INTEGRAL high-energy monitoring of the X-ray burster KS 1741—293

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ABSTRACT
KS 1741—293, discovered in 1989 by the X-ray camera TTM on the Kvant module of the Mir space station and identified as an X-ray burster, had not been detected in the hard X-ray band until the advent of the INTEGRAL observatory. Moreover, this source has recently been the object of scientific discussion, being also associated with a nearby extended radio source that in principle could be the supernova remnant produced by the accretion-induced collapse in the binary system. Our long-term monitoring with INTEGRAL, covering the period from 2003 February to 2005 May, confirms that KS 1741—293 is transient in the soft and hard X-ray bands. When the source is active, from a simultaneous JEM-X and IBIS data analysis, we provide a wide-band spectrum from 5 to 100 keV, which can be fitted by a two-component model: a multiple blackbody for the soft emission and a Comptonized or a cut-off power-law model for the hard component. Finally, by the detection of two X-ray bursts with JEM-X, we confirm the bursting nature of KS 1741—293, including this source in the class of hard-tailed X-ray bursters.

Key words: X-rays: binaries – X-rays: bursts – X-rays: individual: KS 1741—293

1 INTRODUCTION
The first type I X-ray bursting sources were discovered with SAS-3 (Lewin et al. 1976) and OSO-8 (Swank et al. 1977). Woosley & Taam (1976) and Maraschi & Cavaliere (1976) independently discussed the origin of the phenomenon: type I X-ray bursts are explained by thermonuclear flashes of the material accreting from the companion star on the surface of the neutron star. All X-ray sources showing type I bursts are low-mass X-ray binaries (LMXBs). The properties and the theory of X-ray bursts are discussed in the review of Lewin, van Paradijs & Taam (1995).

The X-ray burster KS 1741—293 was first reported by in’t Zand et al. (1991) as one of the two new transient sources near the Galactic Centre (GC) detected during observations performed with the X-ray wide-field camera TTM on board the Kvant module of the Mir space station. KS 1741—293 was detected on three consecutive days in the energy range 5.7–27.2 keV, during which time it exhibited two type I X-ray bursts. KS 1741—293 may be identified with either MXB 1743—29 or MXB 1742—29, two bursting sources detected in 1976 with SAS-3. The single-peaked burst profile excludes the identification of KS 1741—293 with MXB 1743—29 (in’t Zand et al. 1991). Therefore KS 1741—293 and MXB 1742—29 are likely to be the same source. In the BeppoSAX era (1996–2002), KS 1741—293 was detected, together with a large sample of Galactic sources, during the Wide Field Camera (WFC) monitoring of the GC region (in’t Zand et al. 2004) at a peak flux of the order of 30 mCrab in the 2–28 keV energy range. From Medium Energy Concentrator Spectrometer (MECS, on board BeppoSAX) observations, Sidoli et al. (1999) report a 2–10 keV luminosity of the source $<10^{35}$ and $10^{36}$ erg s$^{-1}$ (corrected for absorption) in 1997 September and 1998 March, respectively, assuming a distance of 8.5 kpc. KS 1741—293 was also detected by ASCA during 107 pointing observations of a $5' \times 5'$ region around the GC showing an apparent variability by a factor of 50, while in contrast no burst has been found (Sakano et al. 2002). No hard X-ray detection has been reported by the first gamma-ray imager SIGMA on board the GRANAT satellite and indeed the source is not in the hard X-ray SIGMA catalogue, covering the 40–100 keV range (Revnivtsev et al. 2004). KS 1741—293

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is listed in the BATSE/CGR0 instrument deep sample as one of the 179 sources monitored through the operational life of CGRO (Harmon et al. 2004) even though it is not a firm detection. KS 1741−293 is reported in the third IBIS catalogue (Bird et al. 2007) at a significance level of 67σ with a flux of 5.2 ± 0.1 mCrab in the 20–40 keV band.

A search for optical, infrared and radio counterparts was made by Cherepashchuk et al. (1994) without finding a firm candidate. A Chandra source inside all the KS 1741−293 high-energy error circles has been proposed by Marti et al. (2007) as a possible counterpart. These authors discuss also a possible association with a non-thermal radio nebula that could be the supernova remnant produced by accretion-induced collapse in the binary system. However, this association is still under debate because of the estimated age (about 500 yr) of the supernova remnant, which is very low for a LMXB.

In this work we show that, during 2003 February and 2005 May, KS 1741−293 has been clearly detected in the hard X-ray energy band (>20 keV) with the IBIS imager during two visibility periods, while during the other observations it appears to be in a quiescent state. Using the combined data from the X-ray monitor JEM-X and the IBIS hard X-ray telescope, we obtain in the second period of visibility a wide-band X-ray spectrum from about 5 to 100 keV. We show for the first time the soft component simultaneously with the hard tail for this source. We report also the detection of two bursts with JEM-X and their temporal and spectral properties.

In Section 2 we present the observations and the data analysis tools. In Section 3 we present the data analysis results from flux monitoring, spectral analysis and X-ray burst analysis. Finally the conclusions are summarized in Section 4.

2 OBSERVATIONS AND DATA ANALYSIS

The X-ray and gamma-ray observatory INTEGRAL was launched on 2002 October 17 by a Russian PROTON launcher. The satellite orbits the Earth in 3 d, along a highly eccentric orbit, and the observing time is optimized by this choice. The wide-field gamma-ray imaging and wide-band spectral capabilities of INTEGRAL, coupled with the core programme strategy (Winkler et al. 2003), are a powerful tool to investigate deeply the high-energy behaviour of X-ray bursters as first reported by Bazzano et al. (2004). The scientific instruments on board are the hard X-ray and gamma-ray imager IBIS (Ubertini et al. 2003) covering the energy band 20 keV−10 MeV, the gamma-ray spectrometer SPI (Vedrenne et al. 2003), which works in the same energy band as IBIS but is devoted to fine spectroscopy, the X-ray monitor JEM-X (3–35 keV) (Lund et al. 2003), and the optical camera OMC (Mas-Hesse et al. 2003). The angular resolution of SPI is not good enough to disentangle KS 1741−293 from the nearby sources in a crowded region such as the GC. In the optical band the X-ray sources located in the GC region are generally obscured. Thus SPI and OMC data are not useful for our purposes and we did not analyse them.

We have used the public data from revolution 46 (2003 February 28) to revolution 185 (2004 April 19), and the core programme data from revolution 46 to revolution 307 (2005 May 19). We have selected the data from all pointings in which KS 1741−293 is in the fully coded field of view (FCFV, equal to a square of 9° × 9° and a circle of 4:8 diameter for IBIS and JEM-X respectively), where the instrumental sensitivity has the best value.

The data reduction was carried out with release 5.1 of the off-line scientific analysis (OSA) software (Courvoisier et al. 2003) for IBIS and the last release 6.0 for JEM-X. The reason for this choice is that OSA 6.0 has been released recently and includes relevant updates in the analysis methods of JEM-X but not for IBIS.

In the OSA environment, the standard analysis pipeline requires us to create first a set of data (observation group) and then to run the single tasks. Therefore we have created an observation group for each KS 1741−293 visibility period and we have then performed the data reduction in two steps, obtaining first from the raw data the single-pointing images, and afterwards a mosaic image combining all of the single images.

During the visibility periods when the source is detectable, the IBIS mean spectrum has been obtained from the single-pointing spectra. Because the quiescent emission of the source is below the JEM-X sensitivity for each individual pointing, the JEM-X mean spectrum has been extracted from the mosaic image. The JEM-X burst analysis has been performed by selecting the appropriate good time intervals.

For the spectral analysis, we have used the standard fitting tool XSPEC, version 11.3.1.

3 SCIENTIFIC RESULTS

3.1 Flux monitoring

Table 1 shows the log of our IBIS observations. KS 1741−293 has been clearly detected in the visibility periods labelled as 1 and 3, with a 20–40 keV significance of 28σ and 62σ respectively. The average flux during these periods does not show any meaningful variation, ranging from 9.4 ± 0.3 mCrab during period 1 to 11.1 ± 0.2 mCrab for period 3. For this last period the statistics are good enough to allow a study of the temporal behaviour of the source. When the source is in a quiescent state, i.e. the flux is below the instrumental sensitivity, we report the 20–40 keV flux with upper limits estimated at a significance level of 3σ.

The image mosaic during period 3 is shown in Fig. 1, where the sources are labelled according to Liu et al. (2001). KS 1741−293 and SLX 1744−299 are associated with MXB 1742−29 and MXB 1743−29 respectively, detected by SAS-3 in 1976. Note that at that time 1A 1742−294 (24 arcmin off our source) was not resolved.

| Period | Rev. | Start (MJD) | End (MJD) | Exp. (ks) | Significance | Average flux (mCrab) |
|--------|------|-------------|-----------|-----------|--------------|---------------------|
| 1      | 46–63 | 52698       | 52792     | 306       | 28σ          | 9.4 ± 0.3           |
| 2      | 103–120 | 52871       | 52921     | 1333      | not visible  | <0.5               |
| 3      | 164–185 | 53052       | 53115     | 921       | 62σ          | 11.1 ± 0.2          |
| 4      | 229–249 | 53246       | 53306     | 159       | not visible  | <1.4               |
| 5      | 291–307 | 53431       | 53479     | 43        | not visible  | <3                  |
by SAS-3. In contrast, thanks to the good IBIS angular resolution (12 arcmin) and to the long exposure, we are able to obtain a good separation between these two sources.

In Fig. 2 we show, during period 3, the light curves in the 20–40 and 40–60 keV energy bands and the hardness ratio, here defined as the ratio \(\text{count}(40–60 \text{ keV}) / \text{count}(20–40 \text{ keV})\) between the high-energy and low-energy bands. To increase the statistics of the single IBIS pointings, we have grouped all the IBIS pointing data associated with one satellite revolution. The bin width used for the flux integration is different from one revolution to another, ranging from about 30 min (one IBIS pointing) to 30 h. This explains the differences in the error bars. The light curve in the 20–40 keV band shows a variability of about a factor of 4, smoothly increasing from 0.8 to 2.7 count s\(^{-1}\) in 30 d. Moreover, we find an indication of spectral softening at \textit{INTEGRAL} Julian Date (IJD) equal to about 1550.

The JEM-X observations are reported in Table 2. JEM-X was operated with JMX2 until revolution 170 and since then it has been operating mainly with JMX1. Our source is detected in the 4–15 and 15–30 keV energy bands at significance levels of 27\(\sigma\) and 16\(\sigma\) respectively in period 3b from 2004 March 6 (revolution 170, IJD = 1526) to April 20 (revolution 185, IJD = 1571), while it is not detected during periods 1 and 3a (Table 2). The lack of JEM-X detection during these periods can be explained by both the shorter exposure and the source flux variability on temporal scales of the order of a few days as we observed during period 3. The JEM-X exposures during periods 1 and 3a are factors of 2.5 and 4.2 lower than in period 3b. Assuming a constant flux during all the observations and taking into account the shorter exposure, we would expect a signal at 17\(\sigma\) and 13\(\sigma\) in periods 1 and 3a, respectively. However, the flux is not constant. In fact, the 20–40 keV IBIS light curve during period 3 (Fig. 2, top plot) shows that the flux can vary by more than a factor of 2, reaching its maximum (26 mCrab) during period 3b, which is when we have the JEM-X detection. The mean 20–40 keV flux in period 3b (18 mCrab) is about twice that during period 1 (9.4 mCrab). Thus we would expect from JEM-X in period 1 a signal that is a factor of 2 less than the above calculations (17\(\sigma\)), that is, of about 9\(\sigma\). This is a marginal significance level for a detection with a coded mask telescope. The same arguments can be applied to the lack of detection in period 3a. Moreover, during periods 1 and 3a the signal could be even less significant since we have an indication of spectral softening during period 3b (Fig. 2, bottom plot) when the source is detected by JEM-X.

3.2 Spectral analysis

The IBIS/ISGRI average spectrum has been extracted in the 20–150 keV energy range during the two periods corresponding to source detection, namely period 1 and period 3 (see Table 1). We have fitted
the extracted spectra with a simple power law, a cut-off power law and a Comptonized model with xspec (v.11.3.2). During period 1 we find that all these models provide a good agreement with the data, with marginal evidence of improvement by using the cut-off power law or a Comptonized model (the probability of a chance improvement in $\chi^2$ is $\sim$7 per cent using the F-test). During period 3 the increased statistics, due to the longer exposure than for period 1, enable us confidently to exclude a simple power-law model (with reduced $\chi^2 = 3.3$ with five degrees of freedom). We obtain a comparably good fit with a cut-off power law [$\chi^2(v) = 0.5(4)$] and with a Comptonized model [$\chi^2(v) = 0.5(4)$]. We find no evidence of spectral variability between periods 1 and 3 in the 20–150 keV energy range.

In order to constrain the model parameters, we have extended our spectral analysis to low energies of 4 keV thanks to the simultaneous detection with JEM-X during period 3. Analysis at low energies of this source has already been performed by Sidoli et al. (1999) with BeppoSAX/MECS observations taken on 1998 March 31. From their analysis, the 2–10 keV spectrum was equally well modelled by a simple power law, a thermal bremsstrahlung and a blackbody. Interestingly, in the two former cases, high photoelectric absorption was required by the data, with an equivalent hydrogen column density $N_H$ of a few $\times 10^{21}$ cm$^{-2}$.

We then performed a simultaneous analysis of the JEM-X and IBIS/ISGRI spectra (Fig. 3) on the basis of the previous results. A constant normalization factor has been introduced in the fitting models in order to take into account the systematic errors in the knowledge of the absolute JEM-X and IBIS/ISGRI inter-calibration. We find that, assuming a cut-off power-law model at high energies, none of the previous models used to fit the low energies (Sidoli et al. 1999) can fit the JEM-X data. In contrast, a multicolour disc blackbody component (diskbb in xspec), typically invoked to model the emission from an accretion disc, provides a good fit to the data. The available statistics do not allow us to distinguish between a cut-off power law and a Comptonized model at high energies, thus we obtained similar results also assuming a Comptonized model. At the same time, we were able confidently to exclude a simple power-law model with $\chi^2(v) = 4.8(7)$ rather than a cut-off power law or a Comptonized model. The best-fitting model parameters from these analyses are summarized in Table 3.

We also compared the 2–10 keV flux obtained in 1998 March from the BeppoSAX/MECS observations (Sidoli et al. 1999) with our estimate from the best-fitting models in the same energy range. We find a 2–10 keV flux of $2.4 \times 10^{-10}$ cm$^{-2}$ s$^{-1}$ that is consistent with the previous measure.

Assuming a distance of 8.5 kpc for this source as quoted by Sidoli et al. (1999), we computed the source luminosity from the flux measured during period 3 in the 20–100 keV energy band as $1.7 \times 10^{38}$ erg s$^{-1}$.

### 3.3 X-ray bursts

Two X-ray bursts from KS 1741–293 were detected in the 4–15 keV band by the JEM-X telescope during integral revolutions 53 (2003 March 22) and 63 (2003 April 22). On the instrumental image of the first burst (see Fig. 4) we have superimposed the IBIS position as it is reported with good accuracy (0.6-arcmin 90 per cent error circle) in the survey of Bird et al. (2007). Note that the JEM-X positional accuracy (3-arcmin 90 per cent error circle) is lower than the IBIS one because of the shorter exposure time. As the JEM-X position of KS 1741–293, obtained during the X-ray burst, is in agreement with IBIS, the burst is firmly associated with our source.

The 1-s resolved light curves obtained from the JEM-X data exhibit two X-ray bursts in the energy range 4–15 keV, one in revolution 53 (science window 58) and the other in revolution 63 (science window 92). Both bursts lasted around 20 s, with maximum fluxes of 1.3 and 2.1 Crab respectively. The burst morphology (Fig. 5) confirms previous observations with a single-peaked time profile unlike the double-peaked time profile reported for MXB 1743–29 (in’t Zand et al. 1991).

The JEM-X spectra during the bursts have been extracted by selecting the good time intervals (GTIs) 1176.359–1176.360 and 1207.4116–1297.4120 IJD for the first and second bursts respectively. Both spectra have been fitted with a blackbody model (Fig. 6), with a temperature $kT_{bb}$ equal to $2.1_{-0.3}^{+0.5}$ keV for the first burst and $2.5_{-0.4}^{+0.5}$ keV for the second one at 90 per cent confidence level. The

### Table 2. KS 1741–293 JEM-X observations. The source significance and the average flux are reported in the 4–15 keV (SigmaI, FluxI) and 15–30 keV (SigmaII, FluxII) energy bands.

| Period | Rev. | Start (MJD) | End (MJD) | Exp. (ks) | SigmaI | FluxI (mCrab) | SigmaII | FluxII (mCrab) |
|--------|------|------------|----------|----------|--------|--------------|---------|---------------|
| 1      | 46–63 | 52698      | 52792    | 66       | not visible | $<1.5$ | not visible | $<2$ |
| 2      | 103–120 | 52871       | 52921    | 413      | not visible | $<0.5$ | not visible | $<1$ |
| 3a     | 164–169 | 53052       | 53069    | 39       | not visible | $<2$ | not visible | $<2$ |
| 3b     | 170–185 | 53070       | 53115    | 164      | 27       | 11.6 $\pm$ 0.5 | 16 | 20.2 $\pm$ 1.5 |
| 4      | 229–249 | 53246       | 53306    | 77       | not visible | $<2$ | not visible | $<1.7$ |
| 5      | 291–307 | 53431       | 53479    | 16       | not visible | $<2.5$ | not visible | $<3$ |

### Table 3. Best-fitting parameters from a simultaneous IBIS JEM-X spectral analysis during period 3 assuming a multicolour disc blackbody component plus a cut-off power law (cutoffpl in xspec) or a Comptonized model (ComTT in xspec) with a plan geometry. $T_0$ is the temperature at the inner disc radius, $E_{cut}$ is the cut-off energy, $T_0$ is the input soft photon (Wien) temperature, and $kT_e$ and $\tau$ are the plasma temperature and optical depth, respectively. The errors are at the 68 per cent significance level.

| Model | $N_H$ $10^{22}$ cm$^{-2}$ | $T_0$ keV | $\Gamma$ | $E_{cut}$ keV | $T_0$ keV | $kT_e$ keV | $\tau$ | Flux (2–100 keV) $10^{-10}$ erg cm$^{-2}$ s$^{-1}$ | $\chi^2(v)$ |
|-------|-----------------|---------|--------|-------------|---------|-----------|----|------------------------|-----------|
| const $^a$ wabs(+cutoffpl) | $35 \pm 10$ $^{+12}_{-8}$ | $1.0 \pm 0.2$ | $2.0 \pm 0.2$ | $90_{-20}^{+40}$ | $-$ | $-$ | $-$ | $7.7$ | $1.1(6)$ |
| const $^a$ wabs(+ComTT) | $31 \pm 8$ | $1.1 \pm 0.2$ | $-$ | $0.1$ | $28_{-4}^{+16}$ | $1.0 \pm 0.5$ | $7.7$ | $1.0(6)$ |
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Figure 3. IBIS/ISGRI and JEM-X KS 1741–293 average spectrum obtained in the third visibility period. The solid line is the best-fitting model assuming a multicomponent blackbody (dot-dashed line) plus a Comptonized model (dotted line).

Figure 4. JEM-X KS 1741–293 image in the 4–15 keV energy band during the bursts that occurred in revolution 53 (2003 March 22) with, superimposed, the IBIS positions with a 0.6-arcmin 90 per cent error circle radius. The JEM-X error circle radius with the same confidence level (not plotted in this picture) is equal to 3 arcmin. The 1A 1742–294 source is not detected because of a very short (about 20 s) integration time.

4–20 keV fluxes are $3.6 \times 10^{-9}$ and $1.1 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, respectively. Assuming a distance of 8.5 kpc, the radii of the first and the second bursts are $3.9^{+1.1}_{-0.9}$ and $4.9^{+2.1}_{-1.5}$ km respectively.

The burst emission is not detected by IBIS. This lack of a high-energy (>20 keV) detection can be explained by the soft spectrum of the source emission during the burst activity and by the short exposure. Indeed, taking into account the IBIS sensitivity, we estimate a $2\sigma$ flux upper limit of 140 mCrab in the 20–40 keV energy band for a 20-s exposure (i.e. the burst time interval). Extrapolating the JEM-X burst spectrum, we obtain in this band fluxes of 9 and 7 mCrab for the first and second bursts respectively. These values are significantly below the IBIS 20-s upper limit.

4 CONCLUSIONS

Despite KS 1741–293 being reported for the first time many years ago (in’t Zand et al. 1991), this source was poorly studied, in

Figure 5. Light curves of the two bursts detected during revolutions 53 (upper plot) and 63 (bottom plot) in the 4–15 keV band. The zero time corresponds to IJD 1176.359 and 1207.412 for revolutions 53 and 63 respectively.

Figure 6. JEM-X KS 1741–293 spectrum obtained during the bursts detected in revolutions 53 and 63. The zero time corresponds to IJD 1176.359 and 1207.412 for revolutions 53 and 63 respectively.

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4 CONCLUSIONS

Despite KS 1741–293 being reported for the first time many years ago (in’t Zand et al. 1991), this source was poorly studied, in
particular at high energies. This was mainly due to the source faintness, in both the soft and hard X-ray energy range, and to its position in the crowded GC region, requiring good angular resolution. The IBIS angular resolution, good sensitivity, large field of view and long exposure in the region of the GC are then appropriate to carry out this task. In particular, the IBIS angular resolution (12 arcmin) has allowed us clearly to resolve KS 1741−293 from other X-ray sources in the field of view, especially from the nearest source 1A 1742−294.

Using open time and core programme data, we have monitored, with mCrab sensitivity in the 20–40 keV band, the hard X-ray emission for a time period of more then 2 years. We have obtained a clear IBIS detection only during the visibility periods 52698–52792 and 53052–53115 MJD, showing that hard X-ray emission from this source is not persistent.

The measured orbital periods for LMXBs range from a fraction of an hour to tens of hours (see White et al. 1995). During the third visibility period the source shows a smooth flux variation by a factor of 4, without evidence of periodicity in the light curve on a timescale of 60 d. During the first visibility period there is no evidence of source flux variation.

We have obtained for the first time a wide band (from 5 to 100 keV) spectrum using the simultaneous JEM-X and IBIS data. The spectrum is fitted with a two-component model. While the blackbody soft component could originate from the surface of an accretion disc, the neutron star surface, or both, the hard tail [fitted by a cut-off power law or by a Comptonized model (Titarchuk 1994)] is due to a Comptonization of soft photons in a hot plasma around the neutron star.

We have detected two type I X-ray bursts with JEM-X, at a position clearly consistent with the IBIS KS 1741−293 detection. The temporal analysis with JEM-X confirms the single-peaked bursts of KS 1741−293, as first reported by in’t Zand et al. (1991).

The spectral properties of the hard-tailed LMXBs are discussed by Di Salvo & Stella (2002). KS 1741−293 can be included in this class of sources.

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