UNVEILING THE HIGH ENERGY TAIL OF 1E 1740.7–2942 WITH INTEGRAL*

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ABSTRACT

The microquasar 1E 1740.7–2942 is observed with INTEGRAL since Spring 2003. Here, we report on the source high-energy behavior by using the first three years of data collected with SPI and IBIS telescopes, taking advantage of the instruments complementarity. Light curves analysis showed two main states for 1E 1740.7–2942: the canonical low/hard state of black hole candidates (BHCs) and a “dim” state, characterized by an ~20 times fainter emission, detected only below 50 keV and when summing more than 1 Ms of data. For the first time the continuum of the low/hard state has been measured up to ~600 keV with a spectrum that is well represented by a thermal Comptonization plus an additional component necessary to fit the data above 200 keV. This high-energy component could be related to nonthermal processes as already observed in other BHCs. Alternatively, we show that a model composed of two thermal Comptonizations provides an equally representative description of the data: the temperature of the first population of electrons results as (~30 keV while the second, (~200 keV, is fixed at 100 keV. Finally, searching for 511 keV line showed no feature, either narrow or broad, transient or persistent.

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

1. INTRODUCTION

1E 1740.7–2942 is a bright hard X-ray source located at less than 1° from the Galactic center (GC; Hertz & Grindlay 1984; Cook et al. 1991; Roques et al. 1991), classified as Black Hole Candidate (BHC; e.g., Sunyaev et al. 1991). When Mirabel et al. (1992) discovered a double-sided radio jet reaching large angular distances from the core (~1°), the “microquasar” class was born with 1E 1740.7–2942 as its first member. All observations performed so far revealed that 1E 1740.7–2942 spends most of the time in the canonical Low/Hard (LH) state of BHCs (Smith et al. 2002 and references therein). In this state, the X-ray spectrum is empirically described by a power law with a photon index of 1.4–1.5 plus a roll-over around 100 keV (Zdziarski 2000). In a few occasions, soft spectral states have been observed during the simultaneous International Gamma-Ray Astrophysics Laboratory (INTEGRAL) and Rossi X-Ray Timing Explorer (RXTE) broadband spectral study performed in 2003 reports on an intermediate/soft spectral state that occurred just before the source quenching (Del Santo et al. 2005).

In 1990, the SIGMA telescope on board GRANAT detected a broad line around the electron–positron annihilation energy (Bouchet et al. 1991; Sunyaev et al. 1991). This transient feature appeared clearly during a 13 hr observation and then possibly in two further occasions but at a less significant level. Numerous works dedicated to similar line searches have followed and all led to negative conclusions (see, for example, Cheng et al. 1998 and references therein). In this context, it is interesting to perform a deep analysis of SPI data in this energy domain, and to seek for any feature around 511 keV associated with 1E 1740.7–2942.

The superior energy resolution of the SPI telescope allows for a specific dedicated study of this topic. Indeed, for the first time, an instrument is capable to look for a narrow feature in this particular source. During the first year of observations, no evidence for point source emission at 511 keV has been detected with SPI. The upper limit at 3.5σ level is 1.6 × 10^{-4} ph cm^{-2} s^{-1} for a narrow line (Teegarden & Watanabe 2006) while the IBIS data set a 2σ upper limit of 1.6 × 10^{-4} ph cm^{-2} s^{-1} in the 535–585 keV energy band for an exposure time equal to 1.5 Ms (De Cesare et al. 2006).

We report here on the high-energy spectral properties as revealed with the INTEGRAL high-energy instruments. The sensitivity and imaging capabilities of IBIS/ISGRI allow to determine the contribution of all the emitting sources in large fields of view (FOV), while the SPI telescope brings some additional spectral information above 150–200 keV with a deep investigation of the 511 keV line status.

2. INTEGRAL OBSERVATIONS

Since its launch on 2002 October 17, INTEGRAL (Winkler et al. 2003) observed the GC region 2 times per year, in the Spring and Fall visibility windows. Observations are performed in dither pattern with each pointing (named science window (SCW)) lasting between 1700 and 3600 s. We have analyzed all public data collected between Spring 2003 and Fall 2005 by the spectrometer SPI (Vedrenne et al. 2003) and the imager IBIS (Ubertini et al. 2003).

After image analysis and cleaning, the useful data set consists in about 3500 exposures for a total useful time of 8 Ms divided in six periods (Spring and Fall, 2003, 2004, and 2005, see Table 1).

3. DATA ANALYSIS

3.1. IBIS

The unprecedented IBIS (Ubertini et al. 2003) angular resolution combined with sensitivity (less than 1 mCrab for 1 Ms;
Table 1: Observations Log

| Period      | Start Time (UT) | End Time (UT) | Pointings (or SCW) | Exposure (Ms) |
|-------------|-----------------|---------------|--------------------|---------------|
| 2003 Spring | 2003 Feb 28     | 2003 Apr 22   | 298/434            | 0.62/0.86     |
| 2003 Autumn | 2003 Aug 19     | 2003 Oct 9    | 717/709            | 2.26/2.14     |
| 2004 Spring | 2004 Feb 17     | 2004 Apr 20   | 547/544            | 1.29/1.18     |
| 2004 Autumn | 2004 Aug 21     | 2004 Oct 28   | 747/610            | 1.78/1.35     |
| 2005 Spring | 2005 Feb 16     | 2005 Apr 20   | 802/697            | 1.48/1.27     |
| 2005 Autumn | 2005 Aug 16     | 2005 Oct 5    | 353/407            | 0.70/0.93     |

Bird et al. (2007) allows us to resolve sources lying in crowded field, as the GC. The IBIS Partially Coded FOV is 29° × 29° at zero response, but the full instrument sensitivity is achieved in the 9° × 9° Fully Coded FOV. For our aims, we selected IBIS observations including 1E 1740.7–2942 in the FOV up to 50% coding (19° × 19°; see Table 1). In this paper, we refer to data collected with the IBIS low energy detector, ISGRI (Lebrun et al. 2003), covering the 15–1000 keV energy band.

The IBIS scientific analysis has been performed using the INTEGRAL off-line analysis software, OSA (Goldwurm et al. 2003). The IBIS/ISGRI images have been extracted SCW by SCW in three energy bands, i.e., 20–40 keV, 40–100 keV, and 100–300 keV. Mosaic images by revolution have been used to measure fluxes of all sources within 2° off 1E 1740.7–2942 used as input for SPI analysis (see Section 3.2.1).

Spectra have been extracted SCW by SCW in 35 logarithmic bins spanning from 20 keV to 600 keV. The response matrices (RMF and ARF) used for spectral fitting are those delivered with OSA 5.1 distribution. To take into account the improvements included in the matrices delivered in OSA-7, we modified the ISGRI spectra by the factors corresponding to ratios between the Crab spectra measured respectively with OSA-5 and OSA-7 packages.

### 3.2. SPI

In addition to its spectroscopic capability, SPI can image the sky with a spatial resolution of 2:6 (FWHM) over an FOV of 30° (Roques et al. 2003).

The signal recorded by SPI camera consists of the contributions from sources in the FOV plus background. A system of equations is to be solved to determine sources and background intensities. In order to reduce the number of unknowns necessary to describe the data, we introduce some known information on both components. For the background, the relative count rates of the 19 Ge detectors (uniformity maps) are very stable and can be kept constant within each considered period (see Table 1) while the global normalization factor is determined by 6 hr intervals. Concerning the sources, timescales are chosen in function of the source intensity and temporal behavior, the faintest ones being considered as constant. Detailed description of the data analysis algorithms and methods, using matrices available in the OSA package, can be found in Bouchet et al. (2005, 2008).

Exposures were selected on the basis of their pointing direction which is here required to be less than 12° from 1E 1740.7–2942. This ensures to keep the maximum sensitivity for 1E 1740.7–2942 and reduces the total FOV spanned by the observations, leading to a simpler description of the sky.

The region around 1E 1740.7–2942 is particularly crowded (Bird et al. 2007; Belanger et al. 2006). Due to the modest SPI angular resolution (∼2:6), the spectrum directly extracted at 1E 1740.7–2942 position may contain contributions from other weak/close/“not seen” sources. Nevertheless, it is possible to obtain the emission spectrum of 1E 1740.7–2942 from SPI data thanks to the information provided by IBIS/ISGRI.

For that, we need to determine the fraction of the flux extracted at the 1E 1740.7–2942 position that actually originates from the source itself. This has been determined by a set of simulations. The first step consists to extract the flux of all emitting sources in its neighborhood measured by IBIS. We then simulate the counts projected by them on the SPI detector plane, taking into account the complete (angular dependent) SPI response. Applying the standard analysis method to these simulated data gives us a “1E 1740.7–2942 region” flux that we can compare to the 1E 1740.7–2942 flux injected as input in the simulation. The ratio between these two fluxes corresponds to the factor we have to apply to correct the flux measured by SPI at the 1E 1740.7–2942 position in the observed data to obtain the flux attributable to the source itself. This procedure has been repeated in a few broad bands and for each observational period. This cleaning procedure takes into account a global contribution of all potential contaminations, and the corresponding IBIS error bars can be considered very small compared to the SPI ones. However, the contamination effect which is important in the low-energy domain, becomes negligible when going up to higher energies. In fact, as can be seen in Figure 1, above 100 keV only 1E 1740.7–2942 is detected with a significant flux within 2° off the source.

#### 3.2.2. Modeling the Diffuse Background: $e^+e^−$ Annihilation Line and Positronium Emission

The SPI design makes it sensitive to both source and diffuse emissions. On the other hand, the GC region is dominated in the ∼300 keV up to 511 keV domain by the Galactic diffuse annihilation radiation. The annihilation line emission is detected with SPI with a flux of ∼1 × 10$^{−3}$ ph cm$^{−2}$ s$^{−1}$ and an ∼8° axisymmetric Gaussian spatial distribution centered at the GC (Kn¨odlseder et al. 2005; Bouchet et al. 2008). 1E 1740.7–2942 continuum emission around 511 keV is expected to be (in the “hard state”) of the order of a few percent of the galactic background line intensity. It is thus crucial for our work to determine this latter accurately. This task has been performed using a larger data set (see Bouchet et al. 2008), which includes observations at larger latitudes and longitudes.

The diffuse emission has been described in this process by two Gaussians while eight known sources has been introduced as potential emitters (including 1E 1740.7–2942). Thus, the fitting algorithm (based on a χ$^2$ minimization method, see Bouchet et al. 2008 for more details) is able to adjust simultaneously point source fluxes and the diffuse component contribution in the 511 keV line domain. The energy centroid and width of the positron annihilation line were fixed at 511 keV and 2.5 keV FWHM, respectively (Churazov et al. 2005). The fit procedure results in a model consisting in two Gaussians with FWHM of 3:2 and 10:8 and fluxes of 2.3 and 7.0 × 10$^{−4}$ ph cm$^{−2}$ s$^{−1}$, respectively, as the best description of the annihilation line spatial distribution and flux, without any significant emission from the point sources (see Weidenspointner et al. 2008, supplementary material, for independent analysis).
Concerning the positronium, we assumed it to follow the same two Gaussians spatial distribution as the 511 keV line and determined its flux by the same fitting procedure. This results in a positronium fraction of 0.98, a value that is compatible with all SPI measurements (Bouchet et al. 2008).

Finally, the contributions of these Galactic diffuse components on the detector plane are subtracted from the data in the counts space.

4. RESULTS

4.1. Temporal Analysis

Table 2 gives the 1E 1740.7–2942 averaged fluxes for the different periods in two broad bands. The source mean hardnesses in 2003 and 2005 are similar indicating that 1E 1740.7–2942 was in the LH state. Its intensity is rather stable on the revolution timescale, within 40 and 60 mCrab in the 20–40 keV energy band, except in the Fall 2003 period, during which a continuous decrease, from 85 to 27 mCrab, preceded the quenching observed in 2004 (Del Santo et al. 2005). Indeed, in 2004, the source was weaker with no detection above 5σ within individual revolutions. The data accumulation by periods allows to determine a mean flux of a few mCrab.

A dedicated study in a narrow (10 keV) band around 511 keV has been used to search for any transient emission from the annihilation process. We have tested 0.5 day and 1 day timescales without detecting any significant emission. The actual duration of each temporal bin depends on the observational planning and is thus variable. The 2σ upper limits range from \(4.2 \times 10^{-4}\) ph cm\(^{-2}\) s\(^{-1}\) to \(6.8 \times 10^{-4}\) ph cm\(^{-2}\) s\(^{-1}\) for a 0.5 day timescale, and from \(3.1 \times 10^{-4}\) ph cm\(^{-2}\) s\(^{-1}\) to \(2.3 \times 10^{-3}\) ph cm\(^{-2}\) s\(^{-1}\) with an averaged value of \(6.8 \times 10^{-4}\) ph cm\(^{-2}\) s\(^{-1}\) for a day timescale. These results are illustrated by the distribution of the measurements in σ unit for the 12 hr timescale (Figure 2, solid line) while a 2σ upper limit of \(4.8 \times 10^{-5}\) ph cm\(^{-2}\) s\(^{-1}\) is deduced for the total duration (see Table 2 for upper limits by periods).

Table 2

| Period          | 2003 Spring | 2003 Fall | 2004 Spring | 2004 Fall | 2005 Spring | 2005 Fall | 2003 & 2005 | 2004 Total Period |
|-----------------|-------------|-----------|-------------|-----------|-------------|-----------|-------------|-------------------|
| \(F_{20-40\,\text{keV}}\) mCrab | 51          | 75        | 2.6         | 2.7       | 53          | 53        | 62          |                   |
| \(F_{40-100\,\text{keV}}\) mCrab | 60          | 95        | –           | –         | 56          | 54        | 68          |                   |
| \(F_{511\,\text{keV}} \times 10^{-4}\) ph cm\(^{-2}\) s\(^{-1}\) | <1.22       | <0.66     | <1.02       | <1.10     | <1.10       | <1.32     | <0.48       | <0.74             | <0.40             |

Note. For the 511 keV feature, 2σ upper limits are given for a narrow line (\(\Delta E = 10\) keV).

Figure 1. IBIS images of the 1E region in 2003 (left) and 2005 (right) in the 100–300 keV energy range. The cyan circles are 2° in radius.
Finally, a study has been performed for a broad feature, based on the 240 keV width (FWHM) reported in SIGMA data (Bouchet et al. 1991; Sunyaev et al. 1991). The continuum emission (not negligible in such a broad band) has been estimated by the mean flux over the considered period and subtracted from the data. Here too, no significant excess above the expected continuum emission can be claimed over the 2003–2005 periods (Figure 2, dashed line). The 2σ upper limits span from $1.7 \times 10^{-3}$ ph cm$^{-2}$ s$^{-1}$ to $1.3 \times 10^{-2}$ ph cm$^{-2}$ s$^{-1}$ with an averaged value close to $3 \times 10^{-3}$ ph cm$^{-2}$ s$^{-1}$, for a 0.5 day timescale, and from $1.2 \times 10^{-3}$ ph cm$^{-2}$ s$^{-1}$ to $8.8 \times 10^{-3}$ ph cm$^{-2}$ s$^{-1}$ with an averaged value of $2.5 \times 10^{-3}$ ph cm$^{-2}$ s$^{-1}$, for a day timescale. Note that the line flux reported by SIGMA was $1.3 \times 10^{-2}$ ph cm$^{-2}$ s$^{-1}$.

4.2. Spectral Analysis

After correction of the SPI data (Section 3.2.1), SPI and IBIS/ISGRI spectra have been fitted simultaneously. We have first built averaged spectra for 2003 and 2005 separately. In a second step, being the source in a similar state during these two periods, we achieved an averaged LH state spectrum in order to obtain a better statistics at high energy.

Spectral fitting of these three data sets have been performed with the standard XSPEC version 11.3.1 tools. We have included a normalization factor during each fitting procedure and noticed that it remains between 0.94 and 1.0 (ISGRI factor fixed to 1.0). Indeed, SPI spectra are very similar to the ISGRI ones (as illustrated in Figure 3), even if they present some fluctuations at low energy, easily understandable in terms of residual cross-talk between neighboring sources. However, this effect is limited and even negligible above $\sim 100$ keV.

During both periods, the source emission extends up to 500 keV with a spectral shape presenting a clear cutoff around $\sim 140$ keV. This cutoff is undoubtedly required by the $\chi^2$ statistics: we obtain $\chi^2$ of 10 and 6.6 (for 71 dof) with a power-law model, while adding a high-energy cutoff these values result as 0.9 and 1.14 (70 dof).
Table 3
The Best Fit Parameters for the Combined ISGRI and SPI 1E 1740.7–2942 Spectra with Comptonization Model (COMPTT; Titarchuk 1994)

| Period        | ($kT_1$, $kT_2$) | $\tau_1$ | ($kT_1$, $kT_2$) | $\tau_2$ | $\chi^2$ (dof) | F-test a |
|---------------|------------------|----------|------------------|----------|----------------|----------|
| 2003          | (50.1 ± 2.6, 0.10 ± 0.06) | 1.1 (69) | (48.1 ± 2.0, 0.10 ± 0.05) | 1.8 (69) |
| 2005          | (45.4 ± 2.7, 1.10 ± 0.08) | 1.35 (69) |
| 2003+2005     | (29.4 ± 3.1, 1.6 ± 0.1) | 100 2.2 ± 0.8 1.07 (67) 10^{-8} |

Note. $T_0$ is fixed to 0.3 keV. For the 2003+2005 spectrum, the second line corresponds to a two Comptonization model ($kT_1$, $\tau_1$, ($kT_2$, $\tau_2$) with the second seed photon temperature fixed to ($kT_3$, and ($kT_4$, fixed to 100 keV (see the text).

a For the presence of a second Comptonization component.

Then we used a Comptonization model (COMPTT; Titarchuk 1994) as this mechanism is expected to play the major role in our energy domain and to produce such a cutoff. We obtain electron temperatures ($kT_3$) of roughly 50 keV with optical depths ($\tau$) close to 1 (see Table 3) that are quite canonical values for this class of objects. However, the 2005 and total (2003+2005) spectra give high $\chi^2$ values (1.35 and 1.8 for 69 dof). These, combined with residuals at high energy, suggest the presence of a supplemental component explaining data points above 200 keV. We have studied this hypothesis in the total spectrum since its statistics allows us to better constrain the spectral parameters. In order to model the high-energy data, we added a power-law component and obtained a $\chi^2$ close to 1 with a photon index of 1.9 ± 0.1. The plasma temperature is thus decreased to 27 ± 2.2 keV with $\tau = 1.9 ± 0.25$.

Even though this two components model is quite satisfying, with a classical explanation of a nonthermal process responsible of the power-law emission, as in high soft states, we also made an attempt to test whether alternative scenario with only thermal mechanisms were excluded.

Indeed, a two (thermal) Comptonization model gives a similarly acceptable description of the spectrum. The constraints on the parameters are very poor, so we impose a second population temperature at 100 keV and consider that it Comptonizes photons coming from the first Comptonizing region, i.e., ($kT_{seed_2}$ = ($kT_3$, $\sim$ 30 keV. The optical depths of both regions are found similar and compatible ($1.6 ± 0.1$ and 2.2 ± 0.8) while the $\chi^2$ = 1.07 (67 dof) leads to an F-test probability of $\sim 10^{-8}$ for the existence of such a second component. The results corresponding to this scenario are displayed in Figure 3 and Table 3. Since this analysis is strongly based on ISGRI data at low energy, we performed a fit using SPI data above 100 keV only (no contamination effect) and found that the parameters are unchanged.

5. DISCUSSION AND CONCLUSIONS

Even though the 1E 1740.7–2942 region is particularly difficult to analyze with the SPI telescope, we have demonstrated that the use of the IBIS and SPI complementarity allows us to get a common spectrum of 1E 1740.7–2942 itself. Thanks to the inputs from the ISGRI detector, we have estimated the relative contribution of all sources active in a 1° circle around 1E 1740.7–2942 and showed that we can reconstruct the SPI 1E 1740.7–2942 spectrum with a precision better than 5% relatively to the ISGRI one.

Two main states have been observed: the canonical LH state with a flux of $\sim$50 mCrab and 60 mCrab in the 20–40 keV and 40–100 keV bands, respectively, and a “dim” state during which the flux of 1E 1740.7–2942 is below the IBIS/ISGRI detection limit on the revolution timescale and detected at a level of 2.6–2.7 mCrab ($14\sigma$) when integrated over $\sim$three months periods.

Spectra have been built for periods when the source was clearly detected (2003, 2005, and the sum of both). The problematic of the SPI analysis leads to rather large error bars but in all cases, the emission extends up to $\sim$500 keV, even though a high energy cutoff appears clearly in the data. When adjusted with a single Comptonization model, an additional component is strongly required to fit the data above 200 keV, particularly in the total spectrum because of the very significant emission at these energies.

This high-energy component has been observed in several BHCs (e.g., McConnell et al. 2000; Zdziarski et al. 2001), usually during high soft spectral states, and explained as Compton upscattering by a nonthermal electrons population (Zdziarski & Gierliński 2004). As alternative scenario, jets can easily produce hard X-ray emission via synchrotron radiation in addition to the inverse Compton scattering (Markoff et al. 2003). However, by computing radio-to-gamma-ray spectral energy distribution (SED), Bosch-Ramon et al. (2006) ruled out the jet emission for the hard X-ray spectrum of 1E 1740.7–2942, favoring rather the corona origin.

Recently, high energy excesses have been observed in transient BHCs when in LH state (i.e., Del Santo et al. 2008; Joinet et al. 2007) that could be the result of spatial/temporal variations in plasma parameters (Malzac & Jourdain 2000). We have demonstrated with our data that, for the LH state spectrum of 1E 1740.7–2942, a model consisting of two thermal Comptonization components, with a second hotter population ($kT_2$ fixed to 100 keV) interacting with the photons produced by the first one, provides an interesting alternative to the nonthermal scenarios. This two temperature model could either correspond to two distinct heating mechanisms/regions or reflect the presence of a gradient of temperature in the Comptonizing plasma.

Finally, even though the complexity of the considered region makes it difficult to attribute firmly the detected emission to 1E 1740.7–2942, the presence of photons with energy greater than several hundreds of keV in a more or less persistent way (something as half or $2/3$ of the time), together with previously reported annihilation emission, support a scenario in which 1E 1740.7–2942 is a source of positrons. Indeed, as proposed by van Oss & Belyanin (1995), a plasma detected with a temperature much lower than 1 MeV is able to produce positrons through photon–photon absorption. The basic argument is that the hard X-ray emission comes from the regions close to the central black hole, where the gravity field is very strong. The high local temperature is thus lowered, leading to an observed value far from the relativistic domain, while pairs are created in the innermost disk and driven away. Annihilation outbursts could occur when the accretion flow intercepts the pair wind (van Oss & Belyanin 1995).

Concerning the 511 keV line itself, no feature, broad or narrow, transient or persistent, has been found, confirming the rare occurrence of such a phenomenon in line with numerous different studies already performed on this topic. It is worth to note, however, that SPI/INTEGRAL gives the first opportunity to investigate it in terms of narrow feature (a few keV) with actual constraints on its parameters. Unfortunately, any strong conclusion would require more information on the expected duration (and width) of the emission.
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