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# First hard X-ray detection and broad-band X-ray study of the unidentified transient AX J1949.8+2534

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## ABSTRACT

We present the results from *INTEGRAL* and *Swift*/XRT observations of the hitherto poorly studied unidentified X-ray transient AX J1949.8+2534, and on archival multiwavelength observations of field objects. Bright hard X-ray outbursts have been discovered above 20 keV for the first time, the measured duty cycle and dynamic range are of the order of  $\sim 4$  per cent and  $\geq 630$ , respectively. The source was also detected during a low soft X-ray state ( $\sim 2 \times 10^{-12}$  erg cm<sup>-2</sup> s<sup>-1</sup>) thanks to a *Swift*/XRT followup, which allowed for the first time to perform a soft X-ray spectral analysis as well as significantly improve the source positional uncertainty from arcminute to arcsecond size. From archival near-infrared data, we pinpointed two bright objects as most likely counterparts whose photometric properties are compatible with an early-type spectral nature. This strongly supports a high-mass X-ray binary (HMXB) scenario for AX J1949.8+2534, specifically a Supergiant Fast X-ray Transient (more likely) or alternatively a Be HMXB.

**Key words:** X-rays: binaries – X-rays: individual: AX J1949.8–2534.

## 1 INTRODUCTION

AX J1949.8+2534 is a hitherto poorly studied unidentified X-ray source. It was discovered during the *ASCA* Galactic Plane Survey (Sugizaki et al. 2001) whose observations were carried out from 1996 March to 1999 April, covering the inner Galactic disc at  $|l| \leq 45^\circ$  and  $|b| \leq 0.4$ . The source was detected with a significance of  $3.6\sigma$  and  $21.6\sigma$  in the energy bands 0.7–2 keV and 2–10 keV, respectively. No spectral information is available, the reported 2–10 keV *ASCA* count rate (Sugizaki et al. 2001) converts into an absorbed X-ray flux of  $\sim 8 \times 10^{-12}$  erg cm<sup>-2</sup> s<sup>-1</sup> ( $\sim 6 \times 10^{-12}$  erg cm<sup>-2</sup> s<sup>-1</sup>) if we assume a power law spectral shape with  $\Gamma = 1$  ( $\Gamma = 2$ ). The uncertainty on the source position is  $\sim 1$  arcmin as is typical for *ASCA* X-ray sources, this prohibits the search for counterparts at lower energies (i.e. optical and infrared) which is essential to firmly identify the nature of the source.

For many years, the *ASCA* detection represented the only information available in the literature. Interestingly, Sguera et al. (2015b) have recently reported the first hard X-ray detection of AX J1949.8+2534 above 20 keV. Their communication contained only very short information about the hard X-ray activity detected by *INTEGRAL*, as obtained from analysis of near real time data pertaining to public observations of the Cygnus region.

Here, we present the results of a more detailed spectral and temporal analysis of the consolidated *INTEGRAL* data pertaining to the outburst reported by Sguera et al. (2015b), together with the investigation of additional archival *INTEGRAL* data, with the aim of finding further hard X-ray activity from the source. We also report a Target of Opportunity (ToO) observation made with the *Swift* satellite in order to refine the error circle to arcsecond size as well as to characterize for the first time the spectral shape in the soft X-ray band.

## 2 INTEGRAL

### 2.1 Data analysis

For our study, we used data collected with the ISGRI detector (Lebrun et al. 2003) which is the lower energy layer of the IBIS coded mask telescope (Ubertini et al. 2003) onboard *INTEGRAL* (Winkler et al. 2003). The reduction and analysis of the data have been performed by using the Offline Scientific Analysis version 10.1. For IBIS/ISGRI spectral analysis, we used the standard 13 energy channel response matrix available at the *INTEGRAL* Science Data Centre (ISDC). *INTEGRAL* observations during each orbit (‘revolution’, lasting  $\sim 2.6$  d or 170 ks) are divided into short pointings (Science Window, ScW) having a typical duration of  $\sim 2000$  s.

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**Table 1.** Log of IBIS/ISGRI observations used for our study on AX J1949.8+2534. Orbits in boldface contain the IBIS/ISGRI detections reported in Section 2.2.

Telescope orbit	Date	Observation target	Exposure (ks)
1600	2015 October 18–20	Cyg X-1	~22
1601	2015 October 22–23	Cyg X-1	~8
1602	2015 October 23–25	GPS+Cyg X-1	~14
1603	2015 October 26–28	GPS+Cyg X-1	~7
<b>1605<sup>a</sup></b>	2015 October 31–November 02	GPS+Cyg X-1	~16
1606	2015 November 03	GPS	~3.5
1607	2015 November 05–07	GPS+Cyg X-1	~22
1609	2015 November 12–13	Cyg X-1	~6
1610	2015 November 14–15	Cyg X-1	~12
1611	2015 November 18	GPS	~3.5
1613	2015 November 23	GPS	~4
1614	2015 November 24–26	GPS+Cyg X-1	~20
1616	2015 December 01	GPS+Cyg X-1	~7
1618	2015 December 05	GPS	~4
1619	2015 December 09	GPS	~4
1621	2015 December 13–15	Cyg X-1	~15
1624	2015 December 21–23	GPS+Cyg X-1	~18
1626	2015 December 26–28	ToO V404 Cyg	~17
1627	2015 December 29–31	ToO V404 Cyg	~16
<b>1628</b>	2016 December 31–January 02	ToO V404 Cyg	~18
<b>1629</b>	2016 January 03–05	ToO V404 Cyg	~19
			~255

<sup>a</sup>Detection originally reported by Sguera et al. (2015).

Our total data set consists of all public observations which covered the Cygnus region (i.e. Galactic Plane Scans, GPS, ToO observations of V404 Cyg and targeted observations of Cyg X-1) immediately before and after the hard X-ray detection of AX J1949.8+2534 reported by Sguera et al. (2015b). The corresponding data set amounts to a total exposure of ~255 ks (see Table 1 for details).

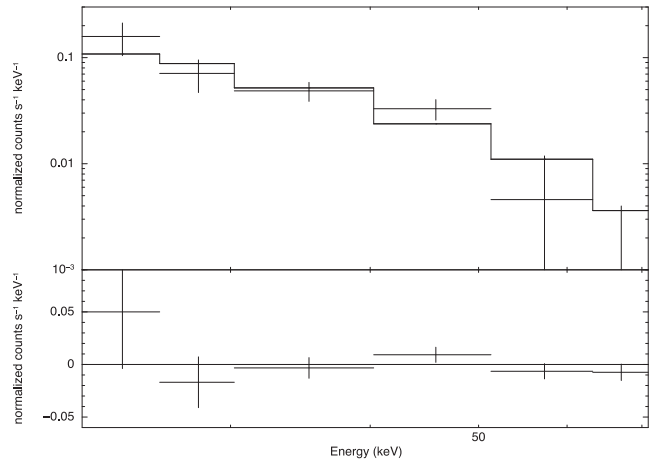
We performed an analysis of the full data set on two different time-scales, i.e. at ScW level as well as at revolution level, in order to search for newly discovered X-ray activity from the source detected with a significance equal or greater than at least  $5\sigma$  and  $7\sigma$ , respectively. Such detection thresholds are essential to avoid false detections/excesses caused by background noise (e.g. Bird et al. 2016). The search was initially performed in the energy band 22–60 keV; this choice takes into account the evolution of the IBIS/ISGRI energy threshold that occurred from revolution number ~900 on. When a significant detection was found, we have also checked the detection at higher energies (i.e. 60–100 keV) or in other different ranges (i.e. 22–30, 30–60 and 22–40 keV). We note that the sensitivity limit for a persistent source detected at  $5\sigma$  level (22–60 keV) in only one ScW of about 2000 s duration is ~18 mCrab (Krivonos et al. 2010).

The X-ray monitor JEM-X (Lund et al. 2003) makes observations simultaneously with IBIS/ISGRI, although with a much smaller Field of View (FoV), providing images in the softer energy band 3–35 keV. JEM-X data were analysed when the source was in its FoV in order to search for X-ray activity in both energy bands 3–10 and 10–20 keV.

Throughout the paper, the spectral analysis was performed using XSPEC version 12.9.0 and, unless stated otherwise, errors are quoted at the 90 per cent confidence level for one single parameter of interest.

**Table 2.** List of *INTEGRAL* orbits during which significant source detections (i.e.  $\geq 7\sigma$ ) were obtained in the energy band 22–60 keV. The table also lists the date of the beginning of the outburst, significance detection over the entire activity, average flux and approximate duration.

Orbit (no.)	Date (MJD)	Significance ( $\sigma$ )	Flux (mCrab)	Duration (days)
1605	57327.35	7.1	$10.0 \pm 1.4$	~1.5
1628	57387.65	7.1	$10.6 \pm 1.5$	~2
1629	57390.31	7.3	$9.5 \pm 1.3$	~2

**Figure 1.** IBIS/ISGRI spectrum of AX J1949.8+2534 (during revolution no. 1605) best fitted by a blackbody. The lower panel shows the residuals from the fit.

## 2.2 Results

We report on newly discovered hard X-ray transient activity from AX J1949.8+2534, the first ever above 20 keV. Hard X-ray detections with IBIS/ISGRI were obtained by analysing data in revolutions number 1605, 1628 and 1629. Table 2 reports a summary of the outbursts' main characteristics.

### 2.2.1 IBIS/ISGRI detection in revolution 1605

First, we note that AX J1949.8+2534 was not detected in any single revolution from no. 1600 to 1603, nor in their mosaic for a total on source exposure of ~50 ks. As a result, we inferred a  $3\sigma$  upper limit of ~2 mCrab (22–60 keV).

Conversely, AX J1949.8+2534 was detected with a significance of  $7.1\sigma$  (22–60 keV) during revolution 1605 (~14 ks on-source exposure) from 2015 November 01 08:28 (UTC) to 2015 November 02 15:48 (UTC). No detection was obtained in the energy band 60–100 keV. The measured average 22–60 keV flux is  $10.0 \pm 1.4$  mCrab (or  $\sim 1.1 \times 10^{-10}$  erg cm<sup>-2</sup> s<sup>-1</sup>). The source was never significantly detected at ScW level (i.e.  $\geq 5\sigma$ ) at any point of the observation, indicating that no major flaring activity took place on short time-scales (i.e. ~2000 s).

The extracted IBIS/ISGRI spectrum was fitted by a power law with  $\Gamma = 2.9 \pm 0.8$  ( $\chi^2_\nu = 1.7$ , 4 degrees of freedom) or alternatively by a thermal bremsstrahlung with  $kT = 24^{+22}_{-9}$  keV ( $\chi^2_\nu = 1.5$ , 4 degrees of freedom). The best fit was achieved by using a blackbody model ( $\chi^2_\nu = 1.15$ , 4 degrees of freedom) with  $kT = 7.9^{+1.8}_{-1.9}$  keV. The average 18–60 keV (20–40 keV) flux is  $1.1 \times 10^{-10}$  erg cm<sup>-2</sup> s<sup>-1</sup> ( $7.8 \times 10^{-11}$  erg cm<sup>-2</sup> s<sup>-1</sup>). Fig. 1 shows the blackbody data-to-model fit with the corresponding residuals.

The source was also in the JEM–X FoV during this observation, however in the combined JEM–X1+JEM–X2 mosaic it was not detected in both bands 3–10 and 10–20 keV (on-source exposure of  $\sim 4.8$  ks). The inferred  $3\sigma$  upper limit (3–10 keV) is of the order of  $\sim 2$  mCrab or  $4.4 \times 10^{-11}$  erg cm $^{-2}$  s $^{-1}$ .

AX J1949.8+2534 was not detected in any single revolution after no. 1605 (from no. 1606 to 1627), nor in their mosaic for a total on source exposure of  $\sim 150$  ks. We inferred a  $3\sigma$  upper limit of  $\sim 1.2$  mCrab (22–60 keV). This, combined with the other upper limit from revolutions no. 1600 to 1603, allows us to confidently constrain the duration of the transient hard X-ray activity detected in revolution no. 1605 to no longer than  $\sim 1.5$  d.

### 2.2.2 IBIS/ISGRI detection in revolutions 1628 and 1629

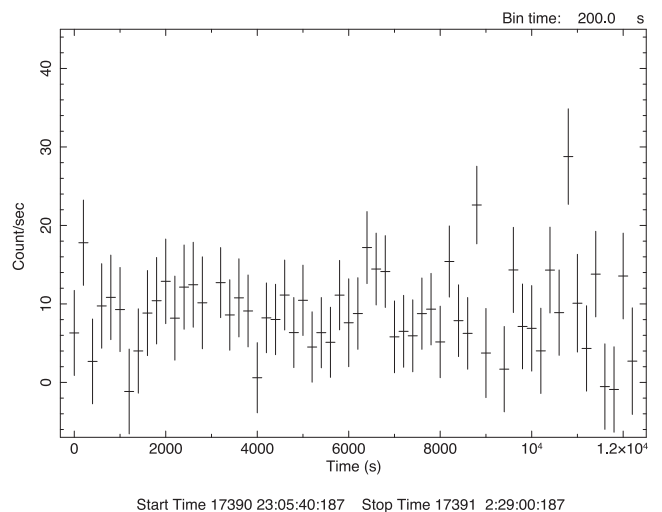
Renewed hard X-ray activity from AX J1949.8+2534 was detected again by IBIS/ISGRI towards the end of 2015 December. In fact, the source was detected in the energy band 22–60 keV in both revolutions no. 1628 ( $\sim 7.1\sigma$ ,  $\sim 18$  ks on-source exposure) and no. 1629 ( $\sim 7.3\sigma$ ,  $\sim 19$  ks on-source exposure), spanning the time range from 2015 December 31 15:40 (UTC) to 2016 January 05 10:37 (UTC). The source showed no sign of flux variation on revolution time-scale since the 22–60 keV measured average fluxes are fully consistent with each other within their uncertainties ( $10.6 \pm 1.5$  and  $9.5 \pm 1.3$  mCrab, respectively). Unfortunately, the source was not in the IBIS/ISGRI FoV again throughout revolutions after no. 1629 so we cannot constrain the duration of this latest transient hard X-ray activity, we can only infer a lower limit of  $\sim 4$  d.

We stacked the data for revolutions no. 1628 and 1629 with the aim of increasing the statistics of the detection. AX J1949.8+2534 was detected in the mosaic with a significance of  $9.8\sigma$  (22–60 keV) for a total on-source exposure of  $\sim 37$  ks. No detection was obtained in the higher energy band 60–100 keV. The 22–60 keV measured average flux is  $9.30 \pm 0.95$  mCrab, which is fully compatible within the errors with that measured during the hard X-ray activity detected two months earlier during revolution no. 1605. The source was never in the JEM–X FoV during these latest observations.

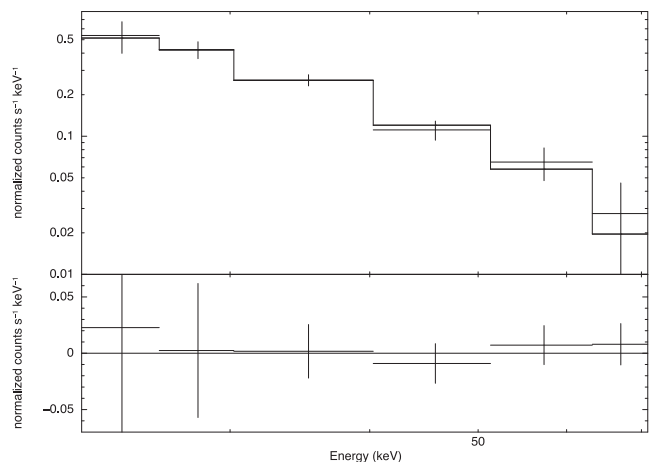
We performed an investigation at ScW level of both revolutions no. 1628 and 1629 with the aim of searching for possible flaring activity on short time-scales (i.e.  $\sim 2000$  s). Interestingly, we found that the source was occasionally bright enough to be significantly detected even at ScW level during the course of the observations. Table 3 lists the single ScWs during which significant detections (i.e.  $\geq 5\sigma$ ) were achieved. In particular, we focused our attention on the four consecutive ScWs from no. 20 to 23 in revolution no. 1629 (they span a continuous temporal range of  $\sim 3.5$  h) in order to extract an IBIS/ISGRI light curve with a fine temporal bin of 200 s. As it can be

**Table 3.** List of single ScWs in revolutions no. 1628 and 1629 during which significant source detections (i.e.  $\geq 5\sigma$ ) were achieved in the energy band 22–60 keV.

Telescope orbit (no.)	ScW (no.)	Flux (mCrab)	Significance ( $\sigma$ )
1628	30	$66.5 \pm 10.2$	6.5
1629	20	$29.4 \pm 5.2$	5.6
1629	21	$22.8 \pm 4.2$	5.4
1629	22	$24.8 \pm 4.3$	5.8
1629	23	$28.5 \pm 5.1$	5.6
1629	33	$76.1 \pm 13.4$	5.7
1629	35	$47.6 \pm 9.2$	5.2

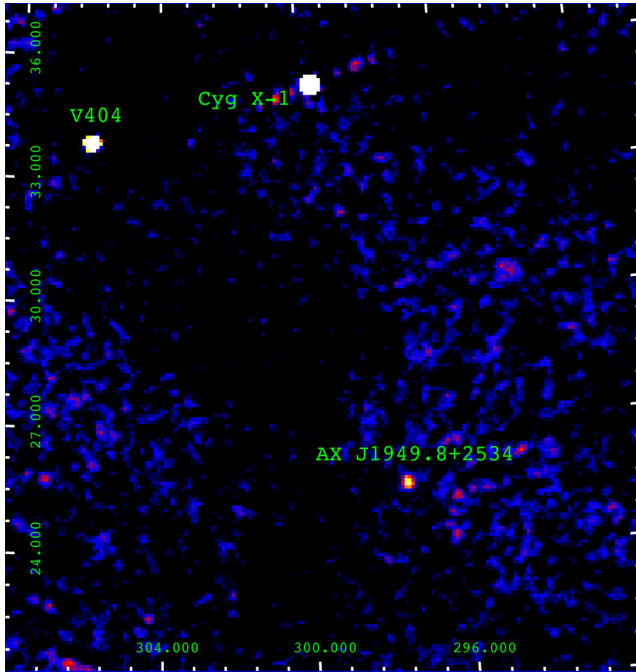


**Figure 2.** IBIS/ISGRI light curve (22–60 keV, 200 s bin time) of AX J1949.8+2534 extracted from the four consecutive ScWs no. 20 to 23 in revolution 1629.



**Figure 3.** IBIS/ISGRI spectrum of AX J1949.8+2534 (during revolution 1629) fitted by a blackbody. The lower panel shows the residuals from the fit.

seen from Fig. 2, AX J1949.8+2534 mainly shows an enhanced and rather constant flux with no major sign of flares. Only towards the end of the light curve there is sign of possibly a couple of short flares on  $\sim 200$  s time-scale, the strongest one (having a significance of  $4.7\sigma$ ) reached a peak-flux of  $180 \pm 38$  mCrab or  $(2 \pm 0.4) \times 10^{-9}$  erg cm $^{-2}$  s $^{-1}$  (22–60 keV). To establish if the source statistically varied during the entire light curve, we fitted it with a constant and applied the  $\chi^2$  test. It was found a chance probability of 0.4 that this result is due to chance, i.e. the source is variable at only 60 per cent confidence level which rejects the hypothesis of variability. We have also made a mosaic of such four consecutive ScWs, this yielded to a source detection of  $\sim 11\sigma$  (22–60 keV). Given the good statistics, we extracted an IBIS/ISGRI spectrum which was best fitted by a blackbody ( $\chi^2_\nu = 0.9$ , 4 degrees of freedom, see Fig. 3) with  $kT = 8.6^{+1.4}_{-1.2}$  keV and average 18–60 keV (20–40 keV) flux of  $\sim 6 \times 10^{-10}$  erg cm $^{-2}$  s $^{-1}$  ( $\sim 4 \times 10^{-10}$  erg cm $^{-2}$  s $^{-1}$ ). We note that both a thermal bremsstrahlung ( $\chi^2_\nu = 0.6$ , 4 degrees of freedom) and a power law ( $\chi^2_\nu = 0.75$ , 4 degrees of freedom) provided a good description of the spectrum as well, with best-fitting parameter values equal to  $kT = 34^{+23}_{-11}$  keV and



**Figure 4.** IBIS/ISGRI significance mosaic map (22–60 keV) obtained by summing revolutions 1605, 1628 and 1629. The source AX J1949.8+2534 is detected at  $\sim 11\sigma$  level.

$\Gamma = 2.5 \pm 0.5$ , respectively. All such best-fitting parameter values are consistent, within their uncertainties, with those obtained from the detection during revolution no. 1605.

### 2.2.3 IBIS/ISGRI refined position and upper limit

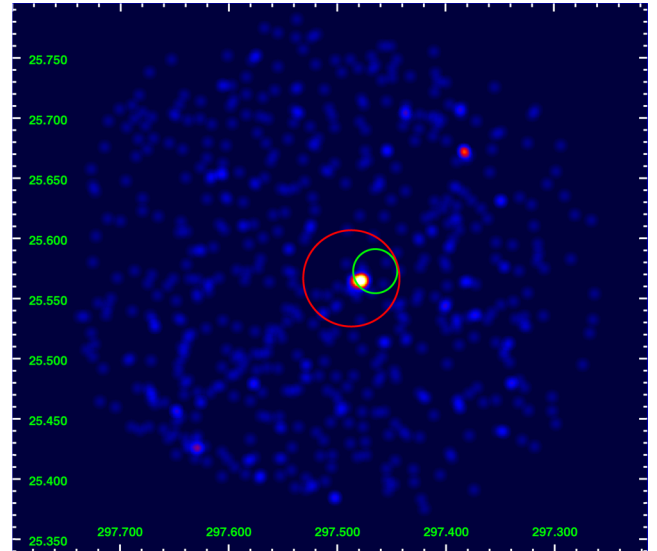
In order to get the most refined IBIS/ISGRI position of the source, we made a mosaic summing up all the three revolutions 1605, 1628 and 1629. AX J1949.8+2534 was detected at  $11.2\sigma$  level (22–60 keV) with a total on-source exposure of  $\sim 50$  ks. Fig. 4 shows the corresponding significance map. The best position is RA = 297:49 and Dec. = 25:57 with a 90 per cent confidence error circle radius equal to 2.4 arcmin.

AX J1949.8+2534 is not listed in the latest published IBIS/ISGRI catalogue (Bird et al. 2016) despite extensive *INTEGRAL* coverage of its sky region ( $\sim 2$  Ms up to revolution no. 1000 considered in Bird et al. 2016) and this information can be used to infer an upper limit on its persistent hard X-ray emission. By additionally considering the source exposure from our present data set ( $\sim 0.25$  Ms), we can infer a  $3\sigma$  upper limit of  $\sim 0.4$  mCrab or  $3.2 \times 10^{-12}$  erg cm $^{-2}$  s $^{-1}$  (20–40 keV) for persistent emission. When assuming the source peak flux as measured by IBIS/ISGRI from the outburst reported in Section 2.2.2, we can infer a dynamic range of  $\geq 625$ .

## 3 SOFT X-RAY OBSERVATIONS

### 3.1 *Swift*/XRT

Following the two newly discovered IBIS/ISGRI detections of AX J1949.8+2534 reported here, we triggered a ToO observation of the sky region with the *Swift* satellite (Gehrels et al. 2004) with the main aims to (i) refine the position of the source with a much higher accuracy and (ii) perform a spectral analysis in soft X-rays for the first time. The observation was performed on 2016 April 25



**Figure 5.** *Swift*/XRT image (0.3–10 keV) with superimposed ASCA (green) and IBIS/ISGRI (red) error circles having a radius of 1 and 2.4 arcmin, respectively. AX J1949.8+2534 is detected inside both error circles at  $\sim 5.3\sigma$  level.

(ID: 00034497001). Standard data reduction and analysis were performed using *HEASOFT* version 6.18 together with the most updated *Swift*/XRT calibration files. The XRT data were reprocessed using *XRTPIPELINE* (v0.13.2).

The *Swift*/XRT (PC) observation resulted in a net exposure time of 2929 s, and it detected a faint X-ray counterpart ( $\sim 5.3\sigma$ , 0.3–10 keV) within both the IBIS/ISGRI and ASCA error circles (see Fig. 5). The best determined XRT position is at RA (J2000) = 19<sup>h</sup>49<sup>m</sup>55<sup>s</sup>.19 Dec. (J2000) = +25°33′57″.5 with an error radius of 3.7 arcsec (90 per cent confidence) using the XRT–UVOT alignment and matching UVOT field sources to the USNO-B1 Catalog (see Evans et al. 2009 and [http://www.swift.ac.uk/user\\_objects](http://www.swift.ac.uk/user_objects)).

We then extracted counts from a circle with a radius of 20 pixels centred on the source position, together with a background from an annular region centred on the source position, with inner and outer radii of 30 and 60 pixels, respectively. The source net count rate in the energy range of 0.3–10 keV was  $(8.08 \pm 1.71) \times 10^{-3}$  counts s $^{-1}$ .

Given the low statistics, we rebinned the spectrum to 1 count bin $^{-1}$  and adopted Cash statistics (Cash 1979) in *XSPEC*. The *Swift*/XRT spectrum was well fitted by an absorbed power law (C-Stat = 20.8, 24 degrees of freedom) where the absorption  $N_H$  was fixed at  $1.18 \times 10^{22}$  cm $^{-2}$  (the total Galactic absorption in the source direction; Willingale et al. 2013). We obtained a photon index of  $\Gamma = 0.2 \pm 0.9$ . The 0.3–10 keV observed flux was  $1.8 \times 10^{-12}$  erg cm $^{-2}$  s $^{-1}$  ( $2 \times 10^{-12}$  erg cm $^{-2}$  s $^{-1}$  corrected for the absorption).

### 3.2 *Chandra*

The ACIS High Resolution Camera onboard *Chandra* (Weisskopf et al. 2000) observed AX J1949.8+2534 on 2008 February 08 for a total exposure time of  $\sim 1.16$  ks. This targeted observation was performed in the context of the ChIcAGO survey (Anderson et al. 2014), aimed at classifying a selected list of unidentified X-ray sources discovered during the ASCA Galactic plane survey. No significant X-ray source was detected inside the entire field of view

**Table 4.** List of NIR sources (as taken from the UKIDSS Galactic Plane Survey) located inside the 90 per cent confidence error circle (no. 1) and 95 per cent confidence error circle (from no. 2 to 5) of AX 1949.8+2534. The table lists their *JHK* magnitudes (lower limits are derived according to Lawrence et al. 2007), offset from the XRT coordinates, *Q* value (see Section 4), inferred spectral type, reddening and distance.

No.	Name	<i>J</i> (mag)	<i>H</i> (mag)	<i>K</i> (mag)	Offset	<i>Q</i>	Spectral type	<i>A<sub>v</sub></i> (mag)	<i>d</i> (kpc)
1	J194955.02+253354.6	>19.9	>19.0	17.788 ± 0.142	3.66 arcsec				
2	J194954.99+253400.2	17.094 ± 0.015	16.182 ± 0.013	15.743 ± 0.022	3.78 arcsec	0.17	Late type		
3	J194955.12+253401.4	14.889 ± 0.003	14.263 ± 0.003	13.902 ± 0.005	4.02 arcsec	0.01	B0V	7.1	17.3
4	J194955.31+253353.8	17.102 ± 0.015	15.878 ± 0.010	15.285 ± 0.015	4.02 arcsec	0.22	K0V	4.4	1.3
5 <sup>a</sup>	J194955.42+253359.9	9.900 ± 0.022	9.071 ± 0.016	8.637 ± 0.018	4.02 arcsec	0.09	B0.5Ia	7.2	8.8

<sup>a</sup>Source also reported in the 2MASS catalogue as J19495543+2533599.

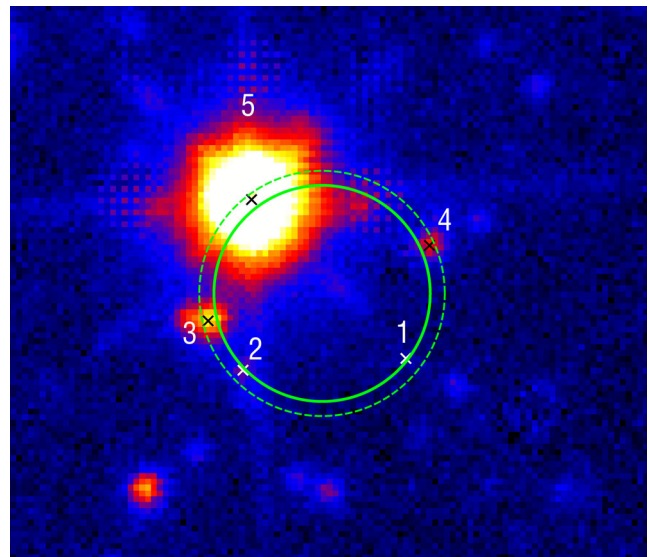
pertaining to this *Chandra* observation, the ChIcAGO survey team reports only a  $\sim 2\sigma$  excess (labelled as ChI 194951+2534\_1 from table 1 in Anderson et al. 2014) located at 1.6 arcmin from the *ASCA* position of AX J1949.8+2534. We used the count rate of ChI 194951+2534\_1 in order to estimate with WEBPIMMS a 0.3–10 keV observed (unabsorbed)  $3\sigma$  upper limit of  $9.6 \times 10^{-13}$  erg  $\text{cm}^{-2}$   $\text{s}^{-1}$  ( $1.05 \times 10^{-12}$  erg  $\text{cm}^{-2}$   $\text{s}^{-1}$ ) for AX J1949.8+2534. We assumed the same spectral model as from the *Swift*/XRT observation. This is a factor of about 2 lower than the X-ray flux measured during the *Swift*/XRT detection.

#### 4 SEARCH FOR INFRARED, OPTICAL AND RADIO COUNTERPARTS

The identification of lower energy counterparts represents a mandatory step in determining the nature of unidentified Galactic X-ray sources. To this aim, we obtained with *Swift*/XRT a 90 per cent confidence source positional accuracy of 3.7 arcsec, which significantly improves the previously available *ASCA* uncertainty of  $\sim 1$  arcmin. This allowed us to perform for the first time a search for counterparts from radio to optical bands, by using all the available catalogues in the HEASARC data base.

No catalogued radio and optical source is located within the arcsecond sized XRT error circle. In the optical *V* band, a lower limit of  $V > 21$  can be inferred from the USNO survey limit as reported in Monet et al. (2003). Conversely, only one near-infrared (NIR) source has been detected by the UKIDSS Galactic Plane Survey (Lucas et al. 2008) inside the 90 per cent confidence XRT error circle, such object is listed in Table 4 as no. 1. Fig. 6 shows both the XRT error circles at 90 and 95 per cent confidence, superimposed on the *K* band UKIDSS image. We note that source no. 1 is located at 3.66 arcsec distance from the XRT coordinates centroid, i.e. on the 90 per cent confidence error circle (radius of 3.7 arcsec, solid circle). It is very faint in the *K* band (magnitude of  $\sim 17.8$ , as such it is not evident in the image) and it is undetected in the *J* and *H* bands. As a consequence, we consider very unlikely the possibility that this extremely faint object could be a reliable NIR counterpart of AX J1949.8+2534. For the sake of completeness, in Fig. 6 we note that a few brighter infrared sources are located at  $\sim 4$  arcsec distance from the XRT centroid, i.e. slightly outside the 90 per cent confidence error circle (radius of 3.7 arcsec, solid circle) and well inside the 95 per cent confidence XRT error circle radius of 4.2 arcsec (dashed circle). Such objects are listed in Table 4 with numbers from 2 to 5.

If we use the reddening-free NIR diagnostic *Q* of Negueruela & Schurch (2007) for the objects no. 2 and 4 in Table 4, then we find that none of them has a *Q* value typical of early-type stars (i.e.  $\leq 0$ ). As a matter of fact, they show *Q* values of 0.17 and 0.22, respectively, which are much more similar to those of intermediate



**Figure 6.** UKIDSS image in the *K* band (as downloaded from the UKIDSS archive, <http://wsa.roe.ac.uk>) with superimposed the *Swift*/XRT error circles at 90 per cent confidence (solid green, radius of 3.7 arcsec) and 95 per cent confidence (dashed green, radius of 4.2 arcsec)

or late-type stars. For example, if we consider the brightest infrared object among the two (no. 4), then we find that it is compatible with being a star of spectral type K0V with a reddening of  $A_v = 4.4$  mag, located at a distance of  $\sim 1.3$  kpc. Its implied *V* magnitude is  $\sim 23.4$ , which is consistent with not detecting it in the *V* band according to the USNO Catalog. As for the brightest infrared object (no. 5), it is also reported in the 2MASS infrared source catalogue (namely J19495543+2533599) with magnitudes equal to  $J = 9.900 \pm 0.022$ ,  $H = 9.071 \pm 0.016$  and  $K = 8.637 \pm 0.018$  as well as in the optical USNO–B1.0 Catalog (1155–0421415) with magnitudes of  $I = 12.87$ ,  $R_2 = 14.62$ ,  $B_2 = 17.35$ . Notably, its *Q* value (0.09) is typical of early-type stars (Negueruela & Schurch 2007). Moreover, by comparing its *K* magnitude with the right-hand panel of fig. 1 in Reig & Milonaki (2016) we note that it is located inside the box populated by blue supergiants. In fact, we found that the observed *K* and *J* magnitudes and the observed *J* – *K* colour are compatible with a B0.5Ia spectral type supergiant star, for a distance of  $\sim 8.8$  kpc and a reddening of  $A_v = 7.2$  mag. Its implied apparent *V* magnitude is  $\sim 15$ , which is consistent with the detection of the source as reported in the USNO Catalog. Finally, also the infrared object no. 3 is characterized by a *Q* value (0.01) typical of an early-type star. In this case, its observed NIR magnitudes are not compatible with being a supergiant star since this would require an extremely large distance ( $\sim 70$  kpc, i.e. object outside the Galaxy) and a high

extinction ( $A_V = 6.7$  mag). On the other hand, it is more compatible with being a main sequence B0V spectral type star, for a distance of  $\sim 17.3$  kpc and a reddening of  $A_V = 7.1$  mag, the implied apparent  $V$  magnitude is  $\sim 19.3$ , which is consistent with the detection of the source as reported in the USNO Catalog with a  $B$  magnitude equal to  $\sim 19$ .

## 5 DISCUSSION

We have presented mainly IBIS/ISGRI results on newly discovered hard X-ray activity from the unidentified transient AX J1949.8+2534, the first ever emission to be reported above 20 keV. Hard X-ray outbursts have been detected twice, on 2015 November and 2016 January, respectively. Furthermore, we point out that we have searched the entire currently available IBIS/ISGRI public data archive (revolution 25–1619; Paizis et al. 2013, Paizis et al. 2017) for possible additional outbursts of AX J1949.8+2534. No detections have been found at ScW level above a significance value of  $7\sigma$  in both energy bands 22–50 and 50–100 keV. The source exposure time obtained from the entire archive is of the order of  $\sim 7$  Ms. The inferred duty cycle is as low as  $\sim 4$  per cent.

We can use all the collected multiwavelength data to consider the possible nature of AX J1949.8+2534.

### 5.1 Low-mass X-ray binary or cataclysmic variable?

As we noted before, two NIR objects, compatible with being late-type spectral stars, are present within the 95 per cent confidence XRT error circle (no. 2 and 4 in Table 4 and Fig. 6). In principle, this could suggest a low-mass X-ray binary (LMXB) nature or alternatively a cataclysmic variable (CV) one. However, in the following we show that both such scenarios suffer serious drawbacks when broad-band X-ray results are taken into account.

The LMXB hypothesis is incompatible with both the very hard X-ray spectrum measured by *Swift*/XRT (i.e.  $\Gamma \sim 0.2$ ) as well as with the particularly short duration of the hard X-ray activity detected by IBIS/ISGRI ( $\sim 1.5$  d, in the only case when it was possible to firmly constrain the duration). In fact, transient LXMBs are known to display X-ray outbursts whose duration is typically of the order of weeks/months, they are characterized by soft X-ray spectra below 10 keV (due to disc blackbody emission). From Table 4, we note that the two NIR objects compatible with a late-type nature (i.e. no. 2 and 4) are particularly weak. If we consider as possible counterpart the brightest among the two (no. 4) then we showed that it is compatible with a late-type star located at  $\sim 1.3$  kpc. The corresponding average X-ray luminosities during the two hard X-ray outbursts detected by IBIS/ISGRI are of the order of  $\sim 2 \times 10^{34}$  erg s $^{-1}$ . This is way too low if compared to typical luminous X-ray outbursts from LMXBs (up to  $\sim 10^{37-38}$  erg s $^{-1}$ ). For the sake of completeness, we note that recently a growing number of LMXBs have been found to show outbursts reaching peak X-ray luminosity of only  $\sim 10^{34-36}$  erg s $^{-1}$  in the soft X-ray band 2–10 keV. They belong to a more general class of X-ray transients dubbed as very faint X-ray transients (VFXTs), which are believed to be the faintest known X-ray accretors (Degenaar & Wijnands 2009, 2011). If we extrapolate the IBIS/ISGRI spectral shape of AX J1949.8+2534 in outbursts to the 2–10 keV X-ray flux, then we obtain a 2–10 keV X-ray luminosity (at 1.3 kpc) of the order of  $\sim 2 \times 10^{33}$  erg s $^{-1}$ , i.e. lower than that typical of VFXTs. With all the above information at hand a LMXB nature for AX J1949.8+2534 seems to be not viable.

Alternatively, we are left with the CV hypothesis. In principle, both the *Swift*/XRT and IBIS/ISGRI spectral X-ray characteristics are compatible with this scenario (Barlow et al. 2006, Landi et al. 2009). However, we note that to date all the CVs detected by both IBIS/ISGRI and *Swift*/BAT above 20 keV are weak persistent hard X-ray sources with typical luminosities in the range  $\sim 10^{32-34}$  erg s $^{-1}$  (Barlow et al. 2006; Revnivtsev et al. 2008; Brunschweiler et al. 2009). No CV has never been detected as a transient hard X-ray source. This is completely at odds with the short transient behaviour of AX J1949.8+2534 as observed by IBIS/ISGRI. Moreover, if we consider the brightest NIR object compatible with a late-type nature (no. 4), then it is compatible with a late-type M5V main sequence star (which is typical of CVs; Smith & Dhillon 1998) located at  $\sim 230$  pc. Consequently, the IBIS/ISGRI upper limit on the persistent hard X-ray emission of AX J1949.8+2534 would translate into a 20–40 keV luminosity of  $\leq 2 \times 10^{31}$  erg s $^{-1}$ , i.e. significantly lower than typical measurements obtained to date with both IBIS/ISGRI and *Swift*/BAT. The same holds for the *Swift*/XRT detection whose soft X-ray flux would translate into a luminosity of  $\sim 1.2 \times 10^{31}$  erg s $^{-1}$ . All the above results point to largely disfavour the CV interpretation for AX J1949.8+2534.

### 5.2 High-mass X-ray binary

The location of the source on the Galactic plane ( $b \sim -0.3^\circ$ ) and both *Swift*/XRT and IBIS/ISGRI spectral characteristics (especially the hardness of the soft X-ray spectrum, i.e.  $\Gamma \sim 0.2$ ) are fully compatible with a high-mass X-ray binary (HMXB) nature. In particular, the hard X-ray transient behaviour (e.g. dynamic range  $\geq 620$  and duration of  $\sim 1.5$  d and  $\geq 4$  d from the two IBIS/ISGRI detected activities, respectively) could be typical of the Be HMXB class. In addition, we note that mentioned X-ray characteristics are compatible as well with a Supergiant Fast X-ray Transients nature (SFXTs; Sguera et al. 2008), which are a newly discovered class of HMXBs (Negueruela et al. 2006; Sguera et al. 2005, 2006).

Although classical SFXTs usually display above 20 keV hard X-ray outbursts lasting much less than a day, a few other SFXTs are known to show unusually longer hard X-ray activity, exceptionally lasting several days (e.g. IGR J18483–0311, Sguera et al. 2015a; IGR J17354–3255, Sguera et al. 2011), i.e. comparable to the duration of the hard X-ray activity detected from AX J1949.8+2534.

We must note that, in principle, this proposed HMXB interpretation could suffer some drawbacks when NIR data are combined with the 90 per cent confidence XRT positional uncertainty. In fact, searching within the latter, we pinpointed only one very faint NIR object (no. 1 in Table 4), whose magnitudes and colours are not compatible with being an early-type spectral star, i.e. at odds with an HMXB nature. However, slightly outside the 90 per cent confidence XRT error circle (radius of 3.7 arcsec) we note the presence of two bright NIR sources (no. 3 and 5) located at 4 arcsec distance from the XRT centroid, i.e. well inside the 95 per cent confidence XRT positional uncertainty (radius of 4.2 arcsec). Both have observed  $K$  and  $J$  magnitudes and  $J - K$  colour compatible with an early-type nature.

Specifically, the characteristics of the NIR object no. 3 are compatible with a main sequence early-type spectral star (B0V), supporting a Be HMXB scenario. If we consider its calculated distance of  $\sim 17.3$  kpc, then the two hard X-ray outbursts detected by IBIS/ISGRI from AX J1949.8+2534 would have a 18–60 keV average (peak) luminosity of  $4 \times 10^{36}$  erg s $^{-1}$  ( $2 \times 10^{37}$  erg s $^{-1}$ ), both such values are typical of periodic type I X-ray outbursts from Be HMXBs. As for the soft X-ray band, the measured *Swift*/XRT

flux translates into a luminosity of  $\sim 6 \times 10^{34}$  erg s $^{-1}$ . Such value is not representative of the X-ray quiescence of Be HMXBs which is usually much lower. Conversely, it could be more typical of quasi-persistent Be HMXBs which are a small subclass characterized by a persistent low X-ray luminosity of  $\sim 10^{34}$  erg s $^{-1}$ , varying by up to a factor of  $\sim 10$  at most, hence not displaying type I or II outburst behaviour (see Reig & Roche 1999). We note that this latter characteristic is at odds with the bright outburst behaviour detected by IBIS/ISGRI from AX J1949.8+2534, as such it represents a significant drawback for the Be HMXB scenario.

As for the association with the brightest NIR object no. 5, their characteristics are fully compatible with being an early-type spectral star of supergiant nature (B0.5Ia). This would fully support an SFXT scenario. We are aware that, in principle, to extend the search for NIR counterparts outside the canonical 90 per cent XRT positional uncertainty could eventually be a dangerous approach because of the possibility that unrelated NIR sources could be included and mistakenly assumed as counterparts. Bearing this in mind, we took into account the possibility that such an association could be simply a chance coincidence and accordingly calculated the probability of a random association with an infrared source having magnitude  $K \leq 8.6$  as given by  $P = 1 - e^{-\pi\rho d^2}$  (where  $d$  is the distance between the XRT centroid and the associated NIR candidate, and  $\rho$  is the local spatial density of NIR sources computed in an area of a few degree radius around the candidate). We estimated a probability of 0.1 per cent, i.e. 0.001 chance coincidence is expected. Such particularly low probability strongly supports a real physical association, hence the viable possibility that this infrared object is a reliable counterpart of the unidentified X-ray source AX J1949.8+2534. If we consider the calculated distance of  $\sim 8.8$  kpc in the case of a B0.5Ia spectral type supergiant for the proposed NIR counterpart, then the two hard X-ray outbursts detected by IBIS/ISGRI from AX J1949.8+2534 would have a 18–60 keV average (peak) luminosity of  $1.1 \times 10^{36}$  erg s $^{-1}$  ( $5.5 \times 10^{36}$  erg s $^{-1}$ ). From archival *INTEGRAL*/IBIS observations, we placed a  $3\sigma$  upper limit of  $\sim 3 \times 10^{34}$  erg s $^{-1}$  for the persistent hard X-ray luminosity. Both such values are very similar to those of known confirmed SFXTs. As for the soft X-ray band, the measured *Swift*/XRT flux translates into a luminosity of  $\sim 2 \times 10^{34}$  erg s $^{-1}$ , which is fully compatible with the so-called intermediate intensity X-ray state during which typical SFXTs spend the majority of their time (Sidoli et al. 2008). In this context, we note that the prolonged duration of the hard X-ray activity discovered from AX J1949.8+2534 ( $\sim 1.5$  and  $\geq 4$  d, respectively) is at odds with the much shorter durations typically marking outbursts from classical SFXTs above 20 keV (i.e. a few hours). A similar characteristic was previously reported only for a few other SFXT sources. Our new findings on AX J1949.8+2534 could strengthen the idea that unusually long hard X-ray outbursts would not be particularly exceptional among the class of SFXTs.

## 6 CONCLUSIONS

We reported on the IBIS/ISGRI discovery of two new hard X-ray outbursts from the unidentified transient AX J1949.8+2534, the first ever emission to be detected above 20 keV. A follow-up observation of the sky region with the *Swift* satellite allowed for the first time to perform a soft X-ray spectral analysis as well as significantly improve the positional uncertainty to arcsecond size. This permitted us to pinpoint two bright infrared sources as most likely candidate counterparts. Both are compatible with being early-type spectral stars hence supporting an HMXB nature, specifically an

SFXT (more viable) or alternatively a Be HMXB. Further detailed NIR or optical spectroscopy is mandatory to confirm their putative supergiant and Be nature, respectively. Unfortunately, we can go no further on this issue because the current X-ray positional uncertainty (3.7 arcsec) prevents us from unambiguously pinpointing the correct single NIR counterpart. Additional X-ray observations of AX J1949.8+2534 using *Chandra*, for example, are strongly needed in order to achieve a finer position with an associated smaller error circle.

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