = 1.34 \pm 0.03$, $E_c = 90^{+18}_{-13}$ keV with $\chi^2_\nu = 63/54$ for the second one. The mean spectrum of the revolutions 119 and 120 was fitted by a simple power-law with $\Gamma = 2.25 \pm 0.05$, which gives $\chi^2_\nu = 82/51$.

Then, two thermal Comptonization models were used: `COMPTT` of Titarchuk (1994) and `COMPPS`[1] of Poutanen & Svensson (1996).

`COMPPS` is a highly accurate iterative scattering Comptonization model, in which subsequent photon scatterings are directly followed (see, e.g., Zdziarski et al. 2000; Zdziarski et al. 2003): this model has been extensively tested against Monte Carlo results. On the other hand, `COMPTT` is based on an approximate solution of the kinetic equation with some relativistic corrections, and the resulting spectra are only approximate (see, e.g., discussion in the appendix of Zdziarski et al. 1996). Unlike `COMPTT` where the input spectrum of low–energy photons is a Wien law, `COMPPS` assumes for the seed photons a simple blackbody or a multicolor disc blackbody spectrum.

We have allowed a free column density, but constrained it to $N_H \geq 1 \times 10^{23}$ cm^{-2} (Gallo & Fender 2002). With the former we have obtained a relatively low temperatures and high Thomson optical depths for the first two spectra, namely $kT_e = 26^{+6}_{-3}$ keV, $\tau = 1.9^{+0.3}_{-0.2}$, $\chi^2_\nu = 59/54$, and $kT_e = 20 \pm 2$ keV, $\tau = 2.9 \pm 0.1$, $\chi^2_\nu = 55/53$, respectively. We have not been able to constrain the temperature for the third spectrum.

The fit results with the `COMPPS` are given in Table 2. We chose a geometry where Compton scattering is computed by the mean of the approximate treatment of radiative transfer using the escape probability for a sphere. The model also includes Compton reflection (Magdziarz & Zdziarski 1995), which is found to be important for the rev. 103 (F-test probability of 10^{-7}). We also fixed the ionization parameter at 0 as PCA has poor energy resolution. The three absorbed spectra are plotted in Fig. 2; in Fig. 3 the related residuals are shown. Figure 4 shows the intrinsic, unabsorbed spectra for rev. 53 and 119–120.

Our PCA data have been background-subtracted in a non-standard way (Sect. 2). This procedure is supposed to remove, in particular, the Galactic ridge Fe Kα emission. In our PCA data, we see no evidence of any Fe K line; however, this simply may be due to residual inaccuracies of the background subtraction.

Nearby sources are excluded by placing the centre of the 1° field of view about 0.5° 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. The spectra indicate an apparent state transition occurring from rev. 103 to 119–120. The spectra for rev. 53 and 103 are consistent with those typical of black-hole binaries in the hard state whereas that for rev. 119–120 is more typical of the soft or intermediate state (Zdziarski & Gierliński 2004). Surprisingly, the Compton reflection component appears the

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[1] Model available at `ftp://ftp.astro.su.se/pub/juri/XSPEC/COMPPS`

Table 2. The parameters of the PCA/ISGRI spectra fitted with the COMPPS model.

Rev.	$N_H{}^a$ 10^{22} cm^{-2}	kT_{bb} keV	kT_e keV	τ	$\Omega/2\pi$	$F_{bol}{}^b$ erg cm^{-2} s^{-1}	χ^2_ν
53	12^{+2}_{-2}	$0.50^{+0.06}_{-0.11}$	110^{+20}_{-30}	$1.1^{+0.6}_{-0.3}$	$0.3^{+0.2}_{-0.2}$	3.6×10^{-9}	70/51
103	11^{+2}_{-1}	$0.41^{+0.09}_{-0.10}$	150^{+60}_{-50}	$0.9^{+0.4}_{-0.4}$	$0.9^{+0.3}_{-0.2}$	4.8×10^{-9}	50/51
119–120	10^{+1}	$0.68^{+0.06}_{-0.05}$	70^{+11}_{-8}	$1.0^{+0.2}_{-0.2}$	$0.0^{+0.1}$	2.1×10^{-9}	44/47

^{a} Constrained to $\geq 10^{23}$ cm^{-2}.

^{b} The bolometric flux of the unabsorbed best-fit model spectrum.
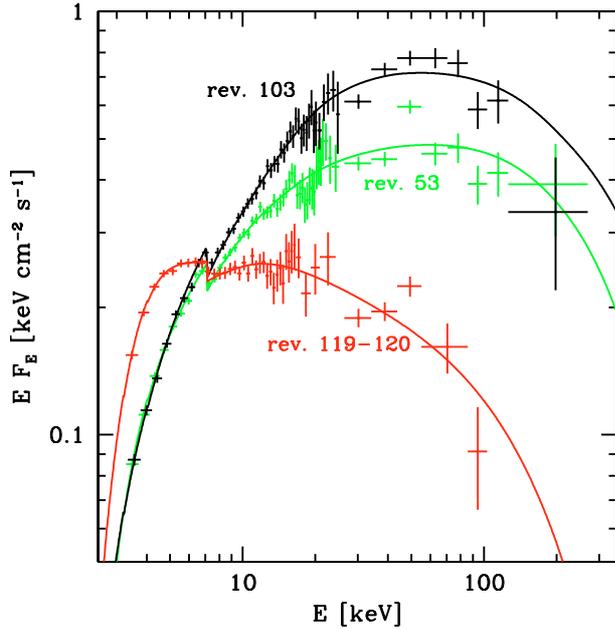
Fig. 2. The observed (absorbed) spectra in rev. 53 (hard state), rev. 103 (hard state) and rev. 119–120 (soft state), as fitted by the thermal Comptonization model COMPPS.
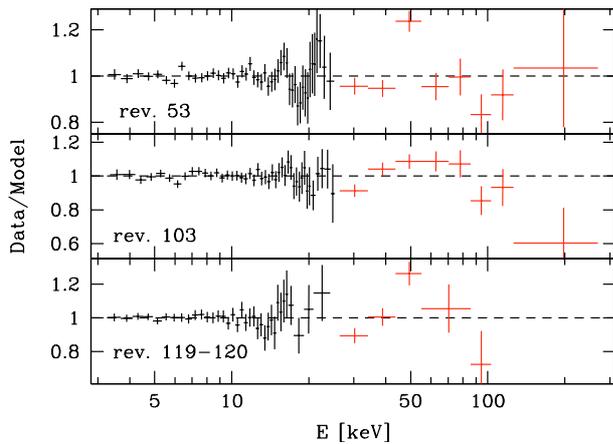
Fig. 3. Residuals for the three data sets of PCA (black, $E < 25$ keV) and IBIS (red, $E > 25$ keV).

weakest in the last data set, which is not typical of black-hole binaries (Gierliński et al. 1999).
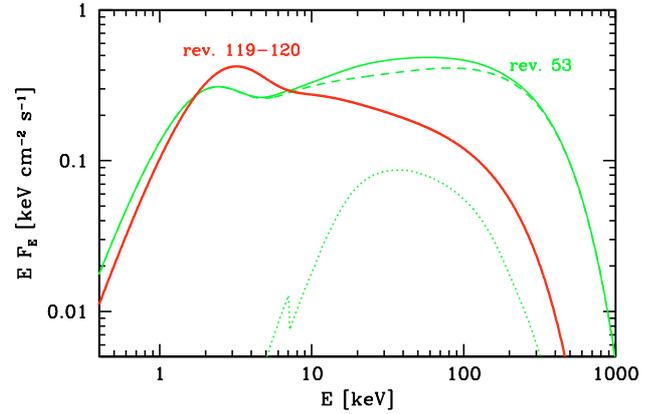
Fig. 4. The unabsorbed thermal Comptonization for rev. 53 (green) and 119–120 (red). For the first spectrum, its components due to thermal Comptonization of blackbody photons (dashed curve) and Compton reflection (dotted curve) are shown.

4. Discussion and conclusions

We have observed several variability patterns of 1E 1740.7–2942. First the estimated bolometric flux increased by ∼1.5 in 6 months (2003 February–August) with an almost constant spectral shape. The spectrum, with a hard X-ray index, a Compton-reflection component, and a cutoff corresponding to $kT_e \sim 100$ keV, is typical of the low/hard state of black-hole binaries, e.g., Cyg X-1 (Gierliński et al. 1997) or GX 339–4 (Wardziński et al. 2002).

However, we observed a spectral state transition. In 2003 October, the flux in the low-energy part of the spectrum increased, and our fits show an increase of the disc blackbody temperature from 0.4–0.5 keV in the hard state up to ∼0.7 keV. The power law had substantially softened, with Γ increasing from 1.3–1.5 to ∼2.3. These spectral characteristics are peculiar to the soft state, e.g., of Cyg X-1 (Gierliński et al. 1999).

Interestingly, the flux of this state was significantly lower than that of the hard state. Although the opposite behaviour, with the flux in the soft state larger than that in the hard state, is most typical of black-hole binaries, the behaviour observed by us is also seen in other low-mass X-ray binaries, e.g., in GX 339–4. Smith et al. (2002a) often observed GRS 1758-258 at low luminosities in the typical soft state. This is due to the existence of two accretion solutions at a given accretion rate, which allows for such a hysteretic behaviour (e.g., Zdziarski et al. 2004). This transient-like type of behaviour is

consistent with occasional quenching of the X-ray emission of 1E 1740.7–2942, as confirmed by our study.

Assuming a distance of 8.5 kpc and 10 $M_\odot$ for the compact object, we estimated the bolometric luminosity of 1E 1740.7–2942 during rev. 53, rev. 103 and rev. 119-120 to be $\sim$0.01 $L_{\rm Edd}$, $\sim$0.03 $L_{\rm Edd}$ and $\sim$0.02 $L_{\rm Edd}$, respectively. Our results are consistent with Maccarone (2003), who shows that the state transition luminosities are at about 1–4% of the Eddington rate for most of the X-ray binaries.

An interesting feature of the observed soft state is the unusual weakness of the Compton reflection component, which usually becomes stronger in the soft state (e.g., Gierliński et al. 1999) than in the hard state. We suggest that it is possible that the accretion disc in 1E 1740.7–2942 precesses, and we could have caught the source at the moment when the disc was edge-on, causing the reflection to be not observable.

In our spectra integrated over time scales of 20 ks and 100 ks, there is no evidence of any high energy feature. In the energy range 485–535 keV in $\sim$1.4 Ms integration time, De Cesare et al. (2004) report an upper limit at the 2σ level of roughly 2.0×10^{-4} ph cm^{-2} s^{-1}, including systematic errors. Based on this result, the 2σ upper limits for our time scales of 20 ks and 100 ks are 1.7×10^{-3} and 7.4×10^{-4} ph cm^{-2} s^{-1}, respectively.

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