

Discovery of heavily-obscured AGN among 7 INTEGRAL hard X-ray sources observed by Chandra

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ABSTRACT

Aims. We identify hard X-ray sources discovered by the INTEGRAL all-sky survey. We complete identification of a unique sample of active galactic nuclei (AGN) selected in the hard X-ray band (17–60 keV) with minimal effects from absorption. Subsequently, we determine the fraction of obscured AGN in the local Universe.

Methods. We observed 7 INTEGRAL sources with the Chandra X-ray Observatory to refine their localization to ~ 2 arcsec and to study their X-ray spectra.

Results. Two sources are inferred to have a Galactic origin: IGR J08390–4833 is most likely a magnetic cataclysmic variable with a white dwarf spin period $\sim 1,450$ s; and IGR J21343+4738 is a high-mass X-ray binary. Five sources (IGR J02466–4222, IGR J09522–6231, IGR J14493–5534, IGR J14561–3738, and IGR J23523+5844) prove to be AGN with significant intrinsic X-ray absorption along the line of sight. Their redshifts and hard X-ray (17–60 keV) luminosities range from 0.025 to 0.25 and from $\sim 2 \times 10^{43}$ to $\sim 2 \times 10^{45}$ erg s⁻¹, respectively, with the distance to IGR J14493–5534 remaining unknown. The sources IGR J02466–4222 and IGR J14561–3738 are likely Compton-thick AGN with absorption column densities $N_{\text{H}} > 10^{24}$ cm⁻², and the former further appears to be one of the nearest X-ray bright, optically-normal galaxies.

Conclusions. With the newly-identified sources, the number of heavily-obscured ($N_{\text{H}} \gtrsim 10^{24}$ cm⁻²) AGN detected by INTEGRAL has increased to ~ 10 . Therefore, such objects constitute 10–15% of hard X-ray bright, non-blazar AGN in the local Universe. The small ratio ($\ll 1\%$) of soft (0.5–8.0 keV) to hard (17–60 keV) band fluxes (Chandra to INTEGRAL) and the non-detection of optical narrow-line emission in some of the Compton-thick AGN in our sample suggests that there is a new class of objects in which the central massive black hole may be surrounded by a geometrically-thick dusty torus with a narrow ionization cone.

Key words. Surveys – Galaxies: Seyfert – novae, cataclysmic variables – X-rays: binaries

1. Introduction

Our analysis of four years of all-sky observations by the IBIS/ISGRI soft gamma-ray imager (Ubertini et al. 2003) aboard the INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL, Winkler et al. 2003) has provided a large (> 130) sample of mostly nearby ($z \lesssim 0.1$) active galactic nuclei (AGN) detected in the 17–60 keV energy band (Krivonos et al. 2007). These AGN populate the whole range of X-ray absorption column densities, from unobscured ($N_{\text{H}} < 10^{22}$ cm⁻²) to Compton-thick ($N_{\text{H}} \gtrsim 10^{24}$ cm⁻²) sources (Sazonov et al. 2007). Thus, the INTEGRAL survey together with the survey by Swift (Ajello et al. 2008; Tueller et al. 2008) for the first time permit a statistical investigation of the properties of the local AGN population in a nearly unbiased manner (except for very Compton-thick sources, $N_{\text{H}} \gtrsim 10^{25}$ cm⁻²), thanks to the detection of sources at energies above the photoabsorption cutoff in their spectra (~ 10 keV).

Almost all INTEGRAL sources out of the Galactic plane ($|b| > 5^\circ$) have already been identified (Krivonos et al. 2007; Bird et al. 2007). This has allowed

us to measure the hard X-ray (17–60 keV) luminosity function and distribution of absorption column densities for nearby AGN (Sazonov et al. 2007). We have also constructed the cumulative spectral energy distribution of local AGN in the 3–300 keV energy range and, by comparing it with the spectrum of the cosmic X-ray background, imposed interesting, new constraints on AGN evolution (Sazonov et al. 2008).

Nonetheless, several tens of INTEGRAL sources remain unidentified, most of them located near the Galactic plane ($|b| < 5^\circ$) and in the Galactic Center region, where searches for X-ray and optical counterparts within the few-arcmin INTEGRAL localization regions are complicated in comparison with the extragalactic sky. Based on the INTEGRAL AGN counts at $|b| > 5^\circ$ (Krivonos et al. 2007), we may expect that a significant fraction of the as yet unidentified sources at low Galactic latitudes should be AGN, including heavily-obscured sources ($N_{\text{H}} \gtrsim 10^{24}$ cm⁻²). There is a lot of interest in searching for such objects, as their census is not yet complete even in the local Universe, let alone at redshift $z \gtrsim 0.1$, and we do not yet fully understand their nature.

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We previously used the Chandra X-ray Observatory, with its excellent angular resolution and sensitivity, to refine the positions of 8 INTEGRAL sources to a few arcseconds and to measure their X-ray spectra. This allowed us to identify 5 of them as nearby AGN with absorption column densities up to $\sim 10^{24} \text{ cm}^{-2}$ (Sazonov et al. 2005). Here we present Chandra observations of another 7 INTEGRAL sources and demonstrate that most of these also are obscured AGN. A cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is adopted throughout the paper. All quoted uncertainties are 1σ unless noted otherwise.

2. Observations and data analysis

For the present study, we compiled a sample of 7 new hard X-ray sources detected with greater than 5σ significance in the summed INTEGRAL sky map. Six of the sources are included in the catalog of Krivonos et al. (2007) and one (IGR J08390–4833) was discovered after the catalog publication. These sources are located significantly far away from both the Galactic plane ($> 2^\circ$) and Galactic Center ($> 30^\circ$), and were not detected in soft X-rays by the ROSAT All-Sky Survey (Voges et al. 1999). The IBIS/ISGRI localization regions are $\sim 3'$ in radius (90% confidence). This INTEGRAL sample was observed by the Chandra Advanced CCD Imaging Spectrometer (ACIS-I) in December 2006–January 2007, with an exposure of $\sim 3.5 \text{ ks}$ per source.

Due to the anticipated brightness of the INTEGRAL sources – typical fluxes of these sources in the 17–60 keV energy band are $\sim 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$, which for unabsorbed spectra would correspond to $\sim 1 \text{ cnt s}^{-1}$ in the ACIS detectors – we undertook special efforts to avoid photon pileup in the ACIS CCDs. Specifically, the sources were intentionally observed with a $\sim 10'$ offset with respect to the optical axis of the X-ray telescope, which resulted in a distribution of X-ray counts from the target source over a wide area ($\sim 10''$ in radius) and prevented pileup problems. Due to this observational scheme, the accuracy of determination of source positions has decreased to 2–2.5''.

We reduced the data following a standard procedure fully described in Vikhlinin et al. (2005). The detector background was modeled with the stowed dataset (<http://cxc.harvard.edu/contrib/maxim/stowed>). We detected point sources with the wavelet decomposition package `wvdecomp` of ZHTOOLS (Vikhlinin et al. 1998)¹. The spectral modeling was done with XSPEC (Arnaud 1996).

3. Results

In Fig. 1, we present the Chandra X-ray images around the INTEGRAL sources and optical (DSS²) or near-infrared (2MASS³) images around their likely X-ray counterparts. The Chandra positions, their offsets from the IBIS/ISGRI ones and the resulting identifications of the INTEGRAL sources are listed in Table 1. In Figs. 2 and 3, we show the broadband (0.5–60 keV) X-ray spectra obtained by Chandra and INTEGRAL for those sources, which we conclude to be AGN and Galactic objects, respectively. Based on these spectra, we have estimated or constrained such

properties of the sources as spectral slopes, line-of-sight absorption column densities, X-ray, and hard X-ray fluxes and luminosities. This information is collected in Tables 2 and 3 for the extragalactic and Galactic objects, respectively. Below we describe our results on a source-by-source basis.

3.1. IGR J02466–4222 – a Compton-thick AGN/X-ray bright, optically-normal galaxy?

In the Chandra field (see Fig. 1), there is a faint (~ 20 counts) X-ray source inside the IBIS/ISGRI localization region. The position of the source is consistent with the center of galaxy MCG -07-06-018, located at redshift $z = 0.0696$ (as given in the NASA/IPAC Extragalactic Database, NED⁴). According to the HyperLeda database⁵, this is a giant ($M_B = -22.64$), early-type (E-S0) galaxy and the brightest galaxy in the cluster AS 0296 (Gonzalez et al. 2005).

Assuming a Crab-like spectrum, the Chandra source has flux $\sim 7 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 0.5–8 keV band. The object is located in the extragalactic sky ($l = 253.5^\circ$, $b = -61.1^\circ$) where the expected number density of X-ray sources with similar or higher fluxes is ~ 20 per sq. deg (see, e.g., Gilli et al. 2007). Thus, there is a significant, $\sim 15\%$, probability of finding by chance a source of such brightness within the IBIS/ISGRI 90%-confidence region. However, we should also consider the fact that giant galaxies like MCG -07-06-018 are very rare. According to the galaxy luminosity function measured at $z = 0$ (e.g., Norberg et al. 2002), there are just ~ 100 galaxies with $M_B < -22.5$ within the local volume of the Universe at $z < 0.1$. Thus, the probability of finding by chance a giant galaxy like MCG -07-06-018, within 3 arcmin of one of the ~ 400 (Krivonos et al. 2007) INTEGRAL sources, is only $\sim 1\%$.

Therefore, IGR J02466–4222 is most likely associated with MCG -07-06-018. We can then estimate the luminosity of the source in the 17–60 keV energy band from the flux measured by IBIS/ISGRI (see Table 2) at $L_{\text{hx}} \sim 3 \times 10^{44} \text{ erg s}^{-1}$. For comparison, the X-ray luminosity of the Chandra X-ray counterpart is only $L_x \sim 8 \times 10^{41} \text{ erg s}^{-1}$ (0.5–8 keV). This suggests that IGR J02466–4222 may be a heavily-obscured, intrinsically-luminous AGN.

It is impossible to perform a detailed analysis of the X-ray spectrum based on the ~ 20 photons detected by Chandra from the source. However, a comparison of the flux measured by INTEGRAL in the 17–60 keV band with the Chandra counts at energies below 10 keV (see Fig. 2) suggests that the material obscuring direct X-ray emission from IGR J02466–4222 must have column density $N_{\text{H}} > 10^{24} \text{ cm}^{-2}$, unless the source has faded by more than a factor of ~ 5 between the INTEGRAL observations in June 2006 and the Chandra observation in January 2007.

The weak X-ray emission detected by Chandra is spatially unresolved, which implies that it originates within $\sim 15 \text{ kpc}$ of the MCG -07-06-018 nucleus. Also, it clearly represents a separate, relatively soft spectral component unaffected by absorption (see Fig. 2). By analogy with well-studied Compton-thick AGN such as NGC 1068, NGC 4945, and others (see, e.g., Matt et al. 2000, and references therein), and taking into account that MCG -07-06-018 is a giant galaxy at the center of a galaxy cluster, the

¹ <http://hea-www.harvard.edu/saord/zhtools/>

² <http://archive.eso.org/dss/dss/>

³ <http://www.ipac.caltech.edu/2mass/>

⁴ <http://nedwww.ipac.caltech.edu/>

⁵ <http://leda.univ-lyon1.fr/>

Table 1. Localization and identification of INTEGRAL sources

INTEGRAL		Chandra position		Offset	Identification	Type	z
Name	α, δ (2000)	α, δ (2000)		(')			
IGR J02466–4222	41.644 –42.360	02 46 36.91 –42 21 59.0		0.6	MCG -07-06-018	AGN	0.0696
IGR J08390–4833	129.728 –48.556	08 38 48.98 –48 31 25.4		2.2	USNO-B1.0 0414-0125587	magn. CV?	
IGR J09522–6231	148.025 –62.523	09 52 20.29 –62 32 36.1		2.1		AGN	0.252
IGR J14493–5534	222.311 –55.589	14 49 12.79 –55 36 21.0		1.0	2MASX J14491283–5536194	AGN	
IGR J14561–3738	224.055 –37.632	14 56 08.23 –37 38 53.8		1.4	ESO 386-G034	AGN	0.0246
IGR J21343+4738	323.625 +47.614	21 34 20.41 +47 38 01.6		2.0	USNO-B1.0 1376-0511904	HMXB	
IGR J23523+5844	358.079 +58.745	23 52 21.96 +58 45 31.5		0.9	USNO-B1.0 1487-0398304	AGN	0.163

Chandra source may be a combination of reflected and/or scattered emission from the active nucleus, superposition of point X-ray sources in the galaxy, and emission from hot gas peaked on the central cluster galaxy. Significantly longer X-ray observations could clarify the origin of the Chandra X-ray emission.

In summary, IGR J02466–4222 is most likely a Compton-thick AGN. To further investigate its nature, we analyzed the optical spectrum of MCG -07-06-018 (=6dF J0246370–422201) from the 6dF survey⁶. Surprisingly, it looks like a typical spectrum of an early-type galaxy with no emission lines that would indicate the presence of an active nucleus. We can put a 3σ upper limit on the luminosity of an [OIII] λ 5007 emission line: $< 6 \times 10^{41}$ erg s⁻¹. Thus, the ratio of the hard X-ray (17–60 keV) to the [OIII] λ 5007 luminosities for IGR J02466–4222 is at least 500 and is thus larger than in at least $\sim 90\%$ of nearby Seyfert galaxies (Heckman et al. 2005), including those discovered by INTEGRAL (Bikmaev et al. 2006; Burenin et al. 2008).

These properties suggest that IGR J02466–4222 may be one of the nearest X-ray bright, optically-normal galaxies (e.g., Comastri et al. 2002) and similar to another INTEGRAL source, IGR J13091+1137. The latter is associated with the optically-normal galaxy NGC 4992 at $z = 0.025$ (Masetti et al. 2006a) and is also a nearly Compton-thick AGN ($N_{\text{H}} \sim 10^{24}$ cm⁻², Sazonov et al. 2005).

3.2. The source IGR J08390–4833

There is a bright Chandra source inside the IBIS/ISGRI localization region (see Fig. 1). The sky density of X-ray sources with similar 2–10 keV fluxes ($\sim 2 \times 10^{-12}$ erg s⁻¹ cm⁻²) is ~ 0.2 deg⁻² in the extragalactic sky and typically ~ 1 deg⁻² in the Galactic plane (Sugizaki et al. 2001). Therefore, since the object is located not far from the Galactic plane ($l = 266.6^\circ$, $b = -4.3^\circ$), the probability of a chance positional coincidence of the Chandra and INTEGRAL sources is $\sim 10^{-3}$ – 10^{-2} . Therefore, the Chandra source is most likely the X-ray counterpart of IGR J08390–4833.

The spectrum measured in the 0.5–9 keV energy band (see Fig. 3) can be well fit ($\chi^2 = 558.3$ for 579 d.o.f.) by a power law with photon index $\Gamma = 0.38 \pm 0.07$. A model of a power-law spectrum absorbed by neutral gas (with column density N_{H}) provides a somewhat better fit, with $\Gamma = 0.54 \pm 0.13$ and $N_{\text{H}} = (1.2 \pm 0.9) \times 10^{21}$ cm⁻². We can put a 3σ upper limit on the N_{H} value of 4×10^{21} cm⁻². This is less than the absorption column density through the whole Galaxy in the direction of the source: $N_{\text{H,Gal}} \sim 7 \times 10^{21}$

and $\sim 5 \times 10^{21}$ cm⁻², according to Dickey & Lockman (1990) and Kalberia et al. (2005), respectively. This hints at a Galactic origin of IGR J08390–4833.

A comparison of the Chandra spectrum with the hard X-ray flux measured by INTEGRAL (see Fig. 3) indicates that the spectrum must steepen between ~ 8 keV and ~ 20 – 60 keV, unless the source experienced a strong outburst during the Chandra observation.

The Chandra count rate history of IGR J08390–4833 (Fig. 4) indicates that the source may be pulsating. The light curve can be fit fairly well ($\chi^2 = 34.5$ for 24 d.o.f.) by a model consisting of a constant and a sine wave with period $P = 1450 \pm 40$ s. For comparison, fitting to a constant yields $\chi^2 = 106.3$ for 27 d.o.f. The inferred pulse fraction $(C_{\text{max}} - C_{\text{min}})/(C_{\text{max}} + C_{\text{min}}) \approx 50\%$, where C_{max} and C_{min} are the maximum and minimum intensities, respectively. No other periodicities have been found by an epoch folding analysis.

Optical and near-infrared catalogs contain a star, USNO-B1.0 0414-0125587, whose position is consistent with that of the Chandra source (see Fig. 1). According to the USNO-B1 and 2MASS catalogs, this likely optical counterpart of IGR J08390–4833 is characterized by the following apparent magnitudes: $B = 17.65$, $R = 16.05$, $I = 16.83$, $J = 15.68$, $H = 15.29$, and $K = 14.52$.

The very hard ($\Gamma \sim 0.5$) X-ray spectrum at energies below ~ 10 keV, with a high-energy cutoff at ~ 20 keV, and the large smooth oscillations of X-ray emission, strongly suggest that IGR J08390–4833 is either a high-mass X-ray binary (HMXB)/X-ray pulsar or a magnetic cataclysmic variable (CV) with the compact object (a neutron star or a white dwarf, respectively) rotating with a period $\sim 1,450$ s. We, therefore, now discuss these two possibilities.

In the HXMB scenario, given the weakness of the optical counterpart ($R \sim 16$) and taking into account that the interstellar extinction toward the source is at most $A_V \approx 2.6$ (Schlegel et al. 1998), IGR J08390–4833 must be located at least ~ 10 kpc from us if this is a $B[e]$ /neutron-star binary and much further away if it is a supergiant X-ray binary (see Negueruela 2004 for a review of the different populations of HMXBs). In this case, the absence of significant absorption in the X-ray spectrum of IGR J08390–4833 would be only marginally consistent with the substantial HI column density through the Galaxy in that direction. Furthermore, at $(l, b) = 266.6^\circ, -4.3^\circ$ the object would be located > 800 pc above the Galactic plane, i.e. extraordinarily high for a Galactic HMXB (Grimm et al. 2002). We thus find the HMXB scenario unlikely.

All the available data seem to be more consistent with IGR J08390–4833 being a magnetic CV. First, the suggested period $\sim 1,450$ s is typical of intermediate polar spin periods, a subclass of magnetic CVs in which the

⁶ <http://www.aao.gov.au/local/www/6df/>

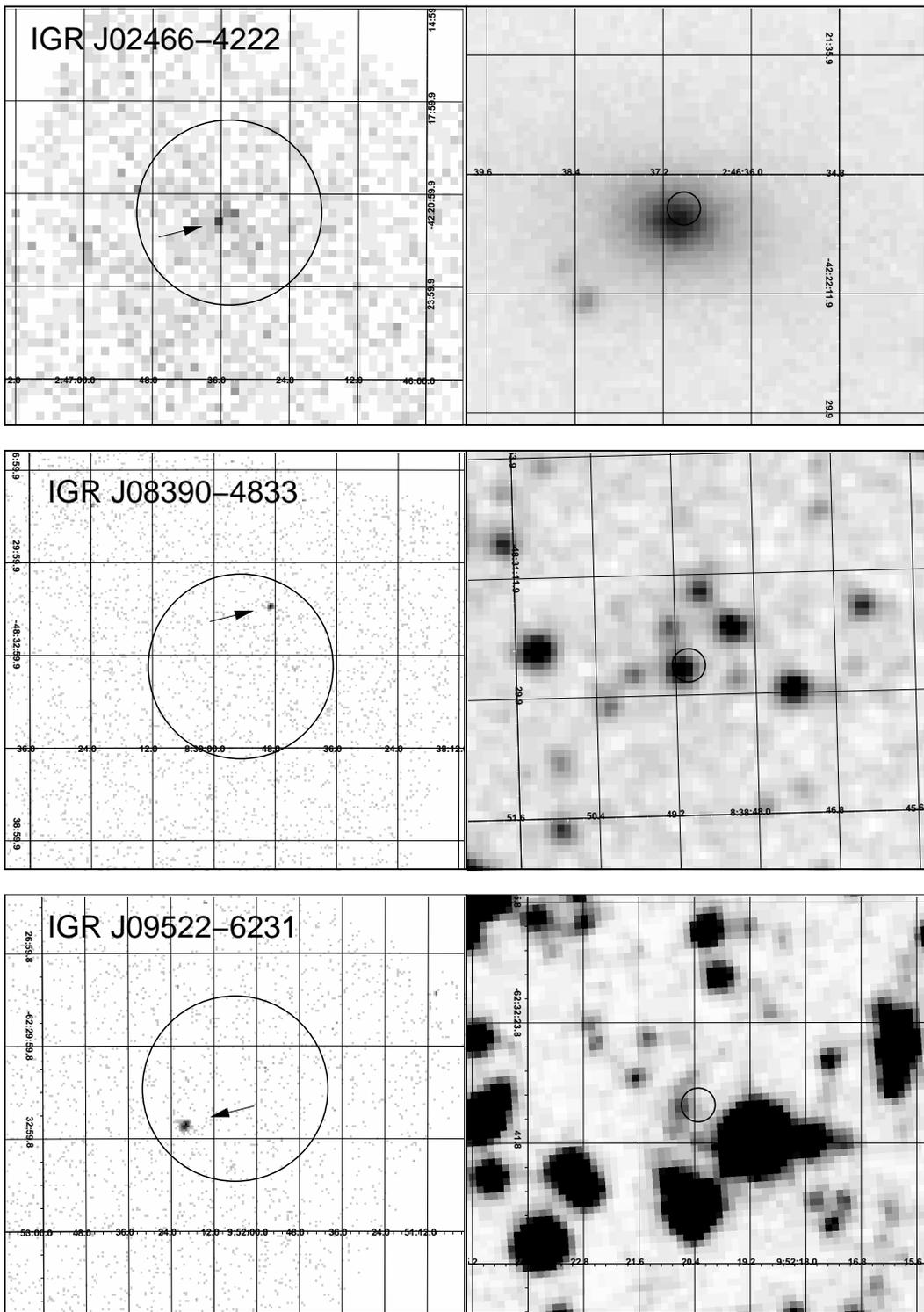


Fig. 1. *Left panels:* Chandra $\sim 12'$ images around the INTEGRAL sources. The $3'$ -radius circle indicates the estimated INTEGRAL 90%-confidence localization region. The arrow points to the likely X-ray counterpart. *Right panels:* Optical (DSS II red) or near-infrared (2MASS, for IGR J14493–5534 and IGR J14561–3738 only) $\sim 1'$ images around the Chandra counterparts. The $2.5'$ -radius circle indicates the estimated uncertainty in the X-ray source position.

white dwarf rotates rapidly compared to the orbital motion (e.g., Patterson 1994). Secondly, the broadband X-ray spectrum of IGR J08390–4833 measured by Chandra and INTEGRAL is similar to those of well-studied magnetic CVs, which are interpreted in terms of multitemperature

optically-thin thermal emission with $kT \lesssim 30$ keV produced in an accretion column at the white dwarf surface, partially absorbed in the surrounding accretion flow (e.g., Suleimanov et al. 2005). We note though that we do not detect any iron K_{α} emission lines at 6.4–7.0 keV in the

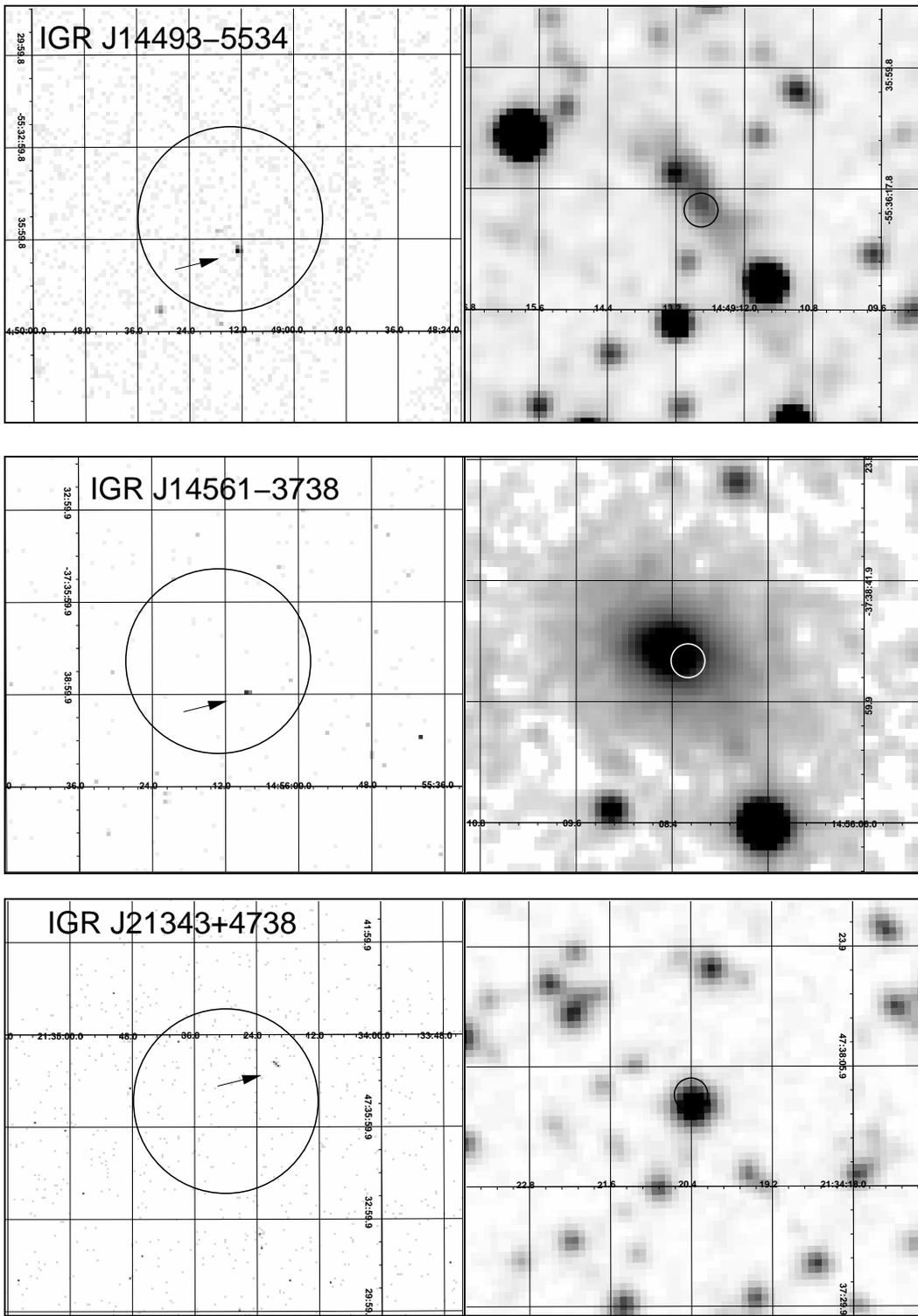


Fig. 1. Continued.

Chandra spectrum of IGR J08390-4833, such as usually observed in the spectra of magnetic CVs. However, the inferred upper limit on the equivalent width of such a line (obtained by fixing the line energy and full width at half maximum at 6.7 keV and 600 eV, respectively), $W_{\text{eq}} < 300$ eV (2σ), is consistent with some of the W_{eq} values measured for polars and intermediate polars (Ezuka & Ishida 1999).

Furthermore, the near-infrared-to-optical spectral energy distribution of IGR J08390-4833 constructed from the *BRIJK* photometric data quoted above resembles the similarly constructed spectra of several magnetic CVs discovered (or co-discovered) by INTEGRAL, including XSS J12270-4859, IGR J14536-5522, IGR J15094-6649, IGR J16167-4957, and IGR J17195-4100, which are all $R \sim 14-16$ objects (Masetti et al. 2006b) and, like

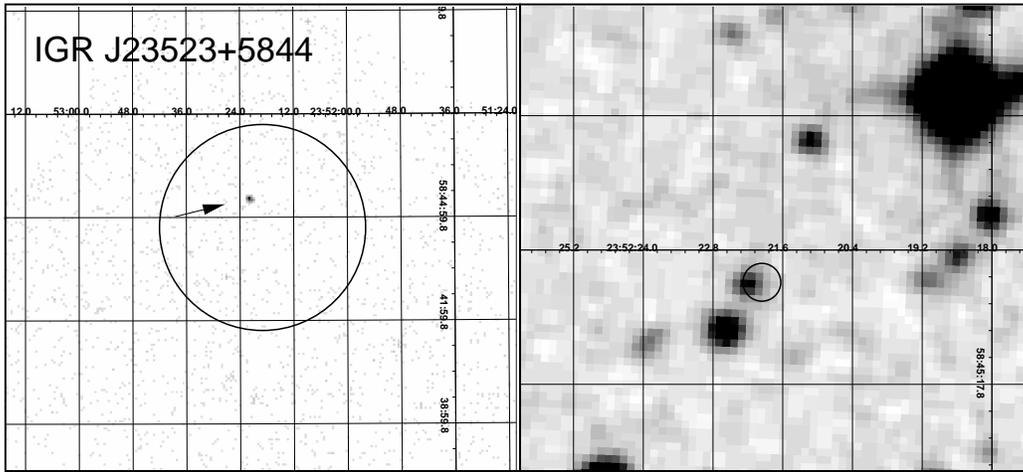


Fig. 1. Continued.

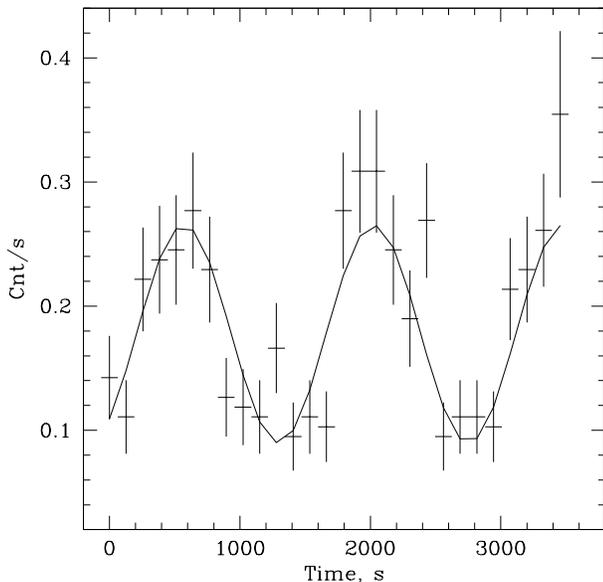


Fig. 4. Count rate history of IGR J08390–4833 recorded by Chandra, binned into 28 intervals of 128 s duration. The solid line is the best fitting model by a sine wave with a period of 1,450 s plus a constant.

IGR J08390–4833, are relatively weak (\sim mCrab) hard X-ray sources.

We, therefore, conclude that IGR J08390–4833 is most likely a magnetic CV with a spin period \sim 1,450 s. Optical spectroscopic observations could verify this hypothesis by revealing Balmer emission lines associated with an accretion disk around a white dwarf.

3.3. The source IGR J09522–6231

Chandra sees a bright X-ray source inside the IBIS/ISGRI localization region (see Fig. 1). Its X-ray spectrum (see

Fig. 2) can be well fit ($\chi^2 = 434.7$ for 579 d.o.f.) by an absorbed power-law model with column density $N_{\text{H}} \sim 6 \times 10^{22} \text{ cm}^{-2}$ (for the photon index fixed at $\Gamma = 1.8$), which is much higher than the Galactic absorption column density in the direction of the source (see Table 2). An extrapolation of this spectral model to higher energies underpredicts the hard X-ray (17–60 keV) flux measured by IBIS/ISGRI by a factor of 2–3. This difference may result from the tendency of INTEGRAL (as of any other mission conducting a sensitivity limited survey) to detect weak sources when they are bright as compared to their long-term average flux level. It may also indicate that the intrinsic X-ray continuum is harder than the assumed $\Gamma = 1.8$ power law, e.g., a Compton reflection component might be present. We note that the same explanation may also be applicable to the spectra of two other sources, IGR J14493–5534 and IGR J23523+5844, considered below.

In the DSS and 2MASS images (see Fig. 1), there is an object with the centroid at RA, Dec = 09:52:20.42, –62:32:35.4 (J2000), which is consistent with the Chandra position. With $R \sim 20$, the object is barely detected on the DSS II red plate. Its near-infrared magnitudes estimated from the 2MASS images are $J = 16.7$, $H = 15.4$, $K = 14.8$. Masetti et al. (2008) have observed this likely optical counterpart with the 3.6 m telescope at the ESO-La Silla Observatory and identified it as a Seyfert 1.9 galaxy at $z = 0.252$. This implies that the source has a hard X-ray luminosity of $\sim 2 \times 10^{45} \text{ erg s}^{-1}$ (see Table 2). This, together with the significantly absorbed X-ray spectrum, indicates that IGR J09522–6231 may be considered a type 2 quasar.

3.4. IGR J14493–5534 – an obscured AGN

There is a bright Chandra source inside the IBIS/ISGRI localization region (see Fig. 1). Similar to the case of IGR J08390–4833, we estimate the probability of a chance positional coincidence at $\sim 10^{-3}$ – 10^{-2} , depending on whether the extragalactic or Galactic $\log N$ – $\log S$ function is used (the object is located at $l = 319.1^\circ$, $b = 3.5^\circ$). This indicates that the Chandra source is likely the X-ray counterpart of IGR J14493–5534.

The Chandra source positionally coincides with galaxy 2MASX J14491283–5536194, whose redshift is unknown.

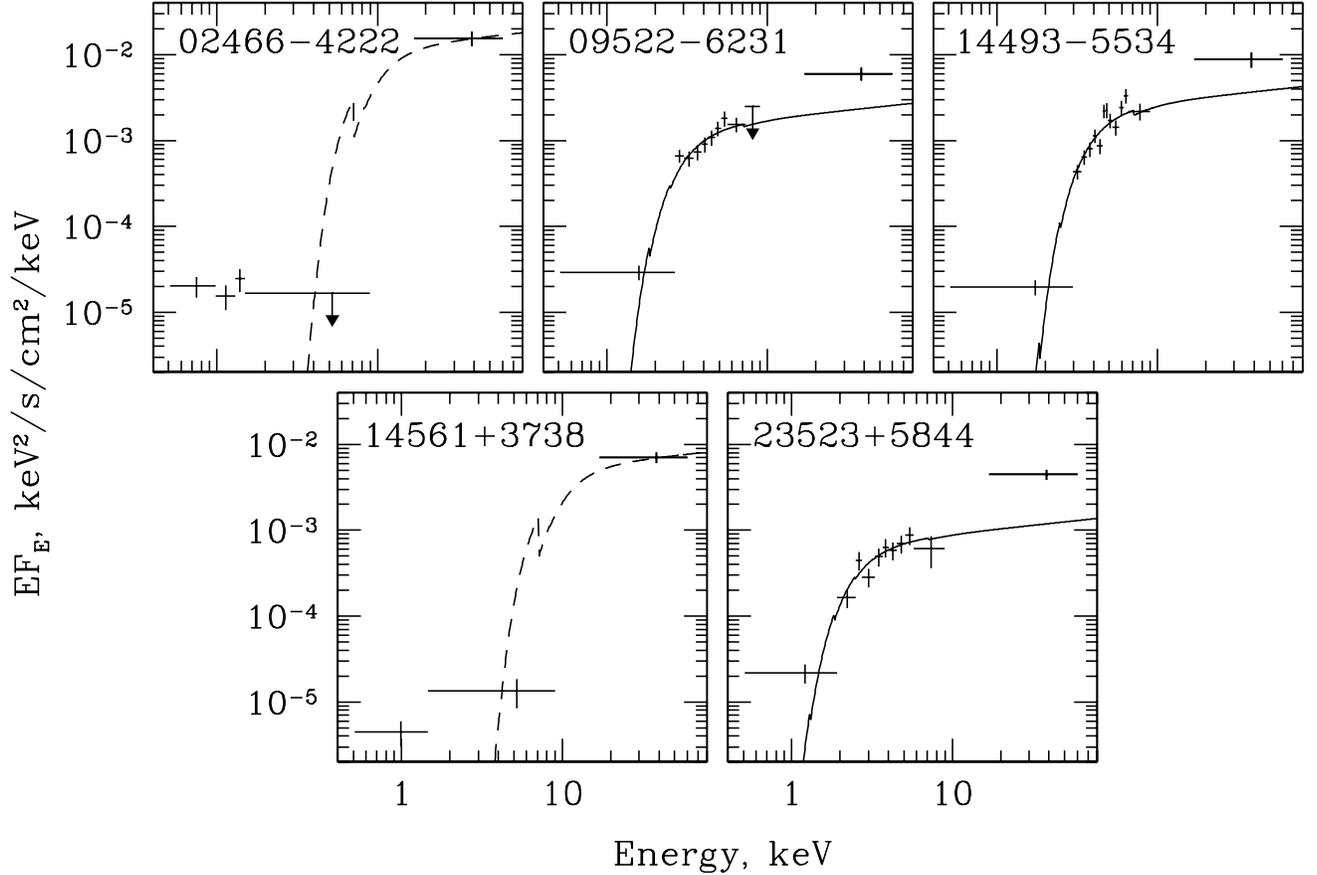


Fig. 2. X-ray spectra of the identified AGN obtained by Chandra (data from 0.5–9 keV) and INTEGRAL (data at 17–60 keV). IGR source names are given in the left upper corner of the panels. The solid lines represent the best-fit models to the Chandra data by an absorbed power-law spectrum with photon index $\Gamma = 1.8$ and absorption column densities as quoted in Table 2. For IGR J02466–4222 and IGR J14561+3738, the dashed line represents the power-law ($\Gamma = 1.8$) spectrum absorbed by neutral material with column density $N_{\text{H}} = 10^{24} \text{ cm}^{-2}$ that matches the INTEGRAL hard X-ray flux.

Table 2. X-ray fluxes, luminosities and absorption column densities of the AGN^a

Source	F (17–60 keV) $10^{-12} \text{ erg/s/cm}^2$	L (17–60 keV) erg/s	F (0.5–8 keV) $10^{-12} \text{ erg/s/cm}^2$	L (0.5–8 keV) erg/s	N_{H} 10^{22} cm^{-2}	$N_{\text{H,Gal}}^{\text{b}}$
IGR J02466–4222	31 ± 6	$(3.2 \pm 0.6) \times 10^{44}$	~ 0.07	$\sim 8 \times 10^{41}$	> 100	0.03
IGR J09522–6231	12 ± 2	$(2.0 \pm 0.4) \times 10^{45}$	2.1 ± 0.2	$(3.6 \pm 0.3) \times 10^{44}$	6.3 ± 0.6	0.27
IGR J14493–5534	16 ± 2		2.3 ± 0.2		12.3 ± 1.1	0.50
IGR J14561–3738	14 ± 3	$(1.7 \pm 0.3) \times 10^{43}$	~ 0.02	$\sim 2 \times 10^{40}$	> 100	0.06
IGR J23523+5844	8.9 ± 1.4	$(5.8 \pm 0.9) \times 10^{44}$	1.2 ± 0.1	$(8.4 \pm 0.6) \times 10^{43}$	3.7 ± 0.5	0.58

^a The 17–60 keV fluxes are adopted from the INTEGRAL catalog (Krivonos et al. 2007). The absorption column densities N_{H} and 0.5–8 keV fluxes were determined by fitting the Chandra spectra in the 0.5–9 keV band by an absorbed power-law model with $\Gamma = 1.8$, except for IGR J02466–4222 and IGR J14561–3738, for which only crude estimates of the X-ray fluxes and lower limits on the N_{H} values are provided (see main text for further explanations).

^b Galactic absorption column from Dickey & Lockman (1990).

The X-ray spectrum measured by Chandra (Fig. 2) can be well fit ($\chi^2 = 435.9$ for 579 d.o.f.) by an absorbed power-law model with column density $N_{\text{H}} \sim 1.2 \times 10^{23} \text{ cm}^{-2}$, which is much higher than the Galactic absorption column density in the direction of the source (see Table 2). We conclude that IGR J14493–5534 is an obscured AGN. We note that IGR J14493–5534 has also been recently ob-

served by the Swift/XRT telescope and the X-ray spectrum (Malizia et al. 2007) is in good agreement with that measured by Chandra.

Spectroscopic optical observations are needed to refine the classification and determine the redshift of IGR J14493–5534=2MASX J14491283–5536194. This should be a feasible task despite the relatively large

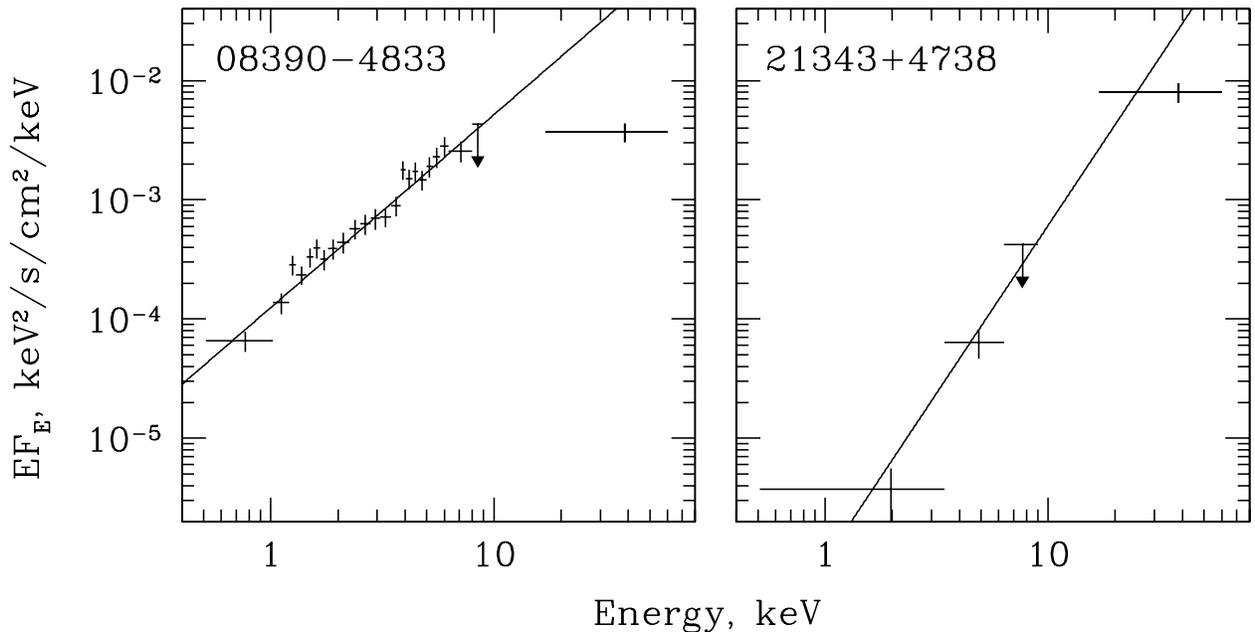


Fig. 3. X-ray spectra of the identified Galactic sources obtained by Chandra (data from 0.5–9 keV) and INTEGRAL (data at 17–60 keV). IGR source names are given in the left upper corner of the panels. The solid lines represent the best-fit power-law models of the Chandra data, with the photon index values given in Table 3.

Table 3. X-ray fluxes and spectral parameters of the Galactic sources^a

Source	F (17–60 keV) 10^{-12} erg/s/cm ²	F (0.5–8 keV) 10^{-12} erg/s/cm ²	Γ	N_{H} 10^{22} cm ⁻²	$N_{\text{H,Gal}}^{\text{b}}$
IGR J08390–4833	7.6 ± 1.4	3.5 ± 0.3	0.38 ± 0.07	< 0.4 (3σ)	0.71
IGR J21343+4738	16 ± 3	~ 0.2	-0.8 ± 0.5		0.32

^a The 17–60 keV flux is adopted from the INTEGRAL catalog (Krivonos et al. 2007) for IGR J21343+4738 and determined from INTEGRAL data for IGR J08390–4833. The quoted values of the power-law index Γ and of the 0.5–8 keV flux were obtained by fitting the Chandra spectra in the 0.5–9 keV energy band by a power-law model. The upper limit on the N_{H} value for IGR J08390–4833 was determined by fitting the Chandra data by an absorbed power-law model.

^b Galactic absorption column from Dickey & Lockman (1990).

Galactic extinction in its direction, $A_V \approx 2.5$ (Schlegel et al. 1998), since the galaxy is relatively bright in the near-infrared band ($K = 10.7$, 2MASS).

3.5. IGR J14561–3738 – a Compton thick AGN

This source was first detected and localized to within ~ 1 deg during the RXTE 3–20 keV Slew Survey (Revnitsev et al. 2004) and received the name XSS J14562–3735. In the $\sim 3'$ IBIS/ISGRI localization region there is a conspicuous object – the spiral (SBa) galaxy ESO 386-G034 at redshift $z = 0.0246$ (NED). Masetti et al. (2008) recently obtained its optical spectrum and found a number of emission lines indicating that this is a Seyfert 2 galaxy.

With Chandra we found a single X-ray source inside the IBIS/ISGRI error box of IGR J14561–3738, which is located at the center of ESO 386-G034 (see Fig. 1). This confirms that this Seyfert 2 galaxy is indeed associated with the INTEGRAL source.

The Chandra source is very weak. The detected ~ 12 counts correspond to a flux of $\sim 2 \times 10^{-14}$ erg s⁻¹ cm⁻²

in the 0.5–8 keV band, assuming a Crab-like spectrum. Combining the Chandra counts with the flux measured by IBIS/ISGRI in the 17–60 keV band (Fig. 2), we infer that direct X-rays from the active nucleus in IGR J14561–3738 are obscured by material with a column density of at least 10^{24} cm⁻². We therefore conclude that IGR J14561–3738 is likely a Compton-thick AGN.

3.6. IGR J21343+4738 – a high-mass X-ray binary

In the IBIS/ISGRI localization region, there is a fairly weak (~ 24 counts) Chandra source, whose position is consistent with that of a $R \sim 14$ star, USNO-B1.0 1376-0511904 (see Fig. 1). This likely counterpart of IGR J21343+4738 has been observed by the Russian-Turkish 1.5-m Telescope (RTT-150) and identified as a B3 star, suggesting that the system is a high-mass X-ray binary (HMXB, Bikmaev et al. 2008).

As should be expected for a HMXB, the X-ray spectrum of IGR J21343+4738 measured by Chandra is very hard (Fig. 3). For example, it can be well fit ($\chi^2 = 558.1$ for 579 d.o.f.) by a power-law model with $\Gamma = -0.8 \pm 0.5$,

although the statistics are insufficient for detailed spectral analysis. We note that the source was clearly detected by INTEGRAL in several observations from 2002–2004 but not in later observations, suggesting strong variability. For this reason, the average INTEGRAL 17–60 keV flux value presented in Fig. 3 should not be directly compared with the Chandra spectrum. We refer the reader to the paper by Bikmaev et al. (2008) for a further discussion of the identification and nature of IGR J21343+4738.

3.7. IGR J23523+5844 – an obscured AGN

There is a bright Chandra source inside the IBIS/ISGRI localization region (see Fig. 1). The position of this likely X-ray counterpart is consistent with that of a faint point-like optical object. It has been observed by the RTT-150 telescope and identified as a Seyfert 2 galaxy at redshift $z = 0.163$ (Bikmaev et al. 2008). Masetti et al. (2008) independently obtained similar results.

The X-ray spectrum measured by Chandra (Fig. 2) can be well fit ($\chi^2 = 398.4$ for 579 d.o.f.) by an absorbed power-law model with column density $N_{\text{H}} \sim 4 \times 10^{22} \text{ cm}^{-2}$, which is much higher than the Galactic absorption column density in the source direction (see Table 2). We therefore conclude that IGR J23523+5844 is a moderately obscured, luminous Seyfert galaxy.

We note that Rodriguez et al. (2008) have recently observed IGR J23523+5844 with the Swift/XRT telescope. They reported a position of the weak X-ray counterpart that differs by just $1''$ from the Chandra position. Also the absorption column density estimated from the Swift/XRT spectrum is consistent with the value found in our analysis.

4. Discussion and conclusions

In line with our expectations, most of the seven INTEGRAL hard X-ray sources chosen for short follow-up observations with Chandra proved to be obscured AGN at redshifts from 0.025 to 0.25. These include IGR J02466–4222, IGR J09522–6231, IGR J14493–5534, IGR J14561–3738, and IGR J23523+5844. Of these, IGR J09522–6231, IGR J14561–3738, and IGR J23523+5844 have been optically classified as Seyfert 1.9–2 galaxies. Based on the X-ray data and 6dF optical spectrum, IGR J02466–4222 appears to be an X-ray bright, optically-normal galaxy. At redshift $z = 0.0696$, it is thus one the nearest known objects of this enigmatic class. For IGR J14493–5534 the distance and optical class are not known yet.

These newly-discovered AGN demonstrate two key features of the INTEGRAL survey: finding AGN in the poorly studied Galactic zone of avoidance (i.e., at $|b| \lesssim 5^\circ$) and finding heavily-obscured AGN. The inferred line-of-sight, X-ray absorption column densities range from several 10^{22} cm^{-2} for IGR J09522–6231 and IGR J23523+5844, through $\sim 10^{23} \text{ cm}^{-2}$ for IGR J14493–5534 to $> 10^{24} \text{ cm}^{-2}$ for IGR J02466–4222 and IGR J14561–3738. Therefore, the latter two objects are most likely Compton-thick AGN. These newly-identified sources increase the sample of heavily-obscured ($N_{\text{H}} \gtrsim 10^{24} \text{ cm}^{-2}$) AGN detected by INTEGRAL to about 10 objects (see Sazonov et al. 2007), with only half of them having been known before the survey.

With these and previous discoveries by INTEGRAL and Swift, the census of nearby heavily-obscured AGN with hard X-ray fluxes higher than 1–2 mCrab may be regarded as nearly complete for most of the sky, except for the Galactic plane and Galactic Center regions, where additional follow-up observations are needed.

Therefore, there is now a well-defined, hard X-ray selected sample of nearby heavily-obscured ($N_{\text{H}} \gtrsim 10^{24} \text{ cm}^{-2}$) AGN, which allows us to place a firm lower limit of ~ 10 –15% on the relative fraction of such AGN in the local Universe. The true fraction may be higher than this estimate due to bias against finding very Compton-thick AGN ($N_{\text{H}} \gtrsim 10^{25} \text{ cm}^{-2}$) even at hard X-ray energies. The list of known nearby heavily-obscured AGN will continue growing in the coming years as the INTEGRAL and Swift surveys deepen their sky coverage.

The very low X-ray (0.5–8 keV) to hard X-ray (17–60 keV) flux ratios determined from Chandra and INTEGRAL observations for the Compton-thick AGN IGR J02466–4222 and IGR J14561–3738 indicate that, in both cases, much less than 1% of the emission from the nucleus is scattered by the ambient medium. Such objects were virtually unknown before the INTEGRAL/Swift era. It is possible that here we are dealing with AGN buried in a very geometrically thick torus that obscures most of the sky as observed from the central massive black hole (Ueda et al. 2007). This could also explain the weakness (or absence) of optical narrow-line emission in IGR J02466–4222, as there would be little radiation escaping from the nucleus to ionize surrounding interstellar medium.

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