CHANDRA LOCALIZATIONS AND SPECTRA OF INTEGRAL SOURCES IN THE GALACTIC PLANE: THE CYCLE 9 SAMPLE

JOHN A. TOMSICK1, SYLVAIN CHATY2, JEROME RODRIGUEZ2, ROLAND WALTER3, AND PHILIP KAARET4
1 Space Sciences Laboratory, 7 Gauss Way, University of California, Berkeley, CA 94720-7450, USA; jtomsick@ssl.berkeley.edu
2 AIM-Astrophysique Interactions Multi-échelles (UMR 7158 CEA/CNRS/Université Paris 7 Denis Diderot), CEA Saclay, DSM/IRFU/Service d’Astrophysique, Bât. 709, L’Orme des Merisiers, FR-91 191 Gif-sur-Yvette Cedex, France
3 INTEGRAL Science Data Centre, Observatoire de Genève, Université de Genève, Chemin d’Ecogia, 16, 1290 Versoix, Switzerland
4 Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA

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ABSTRACT
We report on 0.3–10 keV X-ray observations by the Chandra X-ray Observatory of the fields of 22 sources that were discovered as hard X-ray (20–100 keV) sources by the International Gamma-Ray Astrophysics Satellite (“IGR” sources). The observations were made during Chandra’s 9th observing cycle, and their purpose is to localize the sources and to measure their soft X-ray spectra in order to determine the nature of the sources. We find very likely Chandra counterparts for 18 of the 22 sources. We discuss the implications for each source, considering previous results and new optical or infrared identifications, and we identify or suggest identifications for the nature of 16 of the sources. Two of the sources, IGR J14003–6326 and IGR J17448–3232, are extended on arcminute scales. We identify the former as a pulsar wind nebula with a surrounding supernova remnant (SNR) and the latter as an SNR. In the group of 242 IGR sources, there is only one other source that has previously been identified as an SNR. Seven of the sources are definite or candidate high-mass X-ray binaries (HMXBs). We confirm a previous identification of IGR J14331–6112 as an HMXB, and based on combinations of hard X-ray spectra, inferred distances and X-ray luminosities, and/or column density variations, we suggest that IGR J17404–3655, IGR J16287–5021, IGR J17354–3255, IGR J17507–2647, IGR J17586–2129, and IGR J13186–6257 are candidate HMXBs. Our results indicate or confirm that IGR J19267+1325, IGR J18173–2509, and IGR J18308–1232 are cataclysmic variables (CVs), and we suggest that IGR J15529–5029 may also be a CV. We confirm that IGR J14471–6414 is an active galactic nucleus (AGN), and we also suggest that IGR J19443+2117 and IGR J18485–0047 may be AGNs. Finally, we found Chandra counterparts for IGR J11098–6457 and IGR J18134–1636, but more information is required to determine the nature of these two sources.

Key words: black hole physics – infrared: stars – stars: individual (IGR J07295–1329, IGR J09485–4726, IGR J11098–6457, IGR J13186–6257, IGR J14331–6112, IGR J14471–6414, IGR J15529–5029, IGR J16287–5021, IGR J17354–3255, IGR J17507–2647, IGR J17586–2129, IGR J18173–2509, and IGR J18308–1232) – neutron – white dwarfs – X-rays: stars

Online-only material: color figures, machine-readable table

1. INTRODUCTION
The International Gamma-Ray Astrophysics Satellite (INTEGRAL; Winkler et al. 2003) has been in operation for more than six years and has discovered a large number of new hard X-ray sources at energies >20 keV. This bandpass is above the range where most types of sources can emit thermal blackbody radiation. Thus, INTEGRAL provides a window on the non-thermal emission that comes from Galactic sources (e.g., accreting black holes, neutron stars, and magnetized white dwarfs) as well as extragalactic active galactic nuclei (AGNs). With large field-of-view (FOV) coded aperture mask instruments (e.g., a 29° × 29° partially coded FOV for IBIS; Lebrun et al. 2003; Ubertini et al. 2003), INTEGRAL has observed most of the sky thus far during its mission, but its sky coverage has not been uniform, with more time being concentrated near the Galactic plane. While IBIS has provided a step forward in hard X-ray angular resolution, it localizes 20–40 keV sources to 1°–5°, which is normally not sufficient to identify an optical or infrared (IR) counterpart, leaving the nature of many of the sources uncertain. Thus, throughout the INTEGRAL mission, follow-up observations have been made with soft X-ray (~0.5–10 keV) telescopes (Chandra, XMM-Newton, and Swift) to localize the INTEGRAL sources and determine their nature.

As of 2009 March, INTEGRAL had detected nearly 600 sources, and 242 of these are IGR sources,5 being either newly discovered by INTEGRAL or not previously detected in the ~20–100 keV band (see Bodaghee et al. 2007, for more on the criterion for the IGR classification). The source types of the 242 IGR sources are dominated by 79 AGNs (73 with firm identifications), 67 X-ray binaries (47 with firm identifications), and 15 cataclysmic variables (CVs). There are small numbers of IGR sources in a few other categories (symbiotic stars, active stars, an anomalous X-ray pulsar, and a supernova remnant), and the remaining 72 IGR sources are unclassified. Along with the soft X-ray localizations (e.g., Tomsick et al. 2006, 2008c), the steady increase in the numbers of classified IGR sources depends on ground-based optical and IR follow-up observations (e.g., Masetti et al. 2008, 2009; Chaty et al. 2008; Butler et al. 2009), which are key to obtaining firm identifications.

5 See http://isdc.unige.ch/~rodrigue/html/igrsources.html for a continually updated list of IGR sources.
One of the most interesting categories of IGR sources is the high-mass X-ray binaries (HMXBs), for which INTEGRAL has uncovered two new (and not entirely independent) classes: the obscured HMXBs (Walter et al. 2003, 2006; Matt & Guainazzi 2003) and the supersoft fast X-ray transients (SFXTs; Negueruela et al. 2006; Sguera et al. 2006; Walter & Zurita Heras 2007). The obscured HMXBs have large and, in some cases, variable levels of intrinsic (i.e., local) absorption with \( N_H \approx 10^{21} - 10^{24} \text{ cm}^{-2} \). There is evidence in several cases that a strong stellar equatorial outflow is responsible for the absorption, including the detection of P Cygni profiles (Filliatre & Chaty 2004; Chaty et al. 2008), providing direct evidence for a wind, as well as excess emission in the mid-IR (Rahoui et al. 2008). The strong winds and high absorption explain why INTEGRAL’s hard X-ray imaging was necessary to detect these sources, and it has been suggested that these obscured HMXBs are in a previously unstudied phase of HMXB evolution (Lommen et al. 2005). With the discovery of SFXTs, INTEGRAL found a new type of HMXB behavior where sources undergo high-amplitude (orders of magnitude) hard X-ray flares that only last for timescales of hours (in’t Zand 2005; Sguera et al. 2006). In part, this is thought to be caused by clumps in the supergiant stellar winds (Walter & Zurita Heras 2007), but it may also be related to the interaction between the wind and a strong neutron star magnetic field (Bozzo et al. 2008).

To identify the nature of more of these sources, we have been using Chandra to study the unclassified IGR sources near the Galactic plane. The primary purpose of the observations is to localize the sources to allow for optical or IR follow up. While X-ray positions with an accuracy of several arcseconds (as can be given by Swift or XMM-Newton) can lead to correct optical or IR identifications, in many cases (and especially in the crowded regions of the Galactic plane), the subarcsecond Chandra positions are crucial for obtaining definitive identifications. A second important use for the Chandra observations is to measure the soft X-ray energy spectrum, providing information about source hardness and levels of absorption that help to determine the nature of the source. Our Chandra program began in 2005 with the identification of four IGR sources (Tomsick et al. 2006), and we subsequently used Chandra observations taken between 2007 and 2008 to obtain identifications for 12 more IGR sources (Tomsick et al. 2008a). In this work, we report on 22 Chandra observations taken during Chandra’s 9th observing cycle between late 2007 and early 2009.

2. CHANDRA OBSERVATIONS

For Chandra follow-up observations, we chose sources from the 27th INTEGRAL General Reference Catalog\(^{6}\) that were detected in the 20–40 keV band as of 2007 March. The list that we produced includes IGR sources within 5° of the Galactic plane, and we used information from Bird et al. (2006) and Bodaghee et al. (2007) to select sources that were not known to be transient and whose nature was unknown at the time. Ultimately, we chose the 22 sources listed in Table 1 for \( \sim 5 \text{ ks} \) “snapshot” observations with Chandra to provide precise X-ray localizations as well as information about their soft X-ray spectra.

As listed in Table 1, the observations were made between 2007 November and 2009 February, and we used the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003). The 90% confidence INTEGRAL error circles range from 2′′ to 5′′, leading us to use the 16.9 × 16.9 arcmin\(^2\) FOV of the ACIS-I instrument. Our analysis of the ACIS data began by downloading the most recent versions of the data products as of 2009 January–February. We started with the “level 1” data files, and these were processed at the Chandra X-Ray Center with pipeline (“ASCDs”) versions 7.6.11.2 to 7.6.11.9. We performed further processing with the Chandra Interactive Analysis of Observations (CIAO) version 4.1.1 (except for one part of the analysis as mentioned below) software. Also, we used version 4.1.1 of the Calibration Database (CALDB). We used the CIAO routine acis_process_events to produce the “level 2” event lists that we used to make images and energy spectra. While a level 2 file is provided as part of the standard data pipeline, we reproduced the file in order to use the most recent time-dependent gain information. With a current version of the CALDB, using the CIAO 4.1.1 default parameters when running acis_process_events incorporates the most recent calibration files.

3. ANALYSIS AND RESULTS

3.1. Search for Sources and X-ray Identifications

After producing 0.3–10 keV images, we used the CIAO routine wavdetect to search for X-ray sources on the ACIS-I chips. Although we originally used the version of wavdetect found in CIAO 4.1.1, we noticed that many spurious detections (sources with one or two photons) occurred for some of the observations. However, these spurious detections did not occur with CIAO 3.4, and we used that version of wavdetect for the source searches in this paper. For each observation, we searched for sources in unbinned images with 2048 × 2048 pixels as well as images binned by a factor of 2 (1024 × 1024 pixels) and a factor of 4 (512 × 512 pixels). In each case, we set the detection threshold to a level that would be expected to yield one spurious source (2.4 × 10\(^{-7}\), 9.5 × 10\(^{-7}\), and 3.8 × 10\(^{-6}\) for the three images, respectively). Thus, in the merged lists of detected sources, it would not be surprising if a few of the sources in each field are spurious.

The average number of sources detected per observation over the entire ACIS-I FOV is 20, with the minimum being 12 sources and the maximum being 32 sources. We used three main criteria to determine which of these are likely counterparts to the IGR sources. First, the IGR sources have been detected by INTEGRAL at 20–40 keV flux levels of 0.5–2 mcrab (Bird et al. 2006). At 1 mcrab (20–40 keV), a source with an absorbed power-law spectrum with a photon index of \( \Gamma = 1.0 \) and a column density of \( N_H = 5 \times 10^{22} \text{ cm}^{-2} \) would yield \( \sim 300 \) ACIS-I counts in 5 ks, so we are looking for fairly bright Chandra sources. Second, the sources should have hard spectra, and third, the sources should be within or close to the INTEGRAL error circles.

We estimated the hardness of each of the detected Chandra sources by determining the number of source counts in the 0.3–2 keV band (\( C_1 \)) and the 2–10 keV band (\( C_2 \)). Using the size of the Chandra point-spread function (PSF) as a guide, we used extraction radii of 5′′ for sources within 4′ of the aimpoint, 10′′ for sources between 4′ and 7′ from the aimpoint, and 15′′ for sources more than 7′ from the aimpoint. The background counts were taken from the largest possible rectangular source-free region, and this value was scaled to the size of the source extraction region and subtracted off. We then calculated the hardness according to \( (C_2 - C_1)/(C_2 + C_1) \), which runs from −1.0 for the softest sources (all the counts in the 0.3–2 keV

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\( ^{6} \) See http://isdc.unige.ch/Data/cat.
Table 1

| IGR Name     | ObsID | \( P \) | \( b^0 \) | Start Time             | Exposure Time (s) |
|--------------|-------|--------|---------|------------------------|-------------------|
| J07295−1329  | 9061  | 228.97 | +2.26   | 2008 Feb 11, 0.55 hr UT| 5093              |
| J09485−4726  | 9068  | 273.84 | +4.84   | 2007 Nov 30, 19.98 hr UT| 5055              |
| J11098−6457  | 9066  | 292.43 | −4.17   | 2008 Sep 12, 14.66 hr UT| 5109              |
| J13186−6257  | 9049  | 306.02 | −0.24   | 2008 Sep 11, 22.14 hr UT| 5061              |
| J14003−6326  | 9058  | 310.57 | −1.61   | 2008 Jun 29, 12.13 hr UT| 5077              |
| J14331−6112  | 9053  | 314.90 | −0.72   | 2008 Jan 5, 4.39 hr UT | 4888              |
| J14471−6414  | 9065  | 315.00 | −4.15   | 2007 Dec 27, 7.83 hr UT | 5112              |
| J15529−5029  | 9062  | 329.89 | +2.63   | 2008 Jan 7, 8.58 hr UT | 5071              |
| J16287−5021  | 9054  | 334.16 | −1.13   | 2008 Jan 28, 10.84 hr UT| 4935              |
| J17354−3255  | 9050  | 355.44 | −0.26   | 2009 Feb 6, 7.15 hr UT | 4692              |
| J17404−3655  | 9063  | 352.64 | −3.27   | 2008 Jul 16, 21.02 hr UT| 4894              |
| J17448−3232  | 9059  | 356.84 | −1.76   | 2008 Nov 2, 2.15 hr UT | 4692              |
| J17461−2204  | 9064  | 5.94   | +3.48   | 2009 Feb 6, 5.27 hr UT | 4888              |
| J17487−3124  | 9060  | 358.25 | −1.83   | 2008 Nov 2, 0.33 hr UT | 4888              |
| J17507−2647  | 9048  | 2.42   | +0.15   | 2009 Feb 6, 8.79 hr UT | 4698              |
| J17586−2129  | 9056  | 8.05   | +1.35   | 2008 Oct 30, 3.38 hr UT | 4888              |
| J18134−1636  | 9052  | 13.88  | +0.61   | 2008 Feb 16, 9.52 hr UT | 4891              |
| J18173−2509  | 9067  | 6.79   | −4.26   | 2008 May 6, 1.15 hr UT | 4894              |
| J18308−1232  | 9055  | 19.45  | −1.19   | 2008 Apr 27, 16.69 hr UT| 4698              |
| J18485−0047  | 9051  | 31.90  | +0.31   | 2008 Apr 27, 14.97 hr UT| 4695              |
| J19267+1325  | 9075  | 48.88  | −1.53   | 2008 Feb 27, 2.46 hr UT | 4698              |
| J19443+2117  | 9057  | 57.79  | −1.37   | 2008 Feb 27, 0.68 hr UT | 4888              |

Notes. a Galactic longitude in degrees.
b Galactic latitude in degrees.

Figure 1. Hardness–intensity diagram, including all of the Chandra/ACIS-I sources detected in the 22 Chandra observations. The intensity is given as the number of ACIS-I counts in the 0.3–10 keV energy band. The hardness is given by \((C_2 − C_1)/(C_2 + C_1)\), where \(C_1\) is the number of counts in the 0.3–2 keV band and \(C_2\) is the number of counts in the 2–10 keV band. The squares indicate sources that are inside their respective 90% confidence INTEGRAL error circles. The sources that we consider as possible Chandra counterparts to the IGR sources are plotted with black points and error bars. The two sources marked with diamonds are extended sources.

band) to +1.0 for the hardest sources (all the counts in the 2–10 keV band). To deal with the case where there are zero counts in one of the energy bands, we used the “Gehrels” prescription for determining the uncertainties (Gehrels 1986).

Figure 1 shows a hardness–intensity diagram, including all 434 of the sources detected. For most sources with fewer than ~10 counts, the uncertainties on the hardnesses are very large. However, one can see a group of 19 sources with more than 100 counts per source and hardnesses greater than zero, and we consider these as candidate counterparts to the IGR sources. In addition to the 19 sources, we also consider a 20th source that only has 29 counts, but its hardness is 1.0 ± 0.3, and it is well within the INTEGRAL error circle for IGR J13186−6257. Thus, we consider these 20 sources as candidate counterparts. While 18 of these sources are consistent with being point sources, two of the sources (marked with diamonds in Figure 1) are clearly extended. The Chandra positions, numbers of ACIS-I counts in the 0.3–10 keV band, and hardness ratios (using the definition given above) for the 20 sources are given in Table 2. The 20 sources come from 18 different observations. The candidate counterparts for 16 of the IGR sources are unique, and in two cases (IGR J17354−3255 and IGR J17448−3232), there are two possible counterparts. In Section 3.3, we estimate the probability of spurious Chandra/IGR source associations. For the other four IGR sources (IGR J07295−1329, IGR J09485−4726, IGR J17461−2204, and IGR J17478−3214), there are no strong possibilities for counterparts. However, Chandra sources are detected in each of these four fields as well, and Chandra source lists can be found in the online tables associated with this paper (see the Appendix).

3.2. Spectral Analysis of Point Sources

We produced Chandra energy spectra for the 18 point source candidate counterparts using the CIAO software routines. We used the same source extraction regions described above for determining count rates and hardnesses. For the background, we used rectangular source-free regions as described above, but they were modified so that they would include counts from only the ACIS-I CCD chip that also includes the source. There are four ACIS-I CCD chips, and in some cases, the spacecraft dithering causes source counts to be spread across multiple CCD chips. In this case, we put the background region on the CCD chip containing the largest number of source counts. Once the source and background regions were determined, we used the CIAO routine dmextract to produce energy spectra and
We fitted the 0.3–10 keV ACIS spectra using the XSPEC v12 software. Initially, we rebinned the spectra to 13 energy bins prior to fitting with an absorbed power-law model using mkacismf and mknarf to produce the response files for the source region. In the cases where the source counts are spread over multiple CCD chips, we used a weight map to produce weighted response files.

We fitted the 0.3–10 keV ACIS spectra using the XSPEC $\chi^2$-minimization in order to be able to see if and how the spectra deviate from this basic model. To account for absorption, we used the photoelectric absorption cross sections from Balucinska-Church & McCammon (1992) and elemental abundances from Wilms et al. (2000), which correspond to the estimated abundances for the interstellar medium. For 12 of the 18 point sources, no pattern in the residuals to the absorbed power law are apparent, and the reduced-$\chi^2$ values in these cases range from $\chi^2_{\nu} = 0.22$ to 1.5 for 10 degrees of freedom (dof). For five of the remaining sources (CXOU J144628.2–641624, CXOU J173527.5–325554, CXOU J181722.1–250842, CXOU J183049.9–123219, and CXOU J194356.2+211823), a high energy excess is present.

### Table 2

| CXOU Name          | $\theta^a$ (arcmin) | Chandra R.A.$^b$ (J2000) | Chandra Decl.$^b$ (J2000) | ACIS Counts | Hardness Ratio |
|--------------------|---------------------|--------------------------|---------------------------|-------------|----------------|
| J110926.4–650224   | 6.02                | 11$^{b}$09$'$26.243      | −65$^\circ$02'25.0        | 941.2       | 0.10 ± 0.03    |
| J131825.0–625815    | 1.94                | 13$^{b}$18'25.08         | −62$^\circ$38'15.5        | 29.3        | 1.01 ± 0.33    |
| J140045.6–63254$^d$| 1.47                | 14$^{b}$00'45.69         | −63$^\circ$25'42.6        | 4075.5      | 0.53 ± 0.02    |
| J143308.3–611539    | 4.02                | 14$^{b}$33'08.33         | −61$^\circ$15'39.7        | 644.1       | 0.80 ± 0.05    |
| J144628.2–641624    | 1.46                | 14$^{b}$46'28.26         | −64$^\circ$16'24.1        | 600.3       | 0.38 ± 0.05    |
| J155246.9–502953    | 1.59                | 15$^{b}$52'46.92         | −50$^\circ$29'53.4        | 278.3       | 0.45 ± 0.07    |
| J162826.8–502239    | 3.12                | 16$^{b}$28'26.85         | −50$^\circ$22'39.7        | 484.3       | 0.84 ± 0.06    |
| J173518.7–325428    | 1.83                | 17$^{b}$35'18.73         | −32$^\circ$54'28.7        | 145.2       | 0.69 ± 0.11    |
| J173527.5–325554    | 1.34                | 17$^{b}$35'27.59         | −32$^\circ$55'54.4        | 494.2       | 0.94 ± 0.07    |
| J174026.8–365537    | 0.84                | 17$^{b}$40'26.86         | −36$^\circ$55'37.4        | 227.3       | 0.62 ± 0.09    |
| J174453.4–323254$^d$| 0.33                | 17$^{b}$44'53.44         | −32$^\circ$32'54.1        | 2816.3      | 0.60 ± 0.03    |
| J174437.3–323222    | 3.77                | 17$^{b}$44'37.34         | −32$^\circ$32'23.0        | 389.0       | 0.65 ± 0.06    |
| J175039.4–264436    | 2.97                | 17$^{b}$50'39.47         | −26$^\circ$44'36.2        | 221.1       | 0.98 ± 0.10    |
| J175834.5–212321    | 3.81                | 17$^{b}$58'34.56         | −21$^\circ$23'21.6        | 447.2       | 0.99 ± 0.07    |
| J181328.0–163548    | 0.97                | 18$^{b}$13'28.03         | −16$^\circ$35'48.7        | 149.2       | 0.96 ± 0.13    |
| J181722.1–250842    | 0.86                | 18$^{b}$17'22.18         | −25$^\circ$08'42.5        | 332.2       | 0.62 ± 0.07    |
| J183049.9–123219    | 0.83                | 18$^{b}$30'49.95         | −12$^\circ$32'19.1        | 534.3       | 0.50 ± 0.05    |
| J184852.4–004635    | 0.55                | 18$^{b}$48'25.47         | −00$^\circ$46'35.2        | 115.3       | 0.99 ± 0.15    |
| J192626.9+132205    | 4.79                | 19$^{b}$26'26.99         | +13$^\circ$22'05.1        | 1450.3      | 0.29 ± 0.03    |
| J194356.2+211823    | 4.88                | 19$^{b}$43'56.23         | +21$^\circ$18'23.6        | 2902.2      | 0.38 ± 0.02    |

### Notes.

$^a$ The angular distance between the center of the INTEGRAL error circle, which is also the approximate Chandra aimpoint, and the source.

$^b$ The position uncertainties for these relatively bright sources are dominated by the systematic error, which is 0.64 at 90% confidence and 1" at 99% confidence (Weisskopf 2005).

$^c$ These are the 90% confidence errors given in Bird et al. (2006).

$^d$ Extended source.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
above \( \sim 7 \) keV, which most likely indicates that the spectra are affected by pile-up. We confirmed that pile-up is the most likely explanation by looking at the numbers of counts above 10 keV for all 18 spectra. Although ACIS has very little sensitivity above 10 keV, these five sources have 12, 22, 18, 22, and 24 counts at \( > 10 \) keV compared to an average of 4 counts at \( > 10 \) keV for the other 13 sources. In addition, adding the Davis (2001) pile-up model to the spectral model significantly improves the fits for the five piled-up spectra.

Thus, after accounting for pile-up, 17 of the 18 sources are consistent with a power-law model with various levels of absorption. The one source that is not consistent with a power law is CXOU J143308.3–611539, for which \( \chi^2 = 2.5 \) for 10 dof, and its residuals show a large excess in the energy bin corresponding to the Fe K\( \alpha \) transition energy. This likely indicates the presence of an Fe emission line, and adding a Gaussian with an energy of \( E_{\text{line}} = 6.70^{+0.25}_{-0.17} \) keV, a width of \( \sigma_{\text{line}} = 0.27^{+0.21}_{-0.14} \) keV, and a flux of \( N_{\text{line}} = (7.6^{+7.4}_{-3.4}) \times 10^{-5} \) photons cm\(^{-2}\) s\(^{-1}\) improves the quality of the fit to \( \chi^2 = 1.0 \) for 7 dof. Figure 2 shows the Chandra spectrum (rebinned to 21 bins rather than 13 bins) for CXOU J143308.3–611539, and the presence of the iron line, which has a very large equivalent width of 945 eV, is clear.

After determining the spectral models with the binned spectra, we refitted all 18 of the spectra using Cash statistics (Cash 1979) and unbinned spectra, which have 663 bins after restricting the energy range to 0.3–10 keV. The best-fit parameters with 90% confidence errors are given in Table 3 along with the Galactic \( N_H \) and \( N_{\text{H,local}} \) values for each source (Kalberla et al. 2005; Dame et al. 2001). The column densities measured by Chandra range from being significantly less than the Galactic values to being consistent with sources that are extremely absorbed (\( \sim 10^{22}–10^{24} \) cm\(^{-2}\)). To determine which spectra show evidence for absorption by material local to the source, Table 3 includes limits on local absorption for each source. In each case, the upper limit of this quantity, \( N_{\text{H,local}} \), is the upper end of the 90% confidence error region for the column density measured by Chandra, while the lower limit is given by the lower end of this error region minus the maximum absorption that could be interstellar (\( N_H + 2N_{\text{H,local}} \), where these are the Galactic values). Figure 3 shows the spectra for the six sources that show the highest measured values of \( N_H \). The sources CXOU J131825.0–625815, CXOU J175834.5–212321, CXOU J181328.0–163548, and CXOU J184825.4–004635 require local absorption at the 90% confidence level with \( N_{\text{H,local}} \) ranges of \((2–84) \times 10^{22} \) cm\(^{-2}\), \((9–22) \times 10^{22} \) cm\(^{-2}\), \((4–17) \times 10^{22} \) cm\(^{-2}\), and \((41–96) \times 10^{22} \) cm\(^{-2}\). The other two sources, CXOU J173527.5–325554 and CXOU J175039.4–264436, may or may not have significant levels of local absorption with upper limits on \( N_{\text{H,local}} \) of \( \leq 1.1 \times 10^{23} \) cm\(^{-2}\) and \( \leq 2.1 \times 10^{23} \) cm\(^{-2}\), respectively.

### 3.3. Using X-ray Source Number Densities to Assess the Probability of Spurious Associations

With the spectral parameters for the point sources determined, we can now calculate the probability that the candidate associations between the Chandra and IGR sources are spurious. This calculation requires knowledge of the number density of X-ray sources with fluxes between \( \sim 10^{-12} \) and \( \sim 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\) in the Galactic plane. The broadest survey to date that resulted in a suitable log \( N \)–log \( S \) curve was done by the Advanced Satellite for Cosmology and Astrophysics (ASCA). The survey covers Galactic longitudes from \(-45^\circ\) to \(+45^\circ\) and Galactic latitudes from \(-0.4\) to \(+0.4\). The 2–10 keV log \( N \)–log \( S \) is described as a power law with \( N(>F_{2–10\text{keV}}) = 9.2(F_{2–10\text{keV}}/10^{-12})^{-0.70} \) deg\(^{-2}\), where \( F_{2–10\text{keV}} \) is the absorbed 2–10 keV flux in units of erg cm\(^{-2}\) s\(^{-1}\) (Sugizaki et al. 2001). The flux range for the ASCA survey is 2 \( \times 10^{-13} \) to 10\(^{-10}\) erg cm\(^{-2}\) s\(^{-1}\) (2–10 keV). Smaller surveys of parts of the Galactic plane by XMM-Newton and Chandra that extend the log \( N \)–log \( S \) to lower flux levels give log \( N \)–log \( S \) curves that are consistent with ASCA in the flux ranges where they overlap (Hands et al. 2004; Ebisawa et al. 2005).

To calculate the probabilities of spurious associations, we first used the spectral parameters for the 18 Chandra point source (see Table 3) to determine the absorbed 2–10 keV flux for each source, and these are reported in Table 4. Then, we used the source density expression given above to calculate \( N(>F_{2–10\text{keV}}) \) for each source. To determine the area in which we searched to find the Chandra source, we consider both the angular distance of the Chandra source from the center of the INTEGRAL error circle (\( \theta \) in Table 4) and the radius of the 90% confidence INTEGRAL error circle (\( \theta_{\text{INTEGRAL}} \) in Table 4), and we used the larger of these two quantities to calculate the probability.

As shown in Table 4, this analysis indicates a probability of a spurious association of \( \leq 1% \) in 14 cases and in the 1%–2% range in three cases. The faintest of the sources, CXOU J131825.0–625815, is the only one with an appreciable probability of a spurious association at 5.4%. While this could indicate that the association is spurious, the calculation does not account for the fact that the source is a hard X-ray source and also that it is relatively close to the center of the INTEGRAL error circle. One other case to consider is that of IGR J17354–3255, for which we found two Chandra sources within the INTEGRAL error circle. Although it is possible that both sources contribute to the flux detected by INTEGRAL, it is still probably most reasonable to consider that one of these is a spurious association. While CXOU J131825.0–625815, CXOU J173518.7–325428, CXOU J173527.5–325554 would be the leading candidates for being spurious associations, the results of these calculations increase our confidence in the associations between the Chandra and IGR sources.
Table 3

| CXOU Name | \( N_H \) (\( \times 10^{22} \) cm\(^{-2} \)) | \( \Gamma \) | X-ray Flux\(^a\) | \( \phi \) \(^b\) | Fit Statistic\(^c\) | Galactic \( N_H/\bar{N}_H \) \((\times 10^{22} \) cm\(^{-2} \))\(^d\) | \( N_H/\bar{N}_H \) \((\times 10^{22} \) cm\(^{-2} \))\(^e\) |
|-----------|---------------------------------|-------|-----------------|------|----------------|-----------------|-----------------|-----------------|
| J110926.4–650224 | 0.65\(^{+0.18}_{-0.17}\) | 1.43 \(\pm 0.17\) | 1.12 \(\pm 4.0^4\) | ... | ... | ... | ... | 0.41–96 | 0.11 |
| J131825.9–625815 | 1.68 \(\pm 0.06\) | 1.39 \(\pm 0.03\) | 1.12 \(\pm 0.09\) | ... | ... | ... | ... | 0.26–17 | 2.84 |
| J143308.3–515194 | 2.17 \(\pm 0.04\) | 1.35 \(\pm 0.03\) | 1.12 \(\pm 0.09\) | ... | ... | ... | ... | 0.26–17 | 2.84 |
| J144628.2–641624 | 2.17 \(\pm 0.04\) | 1.35 \(\pm 0.03\) | 1.12 \(\pm 0.09\) | ... | ... | ... | ... | 0.26–17 | 2.84 |
| J155246.9–502953 | 0.59 \(\pm 0.04\) | 1.20 \(\pm 0.04\) | 1.12 \(\pm 0.09\) | ... | ... | ... | ... | 0.26–17 | 2.84 |
| J162826.8–502239 | 0.58 \(\pm 0.06\) | 1.38 \(\pm 0.03\) | 1.12 \(\pm 0.09\) | ... | ... | ... | ... | 0.26–17 | 2.84 |
| J173518.7–325428 | 3.95 \(\pm 0.06\) | 1.35 \(\pm 0.03\) | 1.12 \(\pm 0.09\) | ... | ... | ... | ... | 0.26–17 | 2.84 |
| J184825.4–502953 | 0.59 \(\pm 0.04\) | 1.20 \(\pm 0.04\) | 1.12 \(\pm 0.09\) | ... | ... | ... | ... | 0.26–17 | 2.84 |
| J192626.9+1322050 | 0.59 \(\pm 0.04\) | 1.20 \(\pm 0.04\) | 1.12 \(\pm 0.09\) | ... | ... | ... | ... | 0.26–17 | 2.84 |

Notes. The parameters are for power-law fits to the "Chandra/ACIS" spectra and include photoelectric absorption with cross sections from Balucinska-Church & McCammon (1992) and abundances from Wilms et al. (2000). In general, the measured value of \( N_H \) and the errors on \( N_H \) are scaled down by \( \approx 3\% \) if solar abundances (Anders & Grevesse 1989) rather than the approximation to average interstellar abundances (Wilms et al. 2000). A pile-up correction was applied in the cases where pile-up parameters are given. The PSF fraction (Davis 2001) was left fixed to 0.95 (the default value) except for the CXOU J194356.2+211823 spectrum, where it was left as a free parameter. In this case, the PSF fraction dropped to 0.35\(^+0.13\), presumably because this is a bright source that is relatively far (4.9 arcmin) off-axis. We performed fits without rebinning the data and using Cash statistics. Errors in this table are at the 90% confidence level (\( \Delta C = 2.7 \)).

\(^a\) Unabsorbed 0.3–10 keV flux in units of \( 10^{-12} \) erg cm\(^{-2} \) s\(^{-1} \).
\(^b\) The grade migration parameter in the pile-up model (Davis 2001). The probability that \( n \) events will be piled together but will still be retained after data filtering is \( \phi = \phi^\nu \).
\(^c\) The Cash statistic and dof for the best-fit model.
\(^d\) The atomic hydrogen column density through the Galaxy from Kalberla et al. (2005). We also give the molecular hydrogen column density through the Galaxy, using a CO map and conversion to \( N_H \) (Dame et al. 2001).
\(^e\) The estimate for the column density due to material local to the source (see the text for details on how the limits are derived). An upper limit indicates no evidence for local absorption (although it also cannot be ruled out in any case), and a range indicates evidence for slight or significant local absorption.
\(^f\) A strong iron line is present and is included in the model as a Gaussian. The parameters are \( F_{\text{line}} \) = 6.79\(^{+0.25}_{-0.17} \) keV, \( \sigma_{\text{line}} \) = 0.27\(^{+0.21}_{-0.14} \) keV, and \( N_{\text{H}_{\text{line}}} \) = \( (7.0 \pm 0.3) \times 10^{-4} \) photons cm\(^{-2} \) s\(^{-1} \), with an equivalent width of 945 eV.
\(^g\) This is the spectrum of the point source a few arcminutes from the center of the nebula.

4. DISCUSSION

4.1. Extended Sources

4.1.1. IGR J14003–6326

IGR J14003–6326 was discovered by INTEGRAL in 2006 (Keek et al. 2006). Although it was observed by Swift, no conclusion was reached on its nature (Malizia et al. 2007). Figure 4 shows 0.3–10 keV Chandra/ACIS images of the IGR J14003–6326 field. The widest view (Figure 4(a)) shows the presence of a nearly circular source with a radius of 1.5, and this is the only bright source detected in the 3.9 radius INTEGRAL error circle. The position and the fact that it is a hard source make it essentially certain that this is the IGR source, and the morphology and hardness allow us to identify this source as a supernova remnant (SNR). For Figure 4(b), we zoom-in toward the center of the SNR to show that there is significant structure near the center at size scales of tens of arcseconds. We suspect that this is a pulsar wind nebula (PWN). Finally, Figure 4(c) shows the Chandra image without any pixel binning, and it is clear that there is a point-like source near the center of the SNR where a putative neutron star might reside. The number of counts in the brightest pixel is 82, and the central 9 pixels have 298 counts. The position of this point-like source is R.A. (J2000) = 14\(^{+0.29}_{-0.24} \) 45\(^{+0.69}_{-0.50} \), decl. (J2000) = 63\(^{+2.5}_{-2.4} \) 42\(^{+6}_{-5} \), and it is very close to the center of the SNR. Despite the relative brightness of the point-like source, this is only a small fraction of the 4075 counts collected for the entire SNR. Thus, the emission detected by INTEGRAL likely comes from the PWN or the SNR.

We have used the CIAO routine specextract to produce a spectrum from a circular region centered on the point-like source with a radius of 1.5, while the background is taken from a source-free rectangular region on the same ACIS-I chip. The 0.3–10 keV energy spectrum is well described by an absorbed power law, with this model giving \( x^2 = 0.92 \) for 161 dof. The measured \( N_H \) is \( (3.1 \pm 0.3) \times 10^{22} \) cm\(^{-2} \), which is somewhat higher than the Galactic value of \( N_H \) = 2\( \times 10^{22} \) cm\(^{-2} \). The measured power-law photon index is \( \Gamma = 1.83 \pm 0.13 \), and the unabsorbed 0.3–10 keV flux is \( 3.6 \times 10^{-11} \) erg cm\(^{-2} \) s\(^{-1} \). The unabsorbed 2–10 keV flux is \( 1.9 \times 10^{-11} \) erg cm\(^{-2} \) s\(^{-1} \), which corresponds to \( \sim 1 \) mcrab.
Figure 3. Chandra ACIS-I spectra for the six sources that show the highest column density measurements. IGR J13186—6257 (a), IGR J17586—2129 (d), IGR J18134—1636 (e), and IGR J18485—0047 (f) require levels of \( N_H \) in excess of the Galactic levels (see Table 3), while IGR J17354—3255 (b) and IGR J17507—2647 (c) may or may not be locally absorbed.

Figure 4. Chandra 0.3–10 keV images for IGR J14003—6326. (a) The pixel size in this image is 7.9. The larger circle shows the 90% confidence INTEGRAL error circle, which has a radius of 3.9. The smaller circle has a radius of 1.5, and marks the approximate extent of the SNR. (b) The pixel size in this image is 1.97, and the image is meant to highlight the putative PWN. The 1.5 radius circle is shown. (c) The pixel size in this unbinned image is 0.492, and the image is meant to highlight the point-like source near the center of the SNR. In all three images, north is up and east is to the left.

There has only been one other IGR source identified as an SNR, IGR J18135—1751, and it has been identified as the TeV source H.E.S.S. J1813—178 (Ubertini et al. 2005). Searches of the High Energy Stereoscopic System (H.E.S.S.) source catalog\(^7\) as well as the SIMBAD database and the \textit{Fermi} Large Area Bright Gamma-Ray Source List (Abdo et al. 2009) do not indicate that IGR J14003—6326 is identified with any TeV

\(^7\) See http://www.mpi-hd.mpg.de/hfm/H.E.S.S/pages/home/sources.
or GeV source. The 20–100 keV flux for IGR J14003−6326 is 1.8 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} (Bird et al. 2006), which is only slightly less than the 3 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} flux of IGR J18135−1751 (Ubertini et al. 2005). However, Ubertini et al. (2005) show that the TeV emission for IGR J18135−1751 is more than an order of magnitude in excess of an extrapolation of the X-ray power law, and Helfand et al. (2007) point out that the TeV-to-X-ray luminosity ratio for IGR J18135−1751 is extreme with a value close to unity, which is much higher than the ratio of 0.06 measured for the Crab Nebula and also significantly higher than the highest ratios known for PWNe (e.g., 0.5 for PSR 1509−58 and 0.3 for Vela X). It has been suggested that the possible proximity to the star-forming region W33 to IGR J18135−1751 may provide a higher density of seed photons for inverse Compton scattering to TeV energies (Funk et al. 2007; Helfand et al. 2007). Thus, the nondetection of TeV emission from IGR J14003−6326 is not surprising and suggests that its high-energy properties are more similar to the previously known PWN than to IGR J18135−1751.

4.1.2. IGR J17448−3232

From a Swift observation, Landi et al. (2007b) mentioned the presence of diffuse emission in the IGR J17448−3232 field, and our Chandra observation confirms this. Figure 5(a) shows a rebinned 0.3–10 keV image along with the 2:2 radius

![Figure 5](image-url) Images of the IGR J17448−3232 field. (a) A Chandra 0.3–10 keV image rebinned to a pixel size of 15′. The larger circle shows the 90% confidence INTEGRAL error circle, which has a radius of 2′/2. The smaller circle has a radius of 0′/5, and marks the location of the hard point source, CXOU J174437.3−323222. The extended source is likely an SNR, and we suggest that the hard point source may be an associated pulsar. (b) The pixel size in this image is 0′/98. The same two circles are plotted, and the image is meant to highlight the hard point source. (c) A 2MASS \textit{Ks} band image of the region near the hard point source. The black circle is the same 0′/5 radius circle shown in the other two panels, and the Chandra 90% confidence error circle is shown in white. In all three images, north is up and east is to the left.

### Table 4

| CXOU Name       | \( F_{2-10 \text{ keV}} \) | \( N(> F_{2-10 \text{ keV}}) \) | \( \theta \) | \( \theta_{\text{INTEGRAL}} \) | Probability (%) |
|-----------------|--------------------------|-------------------------------|-------------|-----------------|-----------------|
| J110926.4−650224 | 3.3 \times 10^{-12}      | 0.59                          | 6.02        | 5.5             | 1.9             |
| J131825.0−625815 | 2.6 \times 10^{-13}      | 4.32                          | 1.94        | 3.8             | 5.4             |
| J143308.3−611539 | 6.3 \times 10^{-12}      | 0.35                          | 4.02        | 3.9             | 0.49            |
| J144628.2−641624 | 4.5 \times 10^{-12}      | 0.46                          | 1.46        | 3.7             | 0.55            |
| J155246.9−502953 | 1.6 \times 10^{-12}      | 1.05                          | 1.59        | 3.9             | 1.4             |
| J162826.8−502239 | 6.7 \times 10^{-12}      | 0.33                          | 3.12        | 4.4             | 0.56            |
| J173518.7−325428 | 1.1 \times 10^{-12}      | 1.35                          | 1.83        | 2.5             | 0.74            |
| J173527.5−325554 | 9.7 \times 10^{-12}      | 0.25                          | 1.34        | 3.2             | 0.23            |
| J174026.8−365537 | 7.0 \times 10^{-12}      | 0.32                          | 0.84        | 3.5             | 0.34            |
| J174437.3−323222 | 2.7 \times 10^{-12}      | 0.68                          | 3.77        | 3.5             | 0.34            |
| J175039.4−264436 | 3.0 \times 10^{-12}      | 0.62                          | 2.97        | 2.5             | 0.48            |
| J175834.5−212321 | 7.7 \times 10^{-12}      | 0.30                          | 3.81        | 3.5             | 0.38            |
| J181328.0−163548 | 1.4 \times 10^{-12}      | 1.16                          | 0.97        | 3.8             | 1.5             |
| J181722.1−250842 | 8.4 \times 10^{-12}      | 0.28                          | 0.86        | 3.1             | 0.12            |
| J183049.9−123219 | 8.6 \times 10^{-12}      | 0.27                          | 0.83        | 3.3             | 0.29            |
| J184825.4−004635 | 1.8 \times 10^{-12}      | 0.96                          | 0.55        | 3.4             | 0.97            |
| J192626.9+132205 | 7.9 \times 10^{-12}      | 0.29                          | 4.79        | 3.7             | 0.58            |
| J194356.2+211823 | 1.4 \times 10^{-11}      | 0.19                          | 4.88        | 4.9             | 0.39            |

**Notes.**

\( ^a \) The absorbed 2–10 keV flux in units of erg cm\(^{-2} \) s\(^{-1} \).

\( ^b \) The X-ray source density at the flux level for each source from the ASCA survey of the Galactic plane (Sugizaki et al. 2001).

\( ^c \) The angular distance between the center of the INTEGRAL error circle and the source.

\( ^d \) The 90% confidence INTEGRAL error radius (Bird et al. 2006).
INTEGRAL error circle, which is centered on the extended source. Like the previous source, the extended source associated with IGR J17448−3232 is a nearly circular, and is likely an SNR. However, we do not see any evidence for a PWN within the SNR, and the only point-like source is CXOU J174437.3−323222, which is a hard source at the edge of the SNR (see Figure 5(b)). We extracted a Chandra spectrum from the extended source, using a circular extraction region with a radius of 3′. The spectrum is well described ($\chi^2_{rev} = 0.99$ for 163 dof) by an absorbed power law with $N_H = (2.5^{+0.5}_{-0.4}) \times 10^{22}$ cm$^{-2}$, which is somewhat above the interstellar column density ($N_H + 2N_H$) of 1.6 $\times$ 10$^{23}$ cm$^{-2}$. The power-law photon index is $\Gamma = 1.27^{+0.32}_{-0.21}$, and the 0.3–10 keV unabsorbed flux is $2.3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. We do not find any high-energy counterparts to this SNR in the H.E.S.S. or Fermi catalogs. As discussed above, even though TeV emission is detected for IGR J18135−1751, the nondetection of TeV emission for IGR J17448−3232 is not surprising because IGR J18135−1751 is an extreme case. In addition, IGR J17448−3232 may be even less likely to emit strong TeV emission because we do not see a PWN within the SNR.

The fact that the position at the center of the extended source agrees well with the INTEGRAL position argues that the SNR is primarily producing the 1.1 $\times$ 10$^{-11}$ erg cm$^{-2}$ s$^{-1}$ flux that INTEGRAL is detecting in the 20–100 keV band (Bird et al. 2006). However, it is still possible that the hard point source, CXOU J174437.3−323222, is associated with the SNR. The hard point source does not have counterparts in the Two Micron All Sky Survey (2MASS), DENIS, USNO-B1.0, or USNO-A2.0 catalogs; however, the $K_s$-band image shown in Figure 5(c) shows that the Chandra position is on the edge of the PSF of a relatively bright IR source, so better optical/IR images are necessary. If CXOU J174437.3−323222 is an isolated neutron star that received a kick when the supernova occurred, it should be very faint in the optical and IR. While the association between the SNR and CXOU J174437.3−323222 is intriguing, further work is necessary for confirmation.

4.2. Point Sources

IGR J11098−6457. Based on an earlier Swift observation, two possible counterparts were considered, and it was found that 1RXS J110927.4−650245 is the more likely counterpart due to its hard X-ray spectrum (Landi et al. 2008b). The position of CXOU J110926.4−650224, the source that we find to be the most likely counterpart, is consistent with the Swift position. There are no 2MASS, DENIS, USNO-B1.0, or USNO-A2.0 sources consistent with the Chandra position. However, the $K_s$-band image shown in Figure 6(a) shows that there appears to be a faint IR source at the Chandra position. The Chandra energy spectrum is consistent with a power law with a photon index of $\Gamma = 1.43 \pm 0.17$ and a column density consistent with the Galactic column density (see Table 3). The 2–10 keV absorbed flux is $3.3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. Thus, the spectrum measured by Chandra is consistent with that measured by Swift, which found $\Gamma \sim 1.2$ and a 2–10 keV flux of $2.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (Landi et al. 2008b).

IGR J13186−6257. The position of CXOU J131825.0−625815 is consistent with the Swift position for this IGR source reported in Landi et al. (2008c). The refined Chandra position allows us to identify the IR counterpart as 2MASS J13182505−6258156, which is 0′′2 from the Chandra position and has IR magnitudes of $J = 13.58$, $H = 12.69$, and $K_s = 12.84 \pm 0.05$ (see Table 5 and Figure 7(a)). There are no corresponding sources in the DENIS, USNO-B1.0, or USNO-A2.0 catalogs. Although Landi et al. (2008c) report that the Swift spectrum of this source is unabsorbed, we measure $N_H = (1.8^{+0.6}_{-0.7}) \times 10^{23}$ cm$^{-2}$, and we find that $N_{H,local}$ is in the range $(2–84) \times 10^{22}$ cm$^{-2}$ (see Table 3). While we cannot make a definitive statement about the nature of the source, high and variable column densities have been seen for several of the IGR HMXBs.
For the column densities to be measured in spectra with lower statistical quality (Tomsick et al. 2009), we add a second power-law component to account for a putative soft excess (as in Tomsick et al. 2009), the finding that the column density for the primary power-law component can be as high as $1.1 \times 10^{23} \text{ cm}^{-2}$. 

**IGR J14471—6414.** A *Swift* position was previously obtained for this source (Landi et al. 2007a), and follow-up optical spectroscopy indicated the presence of a Seyfert 1.2 AGN with a redshift of $z = 0.053$ in the *Swift* error circle (Masetti et al. 2008). The position of CXOU J144628.2—641624 is consistent with the position of the AGN, confirming the association.

**IGR J15529—5029.** The position of CXOU J155246.9—502953 is consistent with the *Swift* position for this IGR source reported in Landi et al. (2008c). The refined *Chandra* position allows us to identify the IR counterpart as 2MASS J15524694—5029534, which is 0′′2 from the *Chandra* position and has IR magnitudes of $J = 15.84 \pm 0.10$, $H = 15.27 \pm 0.13$, and $K_s = 14.77 \pm 0.12$. In addition, USNO-B1.0 0395-0509024 and USNO-A2.0 0375-25891641 are 0′′3 from the *Chandra* position, and the optical magnitudes are listed as $R = 18.6$ and $B = 21.4$ for the former and $R = 17.6$ and $B = 20.3$ for the latter (see Table 5). Although we cannot conclude definitively on the nature of this source, the X-ray spectrum measured by *Swift* (a power law with $\Gamma \sim 0.9$) and *Chandra* (a power law with $\Gamma = 0.60^{+0.30}_{-0.28}$) are harder than would be expected for an AGN (Malizia et al. 2007), and we suggest that a CV or X-ray binary nature is more likely.

**IGR J16287—5021.** The *Chandra* information for CXOU J162826.8—502239 was reported previously in Tomsick et al. (2008b), and the *Chandra* and *Swift* results for this source are discussed in detail in Rodriguez et al. (2009). Both *Chandra* and *Swift* detect the source at about the same flux level and with a low level of absorption. However, the *Chandra* power-law index of $\Gamma = -0.82^{+0.06}_{-0.20}$ is significantly harder than the value of $\Gamma = 0.9 \pm 0.8$ found by *Swift*. There are no 2MASS, DENIS, USNO-B1.0, or USNO-A2.0 sources consistent with the *Chandra* position. However, Figure 6(b) shows the 2MASS $K_s$-band image for this field, and there is a faint IR source that appears to be consistent with the *Chandra* position. The very hard X-ray spectrum suggests a CV or X-ray binary nature rather than an AGN nature, and perhaps the lack of an optical counterpart along with the faint IR candidate counterpart favors a relatively distant X-ray binary (likely an HMXB) rather than a CV.

Figure 7. 2MASS $K_s$-band images with *Chandra* 90% confidence error circles for the four IGR sources with new optical/IR identifications (see Table 5). In each image, the pixel size is 1″ and north is up and east is to the left. The images are 60″ in the east–west direction and 45″ in the north–south direction.

(A color version of this figure is available in the online journal.)
There are two relatively bright and hard Chandra sources within the INTEGRAL error circle (see also Tomsick 2009), and these were also detected during a Swift observation made in 2009 April (Vercellone et al. 2009). The position of CXOU J173527.5−325554, the brighter and harder of the two sources, is within 0′.2 of 2MASS J17352760−3255544, which has \( J = 12.51 \pm 0.05, H = 10.99 \pm 0.04, \) and \( K_S = 10.27 \pm 0.03 \). The source also appears in the DENIS catalog with similar \( J \) and \( K \) magnitudes (see Table 5). However, it must be quite faint optically since it is not detected in the DENIS I-band, and it does not appear in the USNO catalogs. The large \( J - K \) value, high inferred optical extinction, and the relatively high X-ray column density \( (7.5^{+3.0}_{-2.5}) \times 10^{22} \text{ cm}^{-2} \) argue that the source is distant, probably either an X-ray binary near the Galactic center or an AGN. However, as argued above, the hard power-law index of \( \Gamma = 0.54^{+0.60}_{-0.55} \) argues against the AGN possibility and for the possibility that the source is an HMXB. The other Chandra source, CXOU J173518.7−325428, does not have 2MASS, DENIS, USNO-B1.0, or USNO-A2.0 counterparts. Although the \( K \)-band image (see Figure 6(c)) shows a faint IR source within a couple of arcseconds, it is not close enough to be associated with the Chandra source. It is possible that both Chandra sources contribute to the flux detected by INTEGRAL, but CXOU J173527.5−325554 would probably be a more interesting source for any further follow-up work. Another reason for interest in pursuing the nature of IGR J17354−3255 is that its position is consistent with the position of the gamma-ray transient AGL J1734−3310 (Bulgarelli et al. 2009).

IGR J17404−3655. A Swift position was previously obtained for this source (Landi et al. 2008c), leading to a likely identification with a USNO-B1.0 source. From follow-up optical spectroscopy that showed a strong Hα emission line but no other strong emission or absorption line features, Masetti et al. (2009) identify the source as an X-ray binary. The position of CXOU J174026.8−365537 is consistent with the X-ray binary, confirming the identification. However, we are dubious about the further classification of the source as an LMXB rather than an HMXB. The Swift spectrum showed a power-law index of \( \Gamma \sim 0.24 \) (Landi et al. 2008c), and Chandra shows an even harder spectrum with \( \Gamma = -0.30^{+0.30}_{-0.24} \), which would be very unusual for typical LMXBs and is more commonly seen for HMXBs that harbor more highly magnetized neutron stars.

IGR J17507−2647. This source was discovered within ~2′.5 of the Galactic center by INTEGRAL (Bird et al. 2006), but no further information about this source has been reported until now. The Chandra energy spectrum for CXOU J175039.4−264436 exhibits a high column density with \( N_H = (1.34^{+0.78}_{-0.65}) \times 10^{23} \text{ cm}^{-2} \). Although this may indicate that the source is obscured (e.g., an obscured HMXB), Table 3 indicates that \( N_H \) is very high along this line of sight, \( 4.7 \times 10^{22} \text{ cm}^{-2} \), and the upper limit on \( N_H \text{,local} \) indicates that the measured absorption may be interstellar. CXOU J175039.4−264436 does not have 2MASS, DENIS, USNO-B1.0, or USNO-A2.0 counterparts (also see Figure 6(d)), providing further evidence that the absorption is interstellar. Although we cannot say definitively what the nature of the source is, the result that there is a high level of interstellar absorption also indicates that the source is distant, possibly close to the Galactic center region at ~8.5 kpc. This would argue for a luminosity of \( \sim 4 \times 10^{34} \text{ erg s}^{-1} \), which would suggest that the source is an X-ray binary rather than a CV.

IGR J17586−2129. This source was discovered by INTEGRAL (Bird et al. 2006), but no further information about this source has been reported until now. As shown in Table 3, CXOU J175834.5−212321 has \( N_H \text{,local} \) in the range \( (9−22) \times 10^{22} \text{ cm}^{-2} \), providing excellent evidence that this source has local absorption. The position of the Chandra source is within 0′.1 of 2MASS J17583455−2123215, which has IR magnitudes of \( J = 11.38 \pm 0.04, H = 9.53 \pm 0.03, \) and \( K_S = 8.44 \pm 0.03 \), and it is within 0′.3 of DENIS J175834.5−212321, which has similar IR magnitudes and an I-band magnitude of 15.26 ± 0.05 (see Table 5). The source is not present in the USNO catalogs. The magnitudes clearly indicate a highly reddened source, suggesting a large distance (likely at least several kpc). The 0.3−10 keV flux (see Table 3) indicates a luminosity of \( 3 \times 10^{34} \text{ erg s}^{-1} \) for a fiducial distance of 5 kpc, which is too bright for the source to be a CV. Also, the hard X-ray spectrum, \( \Gamma = 0.23^{+0.59}_{-0.54} \), suggests an HMXB rather than an AGN. Overall, this source is an excellent candidate for being one of the obscured IGR HMXBs.

IGR J18134−1636. This source was discovered by INTEGRAL (Bird et al. 2006), but no further information about this source has been reported until now. The Chandra spectrum for CXOU J181328.0−163548 shows evidence for local absorption with \( N_H \text{,local} \) in the range \( (4−17) \times 10^{22} \text{ cm}^{-2} \). There are no convincing optical or IR counterparts to the Chandra source in the 2MASS, DENIS, or USNO catalogs. The nearest source in these four catalogs is a USNO-B1.0 source that is 1′.24 away from CXOU J181328.0−163548; however, this is too far away to claim an association. The IR source shown in Figure 6(e) that appears to be consistent with the Chandra position is not listed in the 2MASS catalog, and this may be the IR counterpart. The high column density makes it unlikely that this source is a CV. However, with a power-law index of \( \Gamma = 1.4^{+0.9}_{-0.8} \), it could either be an X-ray binary or an AGN.

IGR J18173−2509. The position of CXOU J181722.1−250842 is consistent with the Swift position for this IGR source reported in Landi et al. (2008a). An optical source in the Swift error circle was followed-up with optical spectroscopy, showing that the source is a CV at a distance of ~330 pc (Masetti et al. 2009). The 0.3−10 keV flux from the Chandra spectrum of 8.5 \times 10^{−12} \text{ erg cm}^{-2} \text{ s}^{-1} is similar to the 2−10 keV value quoted for the Swift spectrum of 1.3 \times 10^{−11} \text{ erg cm}^{-2} \text{ s}^{-1}. At a distance of 330 pc, this flux corresponds to a luminosity of ~10^{32} \text{ erg s}^{-1}, typical of CVs. However, we find that the Chandra spectrum is well described by a single power law in contrast to the two power-law models described for the Swift spectrum by Landi et al. (2008a).

IGR J18308−1232. This source was previously identified with the XMM-Newton slew source XMML1 J183049.6−123218 (Ibarra et al. 2008), and the positions of CXOU J183049.9−123219 and the XMM-Newton source are consistent. Follow-up optical spectroscopy has already been obtained for the correct optical counterpart, USNO-B1.0 0774−0551687, indicating that the source is a CV (Parisi et al. 2008; Masetti et al. 2009; Butler et al. 2009). The Chandra flux level and energy spectrum are significantly different from the XMM-Newton measurements. The unabsorbed 0.3−10 keV Chandra flux level is about four times higher than reported in Ibarra et al. (2008) for XMM-Newton. Also, the Chandra photon index is \( \Gamma = 0.54^{+0.18}_{-0.31} \), which is significantly harder than the value of \( \Gamma = 1.7 \) reported for XMM-Newton. At the estimated distance to the source of 200−300 pc (Masetti et al. 2009; Butler et al. 2009), the Chandra flux level corresponds...
to an X-ray luminosity of $\sim 10^{32}$ erg s$^{-1}$, which is typical for CVs.

**IGR J18485$-$0047.** The position of CXOU J184825.4$-$004635 is consistent with the *Swift* position for this IGR source reported in Landi et al. (2007c). The *Chandra* position does not correspond to any cataloged 2MASS, DENIS, USNO-B1.0, or USNO-A2.0 sources, but the $K_{s}$-band image shown in Figure 6(f) suggests that a faint IR source may be associated with CXOU J184825.4$-$004635. Also, Landi et al. (2007c) noted a possible association between IGR J18485$-$0047 and the radio source GRS 31.897+0.317 (Becker et al. 1994). The *Chandra* source is within 1″ of the radio source, and the 90% confidence error radius on the radio source is 2″/2, so the association is likely. The flux of the radio source is 8.9 mJy at 5 GHz and 21 mJy at 1.4 GHz, and it is consistent with being a point source. As for the X-ray properties, both the *Swift* and *Chandra* spectra show evidence for absorption well in excess of the Galactic value. The association with a radio source may indicate an AGN nature for the source; however, CVs and X-ray binaries can also be radio emitters, so the classification is not certain. If the source is an AGN, then the high levels of absorption would indicate a Seyfert 2 classification.

**IGR J19267+1325.** The *Chandra* information for CXOU J192626.9+132205 was reported previously in Tomsick et al. (2008b), and the *Chandra* and *Swift* results for this source are discussed in detail in Rodriguez et al. (2009). After the identification of the optical counterpart (Tomsick et al. 2008b), follow-up optical spectroscopy showed that the source is a CV (Steehls et al. 2008; Masetti et al. 2009; Butler et al. 2009). Furthermore, an X-ray period of 938.6 s has been measured and is identified as the white dwarf spin period, indicating that the source is a CV of Intermediate Polar type (Evans et al. 2008). A second period may also be present at 4.58 hr, and this may be the binary orbital period (Evans et al. 2008). Somewhat discrepant distances of 580 pc (Masetti et al. 2009) and 250 pc (Butler et al. 2009) have been derived. For this range of distances, the X-ray flux that we measure indicates a range of 0.3–10 keV luminosities of $7 \times 10^{31}$ to $4 \times 10^{32}$ erg s$^{-1}$.

**IGR J19443+2117.** Based on a *Swift* detection of this source, Landi et al. (2009) suggest associations with the radio source NVSS J194356+211826 and the IR source 2MASS J19435624+2118233. We confirm these associations as CXOU J194356.2+211823 is within 0.3 of the 2MASS source. Landi et al. (2009) discuss the nature of the source, which is a relatively bright radio source (103 mJy at 1.4 GHz) and also has a $K_{s}$ magnitude of 13.98 $\pm$ 0.07. The *Chandra* spectrum and flux are similar to those reported by Landi et al. (2009), but we find even stronger evidence that the column density is in excess of the Galactic value. Overall, we agree with the conclusion of Landi et al. (2009) that IGR J19443+2117 is most likely an AGN, but an optical or IR spectral confirmation would strengthen this conclusion.

### 5. SUMMARY AND CONCLUSIONS

The main goal of this *Chandra* project has been to localize and measure the soft X-ray spectra of IGR sources in the Galactic plane in order to determine their nature or to guide follow-up observations to determine their nature. In this paper, we have reported results from 22 *Chandra* observations, and we have identified likely soft X-ray counterparts in 18 cases. Here, we summarize the different types of sources that we have found.

Two X-ray binaries and five X-ray binary candidates. We confirm that IGR J14331$-$6112 is an HMXB based on its positional coincidence with the previously suggested counterpart (Masetti et al. 2008), and we show that this source has a very strong iron Kα emission line, which is similar to what has been seen for some of the other IGR HMXBs. We also confirm the Masetti et al. (2009) optical identification of IGR J17404$-$3655. While we agree that the source is an X-ray binary, we argue that the hard X-ray spectrum may indicate that the source is an HMXB rather than an LMXB. Hard X-ray spectra ($\Gamma < 1$) combined with large optical/IR extinctions (and thus, large distances) argue for an HMXB nature, and we suggest that IGR J16287$-$5021, IGR J17354$-$3255, IGR J17507$-$2647, and IGR J17586$-$2129 may be HMXBs based on this evidence. Finally, comparing *Swift* and *Chandra* spectra shows that the column density for IGR J13186$-$6257 is high and variable, which suggests the possibility that the source is an HMXB.

Three CVs and one CV candidate. For IGR J19267+1325, the *Chandra* position led to the identification of the optical counterpart that was shown to be a CV. In addition, we confirm the previously suggested optical identifications for IGR J18173$-$2509 and IGR J18308$-$1232, and these are also CVs. We also mention the new possibility that IGR J15529$-$5029 may be a CV based on a hard X-ray spectrum ($\Gamma < 1$) combined with relatively low optical/IR extinctions.

One AGN and two AGN candidates. We confirm that IGR J14471$-$6414 is an AGN based on its positional coincidence with the previously suggested counterpart, which is a Seyfert 1.2 at a redshift of $z = 0.053$ (Masetti et al. 2008). We confirm the association of IGR 19443+2117 with 2MASS and radio counterparts (Landi et al. 2009), but spectral confirmation is still required to confirm that this source is an AGN. Finally, we identify IGR J18485$-$0047 with a strong radio source. Based on the radio emission and the strong X-ray absorption, we suggest that it may be a Seyfert 2 AGN.

Tw0 SNRs. IGR J14003$-$6326 and IGR J17448$-$3232 are both circular extended sources, indicative of being SNRs. In the former case, the putative pulsar appears to be embedded in the SNR, and the hard X-ray emission may be dominated by the PWN. In the latter case, a hard point-like source at the edge of the SNR may indicate that the pulsar was kicked when the explosion occurred. Prior to this work, only one IGR source was identified as an SNR, IGR J18135$-$1751, which has also been detected at TeV energies (Ubertini et al. 2005). The *Integral* discovery of two more SNRs may effect estimates of the hard X-ray emission levels from SNRs in general, and may have implications for the numbers of SNRs that future hard X-ray satellites, such as *NuSTAR* (Harrison et al. 2009), will detect.

Two unclassified sources. We have identified IGR J11098$-$6457 with CXOU J110926.4$-$650224 and IGR J18134$-$1636 with CXOU J181328.0$-$163548, but the nature of these sources is unclear.

Sources lacking clear counterparts. We did not find clear *Chandra* counterparts for IGR J07295$-$1329, IGR J09485$-$4726, IGR J17461$-$2204, or IGR J17487$-$3124. This may indicate that these are transient or variable X-ray sources.

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We note that the 90% confidence Chandra as these were the four sources for which we did not find a clear the four sources listed above have radii of 5.

J17461−2204, and IGR J17487−3124, IGR J09485−7, and 3.

The tables do not include hardness ratios for sources with fewer than five ACIS counts as the errors are too large in these cases.

The wavdetect sources are spurious, we removed the sources that have fewer than one count. In addition, the tables do not include hardness ratios for sources with fewer than five ACIS counts as the errors are too large in these cases. The tables for IGR J07295−1329, IGR J09485−4726, IGR J17461−2204, and IGR J17487−3124 may be especially useful as these were the four sources for which we did not find a clear Chandra counterpart. Thus, results from future observations could be compared to these tables to look for X-ray variability that could help to identify the counterparts of the IGR sources. We note that the 90% confidence INTEGRAL error circles for the four sources listed above have radii of 5.4, 4.9, 3.7, and 3.0, respectively.

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