FIVE NEW INTEGRAL UNIDENTIFIED HARD X-RAY SOURCES UNCOVERED BY CHANDRA

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ABSTRACT

The IBIS imager on board INTEGRAL, with a sensitivity better than a milliCrab in deep observations and a point-source location accuracy on the order of few arcminutes, has thus far localized 723 hard X-ray sources in the 17–100 keV energy band, of which about 1/3 are still unclassified. The aim of this paper is to provide subarcsecond localizations of the unidentified sources, necessary to pinpoint the optical and/or infrared (IR) counterpart of those objects whose nature is so far unknown. Cross-correlation between the new IBIS sources published in the fourth INTEGRAL/IBIS Survey catalog and the Chandra/ACIS data archive resulted in a sample of five previously unidentified objects. We present here the results of Chandra X-ray Observatory observations of these five hard X-ray sources discovered by the INTEGRAL satellite. We associated IGR J10447−6027 with IR source 2MASS J10445192−6025115, IGR J16377−6423 with the cluster CIZA J1638.2−6420, IGR J14193−6048 with the pulsar with nebula PSR J1420−6048, and IGR J12562+2554 with the quasar SDSS J125610.42+260130.5. We suggest that the counterpart of IGR J12288+0052 may be an active galactic nucleus/quasi-stellar object type 3 at a confidence level of 90%.

Key words: catalogs – gamma rays: general – surveys – X-rays: general

Online-only material: color figure

1. INTRODUCTION

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL; Winkler et al. 2003) has been operating for seven years and has discovered a large number of new hard X-ray sources at energies >17 keV. With its milliCrab sensitivity and point-source location accuracy of a few arcminutes, the IBIS instrument (Ubertini et al. 2003) has localized more than 723 hard X-ray sources in the 17–100 keV energy band (Bird et al. 2010); about 30% of these objects are still unidentified, unclassified, and/or poorly studied in the X-ray band. A similar picture is found in the all-sky BAT survey performed with the Swift satellite (Cusumano et al. 2010). The IBIS localization is often insufficient to unambiguously identify the optical or infrared (IR) counterpart of a detected source, thus hampering its classification. To overcome this problem, the arcsec positioning now available with the current generation of X-ray telescopes is required. While an X-ray position with an accuracy of several arcseconds (as obtained by Chandra or XMM-Newton) can lead to the correct optical or IR identification, in many cases (and especially in the crowded regions of the Galactic plane and center), the subarcsecond position available with Chandra is crucial to obtaining a firm identification. Furthermore, the Chandra/ACIS instrument allows measurement of the soft X-ray energy emission of the source, providing information on the spectral shape and level of absorption that are important in determining the nature of the unidentified object.

Classification and knowledge of the nature of these unidentified objects are very important to the study of several astrophysical questions. In particular, we need to understand if they belong to new classes of objects, and define their timing and spectral characteristics. The construction of a large complete sample of hard X-ray objects belonging to specific object classes (such as active galactic nuclei (AGNs) detected with INTEGRAL; Malizia et al. 2009) will also allow us to define the spatial distribution and the luminosity function of various classes of objects. With this aim, we have cross-correlated the list of IBIS sources included in the fourth catalog with the ACIS data archive, and derived a sample of five unidentified objects that can be investigated at X-ray energies.

2. DATA REDUCTION AND IMAGE AND SPECTRAL ANALYSIS

For each source in the sample, we extract the IBIS light curve to study any possible variability of the sample. Figure 1 shows these light curves in the 20–100 energy band and demonstrates the absence of any meaningful count rate variation. X-ray data obtained with the ACIS instrument in the 0.5–8 keV energy band have been analyzed for each source in the sample. The log of all observations is given in Table 1, which reports the galactic coordinates, the observation code (ID), the observation date, the detector configuration, and the exposure time. We downloaded the most recent versions of the data products processed at the Chandra X-ray Center using the pipeline ASCDS with versions spanning from 7.6.9 to 7.6.11. In only one case, we reprocessed the data because the pipeline version was lower than 7.6.7. Further processing was done with the Chandra Interactive Analysis of Observations (CIAO) software, version 4.1.2, i.e., the same version of Calibration Database (CALDB), provided by the Chandra X-ray Center, and following the science threads listed on the CIAO Web site.4

The CIAO routine wavdetect was used to search for X-ray sources on the ACIS chips. We searched for sources in the 0.5–2 keV, 2–8 keV, and 4–8 keV images, setting the threshold significance for the output source pixel list to 9.5 × 10−7, corresponding to a level that would be expected to yield only one spurious source. IGR J16377−6423 is an extended source and hence we used the more appropriate CIAO routine vtpdetect to detect sources within the IBIS error box.

4 Available at http://cxc.harvard.edu/ciao/.
In Table 2, for each IBIS detection, we report all the sources detected by ACIS within the IBIS error circles at 90% confidence level, their position with relevant error, and count rates in three energy bands: 0.5–2 keV, 2–8 keV, and 4–8 keV. We do not take into account the new IBIS error box values reported by Scaringi et al. (2010) since the improvements in the source positions are only for higher sigma sources (10σ or more). ACIS detections with significance lower than 4 are not reported. Furthermore, we do not discuss here sources detected only below 2 keV, since they are unlikely to be associated with the IBIS detections. The positional uncertainties reported in Table 2 are 1σ statistical errors calculated by the wavdetect software. With the spatial resolution limited by the physical size of the CCD pixels, a systematic pointing uncertainty should be added to this. The pointing uncertainties are 0.64 arcsec at 90% confidence and 1 arcsec at 99% confidence levels, respectively (Weisskopf 2005; available at http://cxc.harvard.edu/cal/).

We next tried to pinpoint the most likely counterpart of the high-energy source, primarily using the source X-ray properties: harder and brighter objects are most likely to be the true counterparts of the IBIS detections and will be discussed in detail here. Finally, using the restricted Chandra positions at 99% confidence level, we searched for optical/IR counterparts using various online archives such as the NASA/IPAC Extragalactic Database (NED), High Energy Astrophysics Science Archive Research Center (HEASARC),

| IGR Name          | l     | b     | ObsID | Start Time (UTC)       | Detector | Exposure Time (s) |
|-------------------|-------|-------|-------|------------------------|----------|------------------|
| IGR J10447−6027   | 287.89| −1.31 | 9495  | 2008-04-24 00:57:01    | ACIS-I   | 31360            |
|                   |       |       | 9849  | 2008-04-26 16:31:04    | ACIS-I   | 28840            |
| IGR J12288+0052   | 290.30| 63.19 | 7754  | 2007-03-12 13:22:54    | ACIS-S   | 9540             |
| IGR J12562+2554   | 344.27| 88.38 | 3212  | 2002-12-04 15:08:35    | ACIS-S   | 28100            |
|                   |       |       | 7640  | 2007-06-14 21:29:10    | ACIS-I   | 71130            |
| IGR J14193−6048   | 313.44| 0.27  | 2794  | 2002-09-16 19:28:28    | ACIS-S   | 10060            |
|                   |       |       | 2794  | 2002-09-22 01:48:17    | ACIS-S   | 10060            |
| IGR J16377−6423   | 324.59| 11.52 | 1227  | 1999-08-25 09:35:10    | ACIS-I   | 12240            |
|                   |       |       | 1281  | 1999-08-25 05:45:39    | ACIS-I   | 11530            |
Table 2

| No. | R.A. (J2000) | Decl. (J2000) | R.A. Error (′) | Decl. Error (′) | Count Rate (4–8 keV) | Count Rate (2–8 keV) | Count Rate (0.5–2 keV) | Counterparts |
|-----|--------------|--------------|----------------|----------------|----------------------|----------------------|-----------------------|--------------|
| 1   | 161.2162     | −60.4200     | 0.1            | 0.1            | 486 ± 22             | 589 ± 25             | ...                   | 2MASS J10445192−6025115a |
| 2   | 161.1060     | −60.3850     | 0.2            | 0.1            | 66 ± 8               | 140 ± 12             | 17 ± 4                | ...           |
| 3   | 161.2836     | −60.4545     | 1.0            | 0.8            | 20 ± 5               | ...                  | ...                   | ...           |
| 4   | 161.0756     | −60.3692     | 1.9            | 0.6            | 33 ± 6               | ...                  | ...                   | ...           |
| 5   | 160.8617     | −60.4396     | 1.2            | 0.6            | 48 ± 7               | 64 ± 9               | ...                   | ...           |
| 6   | 161.2906     | −60.4615     | 0.8            | 0.5            | 64 ± 9               | ...                  | ...                   | ...           |
| 7   | 161.0879     | −60.5007     | 0.6            | 0.5            | 16 ± 4               | ...                  | ...                   | ...           |
| 8   | 161.1899     | −60.3955     | 0.8            | 0.4            | ...                  | 19 ± 4               | ...                   | ...           |
| 9   | 161.2022     | −60.3953     | 0.7            | 0.5            | ...                  | 18 ± 4               | ...                   | ...           |
| 10  | 161.0314     | −60.3422     | 1.4            | 0.7            | ...                  | 21 ± 5               | ...                   | ...           |
| 11  | 161.2373     | −60.5046     | 1.0            | 1.2            | ...                  | 22 ± 5               | ...                   | ...           |
| 12  | 161.0502     | −60.3420     | 2.2            | 0.5            | ...                  | 21 ± 4               | ...                   | ...           |
| 13  | 161.2696     | −60.4523     | 0.71           | 0.4            | ...                  | 16 ± 4               | ...                   | ...           |
| 14  | 161.2117     | −60.3422     | 0.83           | 0.7            | ...                  | 20 ± 5               | ...                   | ...           |
| 15  | 161.2138     | −60.4354     | 0.91           | 0.2            | ...                  | 16 ± 4               | ...                   | ...           |
| 16  | 161.0611     | −60.3923     | 0.82           | 0.5            | ...                  | 17 ± 4               | ...                   | ...           |
| 17  | 161.0723     | −60.4975     | 1.1            | 0.5            | ...                  | 28 ± 6               | ...                   | ...           |
| 18  | 161.0975     | −60.4759     | 0.53           | 0.5            | ...                  | 29 ± 6               | ...                   | ...           |
| 19  | 161.1461     | −60.3321     | 0.75           | 0.3            | ...                  | 36 ± 6               | ...                   | ...           |
| 20  | 161.336     | −60.437      | 0.48           | 0.2            | ...                  | 44 ± 7               | ...                   | ...           |
| 21  | 161.2073     | −60.3564     | 0.48           | 0.3            | ...                  | 44 ± 7               | ...                   | ...           |

Notes.

The positional uncertainties are 1σ statistical errors as computed by the wavdetect software. Sources with asterisks are detected in the hard band (4–8 keV) but they are outside of the IBIS error box at 99% confidence level.

1 Two Micron All Sky Survey; Skrutskie et al. (2006).

2 Sloan Digital Sky Survey NBC Quasar Candidate Catalog; Richards et al. (2004).

3 Sloan Digital Sky Survey Quasar Catalog; Schneider et al. (2007).

4 SDSS Photometric Catalog, Release 7; Adelman-McCarthy et al. (2009).

5 Veron Catalog of Quasars and AGNs, 12th Edition; Veron et al. (2006).

6 XAssist Source List; Ptak & Griffiths (2003).

7 Sloan Digital Sky Survey DR6 Galaxy Clusters Catalog; Wen et al. (2009).

8 Sloan Digital Sky Survey DR6 Galaxy Clusters Catalog; Wen et al. (2009).

9 CIZA Catalog; Ebeling et al. (2002).

and Set of Identifications, Measurements, and Bibliography for Astronomical Data (SIMBAD); the results of this search are also given in Table 2 but only for sources detected in the 2–8 keV band. In this table, we report in bold the coordinates of the best candidate for the counterpart for each INTEGRAL source.
**Table 3**  
Chandra ACIS Spectral Analysis Results

| Sources   | Off-axis | Model       | $N_H$ $(10^{22}$ cm$^{-2}$) | $\Gamma$ | X-ray Flux (0.3–10 keV) | Extrapolated Flux (20–40 keV) | $\chi^2$/dof |
|-----------|----------|-------------|-----------------------------|---------|------------------------|--------------------------------|--------------|
| IGR J10447–6027 (unidentified, $N_{H\text{gal}} = 1.3 \times 10^{23}$ cm$^{-2}$) | | | | | | | |
| 1         | 0/9      | Power law   | $21 \pm 3$                 | 1.0$_{-0.6}^{+0.9}$ | 1.7 $\pm$ 0.3 | 5.7  | 105/81 |
| 2         | 4/1      | Power law   | $4^{+2}_{-1}$              | 2.2$_{-1.5}^{+2.1}$ | 0.4$_{-0.4}^{+0.6}$ | <1.1 | 19/14 |
| IGR J1228+0052 (AGN?, $N_{H\text{gal}} = 1.9 \times 10^{20}$ cm$^{-2}$) | | | | | | | |
| 3         | 0/4      | Power law   | $2.5^{+5.5}_{-3.1}$        | 1.6 $\pm$ 0.8 | 0.3$_{-0.2}^{+3.0}$ | 0.2  | 6/7    |
| IGR J12562+2554 (Cluster?, $N_{H\text{gal}} = 7.6 \times 10^{19}$ cm$^{-2}$) | | | | | | | |
| 7         | 4/5      | Power law   | ...                        | 1.7 $\pm$ 0.1 | 0.25 $\pm$ 0.04 | 0.3  | 32/30  |

**Notes.** An $N_H$ fixed to the Galactic column density was included in the fit. Error is given at 90% confidence level for one parameter of interest ($\Delta \chi^2 = 2.71$). Unabsorbed 0.3–10 keV and 20–40 keV fluxes are reported in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

Chandra energy spectra have been produced for those counterparts that were detected with a significant number of counts in the 4–8 keV energy band (unless otherwise stated). We extracted source photons from a circular region centered on each source with an extraction region chosen so that more than 95% of the energy was included, using the off-axis angle reported in Table 3. For the background, we used circular source-free regions in the same CCD as the studied source. Once the source and background regions were determined, the CIAO routine dmextract was used to produce energy spectra and routines mkacisrmf and mkarf were used for the response and ancillary files, respectively.

For objects with more than one pointing, having checked for the absence of significant luminosity changes, we performed simultaneous spectral fitting using all the available spectra. A simple power-law model, absorbed by Galactic absorption, has been used to fit ACIS spectra, with XSPEC software v11.3.2. When required by the fit, a power-law model with two absorbers has been used: the first $N_H$ fixed to the Galactic column density (reported in Table 3) and the second as a free parameter in order to study the possible presence of intrinsic absorption. The result of this analysis is reported in Table 3, which lists the column density in excess of the galactic value, the photon index, the 0.3–10 keV flux, and the extrapolated 20–40 keV fluxes. The uncertainties on the various parameters are at 90% confidence level for one parameter of interest ($\Delta \chi^2 = 2.71$).

3. NOTES ON INDIVIDUAL SOURCES

In the following section, the results for each individual source are presented.

3.1. IGR J10447–6027

This source was discovered by Leyder et al. (2008) during the analysis of the region surrounding $\eta$ Carinae and associated with a young stellar object (YSO; IRAS 104236011, R.A.: 10$^h$44$^m$17$^s$.9, decl.: $-60^\circ$27′46″); it has been included in the fourth IBIS catalog as a faint persistent object detected in the 18–60 keV energy band at 5.8$\sigma$ level (Bird et al. 2010). The IBIS/ISGRI mosaic significance image around IGR J10447–6027 in the 18–60 keV energy band (total exposure of 2189 ks) is shown in Figure 2. Within the most recent IBIS error box reported by Bird et al. (2010), we find many soft X-ray sources, with 11 objects in the 2–8 keV energy band but only 2 in the 4–8 keV energy range (see Figure 3); both objects detected at hard energies fall inside the 90% IBIS error box. A bright and hard source (5) is also detected with a signal-to-noise ratio of $\sim$7 at high energies, but it is outside of the 99% confidence error circle. We then performed spectral analysis for the two brightest detections (Sources 1 and 2). Neither of these sources shows any time variability; in fact, in both ACIS pointings the count rates are similar: Source 1 has $(2.02 \pm 0.08) \times 10^{-2}$ counts s$^{-1}$ and $(2.17 \pm 0.09) \times 10^{-2}$ counts s$^{-1}$, while Source 2 has $(3.8 \pm 0.4) \times 10^{-3}$ counts s$^{-1}$ and $(3.1 \pm 0.4) \times 10^{-3}$ counts s$^{-1}$ in the 1–8 keV energy band, in the first and second pointing, respectively.

Source 1 is by far the most intense and coincides with the source detected in the *Swift*/X-ray Telescope (XRT) image (Landi et al. 2010), although the XRT uncertainty was not sufficient to pinpoint a unique counterpart. A simple power-law model with galactic absorption does not give an acceptable fit ($\chi^2$/dof = 554/82), but the addition of an intrinsic absorber reduces the $\chi^2$/dof to 105/81. This model gives an acceptable fit to the data, although a soft excess is also visible below 3 keV in the residuals obtained with respect to the fitted model. Adding a thermal component (modeled in XSPEC with Bremss) resulted in a substantial fit improvement, reducing the $\chi^2$/dof from 105/81 to 65/79. This corresponds to a low F-test chance probability of $6 \times 10^{-9}$. With this two-component model we obtain the following parameters: a very high column density $N_H = (30^{+3}_{-2}) \times 10^{22}$ cm$^{-2}$, a spectral index $\Gamma = 1.2 \pm 0.4$, a temperature of the thermal component of $0.21 \pm 0.07$ keV, and unabsorbed fluxes of $\sim 1.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the 0.3–10 keV energy band. The extrapolated high-energy flux ($\sim 5.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the 20–40 keV energy band) is in full agreement with the IBIS detection ($\sim 4.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in 20–40 keV energy range). The ACIS spectrum of this source is shown in Figure 4.

Source 2 has a softer continuum ($\Gamma \sim 2.4$) and a lower unabsorbed 0.3–10 keV flux ($\sim 0.4 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$) than Source 1; its extrapolated high-energy flux is a factor of $\sim 50$ lower than that reported by Bird et al. (2010) and so it cannot be considered a likely counterpart of the IBIS object. Similarly, all the other objects in Table 3 are unlikely associations.

Sources 3 and 4 are both much weaker (see Table 3) and so very unlikely to be the counterparts of the IBIS source.

This leads us to discard the association between the YSO and the IBIS object proposed by Leyder et al. (2008) and to conclude that Source 1 is the only possible counterpart. We do not see any variability in the source spectral parameters between *Chandra*/ACIS and *Swift*/XRT observations, indicative of a persistent and possible low variability source. In contrast to the
Figure 2. INTEGRAL IBIS/ISGRI mosaic significance image around IGR J10447−6027 in the 18–60 keV energy band for a total exposure of 2189 ks. (A color version of this figure is available in the online journal.)

Figure 3. Left: ACIS 0.5–8 keV image of the region surrounding IGR J10447−6027. A Gaussian smoothing was applied to the counts distribution with a width of 2 pixels. The large circles represent the IBIS position and uncertainties expressed as 90% and 99% confidence circles (as reported by Bird et al. 2010). Crosses indicate detections in the 0.5–2.0 keV band, squares indicate detections in the 2.0–8.0 keV band, and numbers indicate the position of the X-ray sources detected within the IBIS error box in the hard X-ray band (4–8 keV). The asterisk is the position of the YSO, IRAS 104236011. Right: ACIS 4–8 keV image of the region surrounding IGR J10447−6027. A Gaussian smoothing was applied to the counts distribution with a width of 4 pixels. The large circles represent the IBIS position and uncertainties expressed as 90% and 99% confidence circles (as reported by Bird et al. 2010). Circles represent sources detected in the 4–8 keV energy band.

XRT observation, the Chandra-restricted position allows us to pinpoint the IR counterpart of the source to the object 2MASS J10445192−6025115. This source has magnitudes in the $J$, $H$, and $K$ bands of 15.308, 14.967, and 13.977, respectively, which combined with the lack of an optical detection in the USNO B1.0 catalog implies a quite red object. The limit on $R$ is estimated to be around 17 mag in the region surrounding Source 1, implying that $R - K$ is $\gtrsim 3$. The very high column density ($N_H = \sim 2 \times 10^{23} \, \text{cm}^{-2}$) is compatible with the source reddening. Only IR follow-up observations with spectroscopic capability will eventually provide information on the nature of this intriguing object.

3.2. IGR J12288+0052

This source is a new INTEGRAL detection reported as a possible AGN in the fourth IBIS catalog (Bird et al. 2010), with a weak 20–40 keV flux corresponding to $\sim 4.5 \times 10^{-12} \, \text{erg cm}^{-2} \, \text{s}^{-1}$. Indeed, within the IBIS error box there are two AGNs reported in the Catalog of Quasars and Active Galactic Nuclei by Veron-Cetty and Veron (2010; 12th edition): the type 2 quasi-stellar object (QSO) SDSS 122845.74+005018.7 (R.A. = 12h28m45.s7, decl. = +00°50'18") at $z = 0.57$ and the QSO 2QZ J122859+0054 (R.A. = 12h28m59.1s, decl. = +00°54'18") at $z = 1.2$. This sky region, however, is full of
other galaxies, some of which are also listed as quasar candidates selected from the photometric imaging data of the Sloan Digital Sky Survey (SDSS; Richards et al. 2009). Within the IBIS error box at 99% confidence level, we detect various X-ray emitters and five objects in the 2–8 keV energy range (see Figure 5); only one of these five is still visible above 4 keV and is located inside the 90% IBIS error box.

Source 1 has a counterpart in the SDSS (SDSS J122933.46+005139.4), which is still unclassified. Source 2 is instead coincident with a QSO candidate in the SDSS (SDSS J122903.62+005359.5). Source 3 is the only source still visible at high energies. Source 4 is a galaxy listed in the SDSS as SDSS J122828.52+004827.8. Finally, Source 5 has no obvious counterparts in the various archives.

The spectrum of Source 3 (the brightest and hardest of all the objects detected), although of poor quality, is compatible with an AGN canonical power law absorbed by a column density of $\sim 3 \times 10^{22}$ cm$^{-2}$. The extrapolated flux in the 20–40 keV energy range is the highest among the five objects ($0.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$), although it is still much lower than that reported in the fourth IBIS catalog (≈4 $\times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$); this suggests that there is either variable or extremely absorbed and hence Compton thick. This source has been discussed by Vignali et al. (2010) who on the basis of combined optical, mid-IR, and soft X-ray information exclude the possibility that it could be a Compton thick AGN; this leaves the flux variability as a likely explanation for the ACIS and IBIS mismatch. Alternatively, Source 3 could not be the real counterpart of the INTEGRAL detection, given the fact that the entire IBIS error box is not covered by the Chandra observation. Nevertheless, the type II object SDSS J122845.74+005018.7 remains a potentially interesting counterpart candidate that deserves further studies. It is reported as a radio source of 3.14 mJy flux density at 1.4 GHz, as an IRAS object with a 60 μm detection of 120 mJy, and has $B$ and $R$ magnitudes of 22.2 and 20.6, respectively. Only deeper and simultaneous broadband X-ray observation such as is possible with Suzaku could provide more detailed information and confirmation of the source association with the INTEGRAL detection.

3.3. IGR J12562+2554

This source is a new INTEGRAL detection reported in the fourth IBIS catalog (Bird et al. 2010); it has a 20–40 keV flux of $4.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ and is tentatively classified as a cluster of galaxies. Within the IBIS error box, an archival search shows that the fossil group of galaxies RX J1256.0+2556 at $z = 0.232$ is present. Interactions in a galaxy group cause large galaxies to spiral slowly toward the center of the group, where they can merge to form a giant central galaxy, which progressively swallows all its neighbors. If this process runs to completion and no new galaxy falls into the group, then the result is an object dubbed a “fossil group,” in which an elliptical galaxy sits at the center of a hot gas halo emitting X-rays. Therefore, the IBIS source could be associated with the cluster itself, the elliptical galaxy at its center, or any other member of the group.

Within the IBIS positional uncertainty, the Chandra image in Figure 6 shows the presence of a few soft sources and nine objects detected in the 2–8 keV band (although two of these...
are located outside the 99% IBIS error box); only two objects are detected in the 4–8 keV energy band and of these one is an unlikely association as it falls outside the larger IBIS error circle.

The fossil group (Source 3), also serendipitously detected by XMM-Newton as 2XMM J125602.2+255636 (Watson et al. 2009) with a flux of $3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (in the 0.3–10 keV energy band), is only seen below 2 keV. Recent analysis of the X-ray data from this system gives a low gas temperature of 2.4–2.6 keV using both XMM-Newton (Jeltema et al. 2006) and Chandra (Jones et al. 2003) data; we find a similar temperature indicative of a soft and weak X-ray source (see Table 3) which is unlikely to be the counterpart of the IBIS object.

Object 1 is coincident with SDSS J125600.78+255406.0, also serendipitously detected by XMM-Newton as 2XMM J125600.8+255406; Watson et al. (2009), with a flux of $1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (in the 0.3–10 keV energy band) and also listed as a Chandra QSO candidate (CXOXA J125600.7+255406; Ptak & Griffiths 2003).

Object 2 is possibly the galaxy SDSS J125614.76+255535.4, also reported as 2XMM J125614.8+255529 (Watson et al. 2009), with a flux of $6 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (in the 0.3–10 keV energy band).

A number of sources seen in the 2–8 keV band (i.e., 4, 5, 6, and 10) have no obvious identifications while a couple of objects (7 and 8) have a counterpart in the SDSS.

Object 7 is the brightest and hardest source detected by Chandra within the IBIS positional uncertainty, although it is located at the border of the 99% error circle and has a low X-ray flux of $2.5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in the 0.3–10 keV band. It is listed as a quasar candidate at $z = 1.2$ in the SDSS NBCKDE Catalog of Photometrically Selected Quasar Candidates (Richards et al. 2009). The source spectrum is a power law with $\Gamma \sim 1.7$ and galactic $N_H$; the Chandra spectrum extrapolated to the 20–100 keV band gives $\sim 0.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, a factor of 9 lower than the IBIS detection.

Since the IBIS error circle is not fully covered by Chandra, we analyzed the XMM-Newton/EPIC image (observation ID 0012850201) available in the XMM-Newton archive (http://xmm.esac.esa.int/xsa/index.shtml) in the 4–8 keV energy band. This study shows that no other X-ray sources are detected within the IBIS error circle, leaving the association with Object 7 as the only possibility at this stage. To reconcile the source spectrum with the IBIS detection, we again need to assume that Object 7 is either variable or more heavily absorbed than observed. In the latter case, INTEGRAL may have detected a new type 2 quasar at high redshift. The fact that the Chandra spectrum measures a column density in excess of the galactic value indicates flux variability as the origin of the mismatch.

The source is reported in the USNO B1.0 catalog as having $B$ and $R$ in the range magnitudes 19.9–20.8 and 19.2–19.8, respectively, which supports a variable source. In this case as well, a dedicated broadband X-ray observation such as is possible with Suzaku could provide the necessary insight into the nature of this source and of its association with the INTEGRAL object.

3.4. IGR J14193–6049

This source is a very weak new INTEGRAL detection reported in the fourth IBIS catalog (Bird et al. 2010) with a flux of $3.8 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the 20–40 keV energy band and located at R.A. (J2000) = 214.821 and decl. (J2000) = $-60.801$ with a positional uncertainty of $4.3'$ (90% confidence level). Detailed spectral analysis of this sky region was performed by Ng et al. (2005). These authors listed a number of X-ray sources, some of which are related to the so-called Kookaburra complex region that has two supernovae/pulsar wind nebulae emitting nearby and also detected at TeV energies (Aharonian et al. 2006). Within the IBIS error box at 99% confidence level, Ng et al. (2005) reported four sources. Two are bright and soft X-ray objects (Star1: R.A. = 14$^h$19$^m$11.75, decl. = $-60.49'$33.8'; Star2: R.A. = 14$^h$19$^m$31.65, decl. = $-60.46'21.3'$) clearly identified with bright field stars. The faintness in X-rays and the soft spectra (few counts above 2 keV) of both objects suggest that their association with IGR J14193–6049 is very unlikely. The third source is called Sr3 (R.A. = 14$^h$18$^m$37.83, decl. = $-60.45'01.1'$); Ng et al. (2005) suggested that this object is an AGN also detected in the radio band as a flat spectrum, a variable point source with a radio flux of a few mJy. With an extrapolated 20–40 keV flux of $\sim 0.3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (using the spectral...
parameters reported by Ng et al. 2005), however, this source is too weak to be the counterpart of the IBIS source. But, if we enlarge the error box to the 99% confidence level, we find a new detection in PSR J1420–6048, a pulsar which also possesses a surrounding nebula (Roberts et al. 2001); this source is the brightest and hardest of all the sources detected by Chandra in the IBIS error box. Figure 7 shows the ACIS image together with the H.E.S.S. (Aharonian et al. 2006) and IBIS error circles, which clearly suggests that both are detecting the same object. Using the total flux of PSR J1420–048 (PSR plus PWN) and a spectral index of −1.6 as reported by Possenti et al. (2002), we obtained an extrapolated flux of ∼4.3 × 10−12 erg cm−2 s−1 in the 20–40 keV energy band, which is in very good agreement with the IBIS detection reported by Bird et al. (2010). We therefore conclude that PSR J1420–6048 (pulsar and nebula) is the counterpart of the IBIS source. Pulses and their nebulae are strong emitters in the keV and TeV bands; indeed, 13 such systems have now been detected by INTEGRAL in the 20–100 keV energy band, and of these, nine have a counterpart in H.E.S.S., strengthening the association of PSR J1420–6048 with IGR J14193–6049.

3.5. IGR J16377–6423

IGR J16377–6423 is a source detected by INTEGRAL in the 17–30 keV energy band and tentatively associated by Bird et al. (2010) with a cluster of galaxies. This was mainly due to the fact that ROSAT observations clearly indicate the presence of a bright galaxy cluster CIZA J1638.2−6420 (Stephen et al. 2006). It was not clear if INTEGRAL had detected the cluster itself or one of its members. Within the IBIS error box, we find an extended and bright X-ray source clearly identified with the galaxy cluster even at high energies (see Figure 8). The analysis of the spectrum was performed by Snowden et al. (2008), showing that this cluster has a thermal spectrum with a very high plasma temperature in the range 8–13 keV and a flux of 0.1–3.3 × 10−12 erg cm−2 s−1 in the 0.3–10 keV energy band. Such high values of gas temperature could provide detectable
emission in the IBIS waveband, making the association with the INTEGRAL source plausible. In fact, using the fit parameters obtained by Snowden et al. (2008), we derive an extrapolated 20–40 keV flux of $\sim 3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, comparable with the one reported by Bird et al. (2010; $\sim 7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$). The fourth INTEGRAL survey (Bird et al. 2010) reports only 4 clusters of galaxies out of the 723 sources detected; all four of them are bright with a high temperature. This suggests that the high-energy emission is directly linked to this cluster property.

4. CONCLUSIONS

One of the more difficult tasks associated with the observation of the high-energy sky, even with non-focusing optics, is the identification of a substantial fraction of newly discovered sources. From the Swift ground telescope to the Cherenkov ground telescope at TeV energies, optical identification remains a very difficult task. This task becomes at least impossible whenever timing information or evident source variability are not detected at high statistical significance at different wavelengths (e.g., GRBs, pulsars, AGNs, etc.). In particular, for weak objects, the optical and/or IR identification remain a challenge if the arcsec X-ray counterpart position is not available.

To overcome this problem, a robust program has started in parallel with the different INTEGRAL/IBIS survey productions to obtain, whenever possible, X-ray fields containing counterparts for the high-energy unknown detected objects. This approach has been successful in using archival data from ROSAT and TOO dedicated observation and archival data from XRT, XMM-Newton, and Chandra. These data were essential to trigger a robust program of ground-based optical observations and identification that has been very successful so far (Masetti et al. 2009 and references therein).

In this paper, we have used a cross-correlation between the more recent INTEGRAL IBIS survey results and the Chandra archival data to disentangle the nature of five still unclassified objects. So far, we have identified candidate soft X-ray counterparts in four cases and extracted their soft X-ray spectra. Moreover, the present data have provided further basic information into the nature of these sources and better than 1 arcsec refined positions essential for the planned follow-up observations.

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