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GMRT observations of the field of INTEGRAL X-ray sources. II

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ABSTRACT

We conducted low-frequency radio observations with the Giant Metrewave Radio Telescope (GMRT) of the 40 new hard X-ray sources discovered by the INTEGRAL satellite. This survey was conducted in order to study radio emissions from these sources, to provide precise position, and to identify new microquasar candidates. Our observations show that 24 of the X-ray sources have radio candidates within the INTEGRAL error circle. Based on the radio morphology, variability, and information available from different wavelengths, we categorize them as seventeen Galactic sources (4 unresolved, 7 extended, 6 extended sources in diffuse regions) and seven extragalactic sources (2 unresolved, 5 extended). A detailed account of seventeen of these sources was presented in an earlier paper. Based on the radio data for the remaining sources at 0.61 GHz and on the available information from NVSS, DSS, 2MASS, and NED, we have identified possible radio counterparts for the hard X-ray sources. The three unresolved sources, i.e., IGR J17303−0601, IGR J17464−3213, and IGR J18406−0539, are discussed in detail. These sources have been associated with compact sources that are variable in radio and X-rays. The remaining fourteen sources have an extended radio morphology and either are diffuse Galactic regions or have an extragalactic origin.

Key words. radio continuum: stars – stars: binaries: general – radiation mechanisms: non-thermal – instrumentation: interferometers – methods: observational – catalogs

1. Introduction

Many new hard X-ray emitting sources have been discovered during the deep Galactic plane survey of the *INTEGRAL* satellite mission. The IBIS instrument has a point-source location accuracy (PSLA) of typically 1−3′ within a large field of view 29° × 29° (Ubertini et al. 2003). A list of fifty-five new hard X-ray sources have been reported in the literature. A majority of these sources are believed to be Galactic X-ray binaries with a compact object orbiting a companion star (Bird et al. 2004). A few among these sources are identified as AGNs, radio galaxies, pulsars, CVs, and dwarf nova. A detailed study of X-ray sources in the multi-wavelength band is essential for understanding the emission mechanism and the accretion process onto the compact companion neutron stars (NS) or black holes (BH). The radio imaging of these sources can establish whether some of these are radio-emitting X-ray binaries (REXBs) and show any microquasar like features. Due to their similarity to quasars, the jet feature in microquasars provides important information about the underlying physical phenomenon and the possible disk-jet connection that may power the observed emission in different wavebands. Their X-ray, infrared, and radio properties can lead to classification schemes.

The detailed radio observations of these sources were made immediately after their discovery using the GMRT, to find the possible radio counterparts within the location error box of the X-ray source, to measure precise position if detected, and to study the low-frequency radio nature of the hard X-ray sources. The radio morphology of a source also provides its identification as Galactic, which is mainly compact (Becker et al. 1990) or extragalactic, which is mostly extended (Jackson 1999). At meter wavelengths REXBs show a point-source morphology (Pandey et al. 2005a). We also analyzed the available NVSS images at 1.4 GHz and other radio data in order to understand the radio spectrum of these sources. The archival data, from DSS, 2MASS, and NED images, are also used in our analysis to facilitate a complete study of these sources.

2. Observations and analysis

The radio observations were carried out at 0.61 GHz with bandwidth of 32 MHz using the GMRT. The full-array synthesized beam of the GMRT antenna at 0.61 GHz is ~5 arcsec.

As described in Paper I (Pandey et al. 2005b), association of the possible radio counterpart to the *INTEGRAL* source was based on the observed radio morphology, flux density variability, and cross-correlation with the NED catalogue. During the observations in the Galactic center region at low radio frequencies, the decrease in gain due to the system temperature becomes significant, so that system temperature corrections were applied to the flux densities of the radio measurements. The flux density scale was set by observing the primary calibrators 3C 286, 3C 147, and 3C 48. The phase calibrators were observed near the target source for ~5 min scan interleaved with 25 min scans of *INTEGRAL* sources. The data recorded from GMRT was converted into FITS files and analyzed using the Astronomical Image Processing System (AIPS). Details of the observation and analysis procedures are discussed in Paper I.

During our observations, radio sources were detected in the field of sixteen hard X-ray sources. A possible radio counterpart for the seventeenth source was detected from the archival

Table 1. List of target INTEGRAL sources observed with GMRT.

Source	Type	Integral Pos. Unc. 1.6σ	Variable 100 s–1 ks $\frac{\text{IBIS}}{\text{ISGRI}}$	X-ray Flux 15–40 keV (mCrab)	X-ray/optical/ UV/IR/Radio sources in X-ray error circ.	No. of sources in the X-ray error circ.
IGR J00370+6122	HMXB[1,2]	2′	Yes	–	BD+6073	
IGR J01363+6610	HMXB[2]	2′	Yes	17	HD9603	
IGR J16167−4957	–	6″	–	2	–	
IGR J16195−4945	HMXB(?)[*,10]	16″	–	–	HD146628	
IGR J16207−5129	–	2′	–	–	HD146803	
IGR J16358−4726	LMXB(?)[3,4] Pulsar[5]	0.6″	Yes	20–50 4.63	2MASS J163553−472539	
IGR J16393−4643	HMXB(?)[*] Pulsar[5,6,7,11]	2′	Yes	3		20[**]
IGR J16558−5203	–	8″	–	–	1RXS J165605−520345 USNO-B1.0 0379−00008129	
IGR J17195−4100	–	8″	Yes	–	1RXS J171935−410054 USNO-B1.0 0489−00511283	
IGR J17200−3116	–	9″	Yes	–	1RXS J172006−311702	
IGR J17252−3616	HMXB[8] Pulsar[*]	2′	–	–	IRAS 17220−3615 NVSS J172510−361614 HD319824	
IGR J17254−3257	–	14″	–	–	1RXS J172525−325717 USNO-B1.0 0570−00727635	
IGR J17285−2922	XB[9]	2′	Yes	–	IRAS 17252−2922 [T66b]320	
IGR J17303−0601	LMXB[*]	7″	Yes	–	H1726−058 USNO−A2.0 0825−10606993 1RXS J173021.5−055933	
IGR J17456−2901	–	1′	–	–	1LC G359.923−00.013	90[**]
IGR J17460−3047	–	2′	–	–		80 IR[+] sources[**]
IGR J17464−3213	BHC[*] LMXB[3]	0.5′	Yes	60	H1743−322 2MASS 17461525-3213542 USNO-A2.0 0525-294112269	
IGR J17475−2822	Sgr B2[5]	2–3′	–	–		200 [**]
IGR J17488−3253	–	12″	Yes	–	1RXS J174854.7−325444	
IGR J18027−2016	Pulsar[6]	1′	–	4.06	HD312525 1LC G000.683−0.035 IRAS 17594−2021	
IGR J18406−0539	–	2–3′	–	–	IRAS 18379−0546 AX J1840.4−0537 NVSS J184037−054317 GSC2.2	
IGR J18450−0435	–	2–3′	–	–	IRAS 18422−0437 PMN J1845−0433	
IGR J18490−0000	–	2–3′	–	–	–	

[1] High mass X-ray binary, [2] Reig et al. (2005), [3] Bird et al. (2004), [4] Low mass X-ray binary, [5] Revnivtsev et al. (2004), [6] Lutovinov et al. (2005), [7] Boudaghee et al. (2005), [8] Zurita et al. (2005), [9] X-ray binary, [10] Sidoli et al. (2005), [11] Soldi et al. (2005).
[*] `http://isdc.unige.ch/~rodrigue/html/igrsources.html`, [**] field sources, [+] infra red.

data of the NVSS survey. All seventeen possible radio counterparts of the twenty-three hard X-ray sources are reported in this paper, and for the remaining sources no possible radio counterpart was detected within the 3σ position error circle of the X-ray source. In Table 1, we list the physical properties of the sources observed during our survey, along with the other available data, the inferred class of the object, and the field sources in other wave bands within the *INTEGRAL* error circle.

A summary of the results of the GMRT observations is given in Table 2. The best-fit radio positions for the counterpart and the position offset with respect to the X-ray position is given in Cols. 5 and 6. Column 3 gives the radio flux density for the point (peak) and extended (total) sources, while Cols. 7 and 8 give the information about the source morphology at GMRT frequencies and the flux density at 1.4 GHz of the NVSS survey, respectively. The rms noise given in Col. 4 of the table corresponds to the average background noise in the image field and is higher in the Galactic plane. In the radio images presented below, the source marked with "A" indicates the radio counterpart close to the X-ray source. We have grouped sources based on their radio morphology into point and extended sources, and discuss in detail some of these sources with genuine radio – X-ray association.

3. Results

3.1. Point radio sources within the field of INTEGRAL sources

1- IGR J17303−0601. This source was detected in the Norma arm region (Walter et al. 2004) and in coincidence with the

Table 2. Possible Radio counterparts of target INTEGRAL sources observed with GMRT at 0.61 GHz.

Source	Date dd/mm/yy	S_ν (Peak/Total) (mJy)	σ (mJy b^{-1})	Radio Pos. GMRT RA and Dec	Pos. Off. w.r.t Integral Pos.	Radio Structure GMRT	S_ν(NVSS) (Peak/Total) (mJy)
IGR J00370+6122	25/06/04	≤7.00	2.18	–	–	–	≤1.6
IGR J01363+6610	25/06/04	≤7.00	2.31	–	–	–	≤2.5
IGR J16167−4957	23/07/04	725	2.90	$16^h16^m44.29^s \pm 0.91$ $-49^\circ57'10.02'' \pm 0.71$	0.12′	Extended (DG)	N/A
IGR J16195−4945	30/07/04	256.4	0.84	$16^h19^m35.07^s \pm 0.21$ $-49^\circ44'59.01'' \pm 0.28$	0.84′	Extended (DG)	N/A
IGR J16207−5129	30/07/04	60.50	0.78	$16^h20^m48.54^s \pm 0.77$ $-51^\circ29'50.01'' \pm 0.98$	1.33′	Extended (DG)	N/A
IGR J16358−4726	31/07/04	≤7.50	2.5	–	–	–	N/A
IGR J16393−4643	23/07/04	79.25	1.63	$16^h39^m03.9^s \pm 0.51$ $-46^\circ42'15.55'' \pm 0.59$	2.58′	Extended (DG)	N/A
IGR J16558−5203	30/07/04	27.24	0.78	$16^h55^m46^s \pm 0.04$ $-52^\circ03'58'' \pm 1.04$	0.69′	Extended (E)	N/A
IGR J17195−4100	23/07/04	33.44	0.56	$17^h19^m34^s \pm 0.22$ $-41^\circ00'00'' \pm 1.24$	0.98′	Extended (DS-E)	N/A
IGR J17200−3116	23/07/04	33.03	0.51	$17^h19^m55^s \pm 0.74$ $-31^\circ16'01'' \pm 0.70$	0.55′	Extended (DS-E)	20 (E)
IGR J17252−3616	25/07/04	36.74	1.88	$17^h25^m11.09^s \pm 1.71$ $-36^\circ16'48.01'' \pm 0.20$	0.82′	Extended (DG)	700 (E)
IGR J17254−3257	25/07/04	359.65	0.43	$17^h25^m24^s \pm 1.22$ $-32^\circ55'10'' \pm 1.33$	3.12′	Extended (DG)	≤2.5
IGR J17285−2922	25/07/04	74.88	0.59	$17^h28^m28.75^s \pm 0.07$ $-29^\circ21'04.51'' \pm 1.24$	0.96′	Extended (E)	≤2.7
IGR J17303−0601	25/06/04	≤6.00	1.84	–	–	–	18 (P)
IGR J17456−2901	23/07/04	23.11	1.53	$17^h45^m38.07^s \pm 0.04$ $-29^\circ00'40.00'' \pm 1.87$	0.56′	Extended (DS-E)	17200 (E)
IGR J17460−3047	30/07/04	2.50	0.46	$17^h45^m59.69^s \pm 0.03$ $-30^\circ46'58.00'' \pm 2.33$	0.076′	Extended (E)	≤2.3
IGR J17464−3213	25/07/04	2.75 ± 0.52	0.50	$17^h46^m15.61^s \pm 0.28$ $-32^\circ13'59.9'' \pm 0.21$	0.64′	Point	≤2.4
IGR J17475−2822	23/07/04	12.50	1.27	$17^h47^m25.68^s \pm 0.62$ $-28^\circ22'21.96'' \pm 1.21$	1.02′	Extended (DG)	1920 (E)
IGR J17488−3253	30/07/04	≤2.10	0.67	–	–	–	≤1.6
IGR J18027−2016	25/06/04	≤7.00	2.32	–	–	–	≤1.3
IGR J18406−0539	23/07/04	28.03 ± 0.76	0.76	$18^h40^m37.61^s \pm 0.12$ $-05^\circ43'17.99'' \pm 0.18$	4.31′	Point	165 (P)
IGR J18450−0435	23/07/04	207.94	0.76	$18^h45^m12.05^s \pm 1.06$ $-04^\circ40'05.99'' \pm 1.69$	5.90′	Extended (E)	74 (E)
IGR J18490−0000	23/07/04	≤3.5	1.25	–	–	–	≤1.4

[2] DS-E: Double Source Extragalactic; E: Extended; P: Point; DG: Diffused Galactic Region.

ROSAT source 1RXS J173021.5−055933 (Voges et al. 1999; Stephen et al. 2005). Two optical objects with $R \sim 15.5$ and $R \sim 18$ are found within the *ROSAT* error box of 7″ in the Digitized Sky Survey (DSS) field (Monet et al. 2003; Stephen et al. 2005). Two near-infrared sources in the (2-MASS survey) are also coincident with the optical sources. The optical spectra of both these sources acquired with the Bologna Astronomical Observatory show features identical to other X-ray emitting objects (Masetti et al. 2004). The brighter source within the *ROSAT* error box was considered to be the optical counterpart to IGR J17303−0601. All the optical emission lines of this object are at zero red-shift, indicating its Galactic origin. The presence of the He II line strongly indicates that this object is undergoing mass accretion onto a compact star (e.g. van Paradijs & McClintock 1995), thereby suggesting the X-ray source to be a low mass X-ray binary. The optical photometry of the source, however, suggests the hard X-ray source is an intermediate polar with a spin period of 128 s (Gansicke et al. 2005).

The NVSS data at 1.4 GHz with the VLA (Condon et al. 1998) was analyzed to look for radio counterpart. The radio image of the field is shown in Fig. 1. A compact point source "A" of ∼18 mJy at 1.4 GHz is detected coincident with the *INTEGRAL* and *ROSAT* source position. The precise position with the radio observations is RA: $17^h30^m21.50^s$ and Dec: $-05^\circ59'33.5''$ (J2000). Two other compact field sources "B" with radio flux density ∼5 mJy and RA: $17^h30^m45.48$ and Dec: $-06^\circ01'57.17''$ and "C" with radio flux density ∼16 mJy and RA: $17^h30^m28.41$ and Dec: $-06^\circ05'56.27''$, were clearly detected within the field and lie outside the *INTEGRAL* error circle. In order to search for the radio source at lower frequencies, GMRT observations on this source were performed at 0.61 GHz. No radio source was found coincident in position with the NVSS source "A" during our observations at 0.61 GHz. The 3σ upper limit in the GMRT image was ∼6 mJy and the rms noise was ∼1.84 mJy beam^{-1}. The sources "B" and "C" with radio flux density ∼18 mJy and ∼15.5 mJy were clearly detected coincident in position with the NVSS sources.

At radio wavelengths the detection at 1.4 GHz and non-detection at 0.61 GHz with positive detection of other field

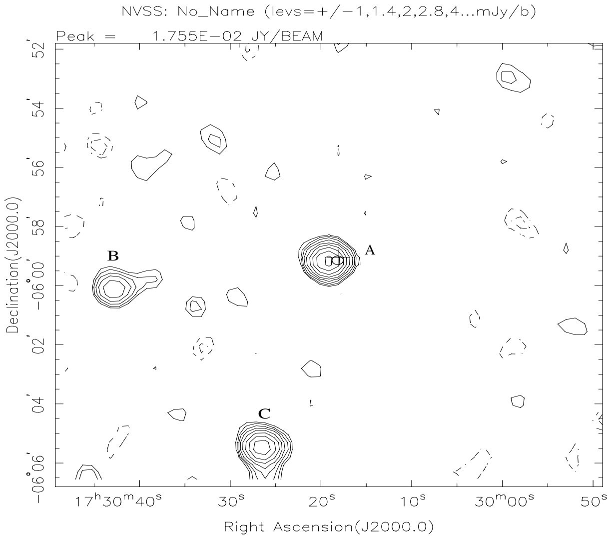

Fig. 1. NVSS image of IGR J17303−0601 at 1.4 GHz with the *INTEGRAL* position marked with +. Source "A" is coincident in position as IGR J17303−0601. Sources "B" and "C" are field sources. The circle shows the *INTEGRAL* uncertainty error circle of 3σ (14″).

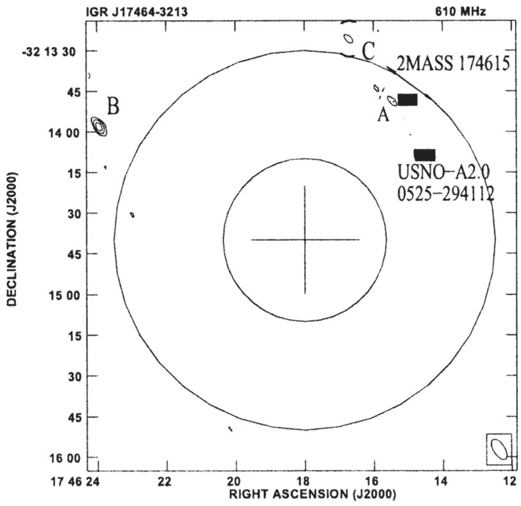

Fig. 2. GMRT image of IGR J17464−3213 at 0.61 GHz with the *INTEGRAL* position marked by a +. The small and large circles show the *INTEGRAL* uncertainty error circles of 1.6σ and 3σ. The contour levels are 2 mJy × 1, 1.4, 2. The field sources 2MASS 17461525-3213542 and USNO-A2.0 0525-294112269 are marked in the figure.

sources suggest that IGR J17303−0601 is a radio-emitting X-ray binary (REXB). And the source is highly variable or absorbed at low frequencies. The absorption may be due to the synchrotron self-absorption process dominant at low frequencies as seen for most of the X-ray binaries (Pandey et al. 2004). In both cases, a non-thermal origin of the radio emission is favored. Like a few other sources in the Norma Arm region, even this source was highly absorbed at low frequencies (Pandey et al. 2005c).

2- IGR J17464−3213. This transient BH candidate was detected by the *INTEGRAL* satellite on 21 March 2003 (Revnivtsev et al. 2003). The position of the source is consistent with the position of the HEAO source H1743−322 (Markwardt & Swank 2003; Gursky et al. 1978). The spectral fit to the JEM-X/IBIS data shows the presence of a soft component fitted by a multi color disk black body and a hard power-law tail with a photon index of 2.2 that extends to 80 keV. The observations made during the outburst show that the light curve is typical of a X-ray nova (Steeghs et al. 2003). It is therefore believed that IGR J17464−3213 is a classical X-ray nova – a LMXB harboring a BH – that experienced a recurrent outburst in 2003 (Lutovinov et al. 2005).

The RXTE pointed observations on 28 March 2003 gave mean fluxes 50, 200, and 220 mCrab in the 2−10, 15−40, and 40−100 keV ranges respectively. A strong quasi-periodic oscillation (QPO) with the period ~20 s was also seen in the X-ray light curve. The X-ray spectrum is consistent with an absorbed power law with photon index 1.49 ± 0.01 and an absorption column of 2.4×10^{22} cm^{-2}. Compton reflection signatures are seen in the continuum spectrum (Grebenev et al. 2003; Capitanio et al. 2005). The RXTE monitoring of the source between May–July 2004 observed IGR J17464−3213 in several BH states and revealed various types of variability, including QPOs of 7.8 Hz (Homan et al. 2005).

During the follow-up observations with the VLA on 30 March and 1 April 2003, a compact, variable source was detected at 4.8 GHz at RA: $17^{\rm h}46^{\rm m}15.61 \pm 0.01^{\rm s}$, Dec: $-32°13'59.9 \pm 1.0''$ (J2000), and approximately 0.64′ from the original *INTEGRAL* position. It is consistent with the position of H1743−322 (Swank et al. 2004). The source flux was 4 mJy on 30 March and had brightened by about 50% on 1 April. A strong radio flare was detected on 8 April 2003 (Rupen et al. 2003a). The ATCA radio observations of H1743−322 performed from Nov. 2003–June 2004 led to the discovery of large-scale radio jets on each side of the BHC H1743−322 (Corbel et al. 2005).

The optical observations in the *I*-filter at the radio position show a marginal detection of an optical counterpart at a level of $I_{\rm mag} \sim 20$ (Khamitov et al. 2003; Remillard et al. 2003; Steeghs et al. 2003; Rupen et al. 2003b).

On 3 July 2004, a second outburst was detected in the X-ray light curve of IGR J17464−3213, and it went into hard X-ray state (Swank et al. 2004). During the end of the X-ray state, the radio source was not detected at the position mentioned by Rupen et al. (2003a) until 4 Aug. 2004 during VLA observations at 4.86 GHz; however, it was positively detected by the VLA on 5th Aug. 2004, with a flux density of 1.96 ± 0.15 mJy (Rupen et al. 2004). During GMRT observations on 25 July 2004, a radio source was detected coincident with the VLA position reported by Rupen et al. (2003a) at a radio flux density of 2.75 ± 0.52 mJy (source "A" in Fig. 2). It is also interesting to note that two compact sources, (B) of flux level 6 mJy at position coordinates, RA: $17^{\rm h}46^{\rm m}24.17^{\rm s}$ and Dec: $-32°13'59.92''$ and (C) of flux level 2 mJy at position coordinates, RA: $17^{\rm h}46^{\rm m}16.55^{\rm s}$ and Dec: $-32°13'29.89''$ are also detected within the field of IGR J17464−3213; however, they clearly lie outside the *INTEGRAL* 3σ position error circle. The analysis of the NVSS data at 1.4 GHz shows no point sources coincident with the radio sources (A) and (B), as detected by the GMRT; however, source (C) was positively detected in the NVSS field at a flux level of ~1.05 mJy. There were no other radio observations reported at this epoch. Hence, two variable radio sources (A, B) are detected within the field of *INTEGRAL* source; however, the source (A) is most likely to be associated with the hard X-ray source and it clearly shows transient behavior at radio wavelengths like other LMXBs.

In order to determine IR and optical counterparts, we analyzed the 2MASS and USNO data near the radio source (A) position for the field of IGR J17464−3213.

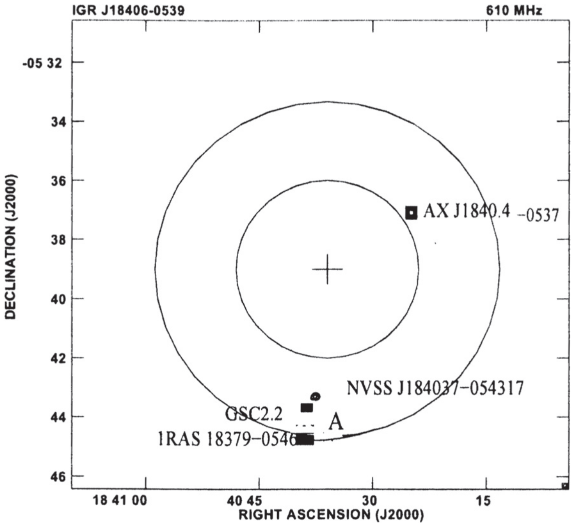

Fig. 3. GMRT image of IGR J18406−0539 at 0.61 GHz with a *INTEGRAL* position marked with +. The small and large circles show the *INTEGRAL* uncertainty error circles of 1.6σ and 3σ. The contour levels are 5.5 mJy × 1, 2, 4, 8. The boxes show the ASCA, optical, and IR sources within the *INTEGRAL* error circle. The field sources AX J1840.4−0537, IRAS 18379−0546, NVSS J184037−054317, and GSC2.2 are marked in the figure.

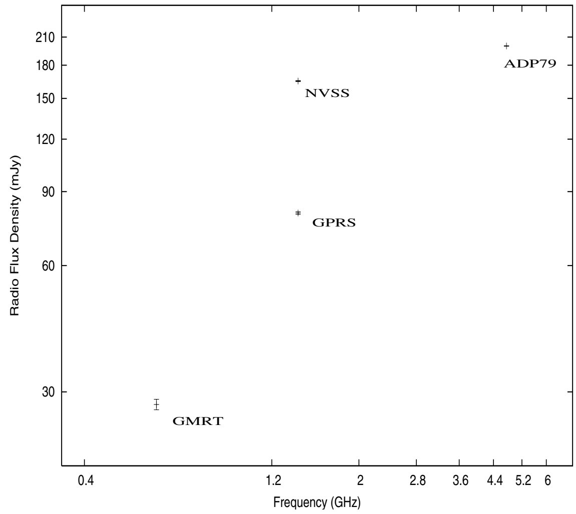

Fig. 4. Radio spectrum for IGR J18406−0539.

An IR point source, 2MASS 17461525-3213542 with coordinates RA: $17^h46^m15.25^s$ and Dec: $-32°13'54.2''$ and magnitudes $J = 16.2, H = 13.8, K = 13.16$ and an optical source, USNO−A2.0 0525−294112269 with position coordinates RA: $17^h46^m14.77^s$ and Dec: $-32°14'06.02''$ and magnitudes $B = 19.6, R = 17.4$ lies within the error circle of the hard X-ray source but separated from the radio source more than the position error box (Voges et al. 2004). Thus, if H1743 322 is most likely associated with IGR J17464 3213, then no optical and infrared counterpart has been found.

3- IGR J18406−0539. This source was discovered during observations of the Sagittarius arm region by the IBIS telescope in 2003 (Belanger et al. 2004). We carried out cross identification of this source, with the data available from various catalogues, to identify the nature of the source. A hard X-ray source, AX J1840.4−0537 discovered during ASCA observations with RA: $18^h40^m24^s$ and Dec: $-05°37'00''$ lies within the position error circle of the source (Bamba et al. 2003). The field is further complicated by the presence of an optical source, GSC2.2 with magnitudes $B = 16$ and $R = 19$ and position RA: $18^h40^m38.094^s$ and Dec: $-05°43'19.30''$ lying within error circle (Monet et al. 1998).

An IR point source, IRAS J18379−0546 (Cutri et al. 2003), with coordinates RA: $18^h40^m38.04^s$, Dec: $-05°43'20''$ and magnitudes $J = 12.89$, $H = 11.91$, $K = 11.61$, also lies within the 2σ position error ellipse of the hard X-ray source.

During GMRT observations, a point source was detected with a radio flux density of ∼28 mJy and at RA: $18^h40^m37.61^s$ and Dec: $-05°43'17.99''$, which is $4.31'$ away from the hard X-ray source. The NVSS image of the field also shows a point source of 165 mJy coincident with the GMRT position. Figure 3 shows the radio image of the field of IGR J18406−0539 at 0.61 GHz with the other known field sources.

Using the various radio surveys, we computed the radio spectrum for the source (non-simultaneous measurement) in Fig. 4. It can be seen from the figure that the spectrum is highly inverted at meter wavelengths. Note that the NVSS survey at 1.4 GHz and the Galactic Plane Radio-source Survey at 1.4 GHz (Zoonematkermani et al. 1990) for the compact Galactic source at different epochs give the radio flux density of 165 mJy and 80 mJy, respectively. A variability in the radio flux density by a factor of two is clearly measured. The Galactic plane survey at 4.87 GHz by Altenhoff et al. (1979) gave the radio flux density for the source as 200 mJy. This information implies that the source is variable in nature. As can be seen in Fig. 3, the radio source detected with GMRT (and coincident with the VLA/NVSS source) has no IR/optical counterpart. It is important to do further observations in the optical and infrared bands to find the counterpart and to estabilsh the nature of the companion star.

3.2. Extended radio sources within the field of INTEGRAL sources

In this section the nature of the extended sources lying within the position error circle of the *INTEGRAL* sources are discussed in detail.

3.2.1. Extragalactic radio sources

The Galactic binary X-ray sources are mostly unresolved on an arcsec scale (Pandey et al. 2005a). Statistically most of the Galactic sources (e.g. XBs) are compact, and extragalactic sources (e.g. radio galaxies) are extended in morphology. The possible radio counterparts with extended double-source morphology can thus be categorized as extragalactic in nature. From our GMRT observations, we find that among the remaining twenty sources, the possible counterpart of three sources, viz, IGR J17195−4100, IGR J17200−3116, and IGR J17456−2901 have an extended double source morphology, which is typical of extragalactic sources. In Fig. 5, we plot the GMRT image of IGR17195-4100 taken at 0.61 MHz. The data clearly suggest these sources are radio galaxies. The cross identification with the NED catalogue (Voges et al. 1999; Condon et al. 1982; Pappa et al. 2001) also confirms their double-source morphology and classifies them as radio galaxies. Hence, these three sources are extragalactic radio sources. As for the true association of the radio source with the hard X-ray source, it is quite likely that the X-ray sources are indeed extragalactic. No X-ray

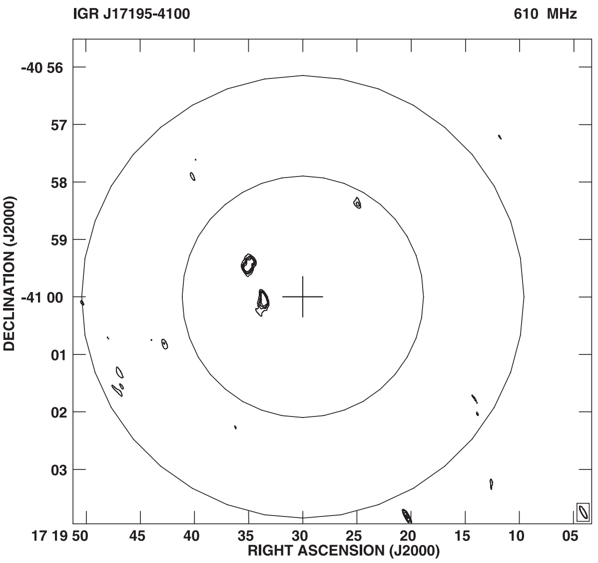

Fig. 5. GMRT image of IGR J17195−4100 at 0.61 GHz with the *INTEGRAL* position marked with a +. The small and large circles show the *INTEGRAL* uncertainty error circles of 1.6σ and 3σ. The countour levels are 2.3 mJy × 1.0, 1.2, 1.3, 1.4, 2.0, 2.8, 4.0, 8.0, 16.0, 32.0.

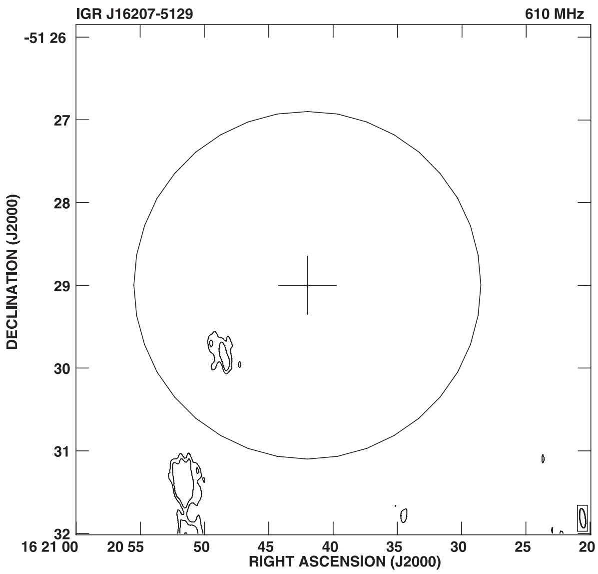

Fig. 6. GMRT image of IGR J16207−5129 at 0.61 GHz with the *INTEGRAL* position marked with a +. The circle show the *INTEGRAL* uncertainty error circle of 1.6σ. The countour levels are 3.0 mJy × 1.0, 1.2, 2.0, 2.8, 4.0, 8.0, 16.0, 32.0.

spectral data is available yet to infer the galactic origin of the source. However, if the X-ray sources are galactic in origin, then the observed radio association will be a case of fortutious line of sight coincidence. We list the known field sources within the *INTEGRAL* error circle in Table 1. The optical counterpart for IGR J17195−4100 is also listed in the Table 1, as taken from the USNO catalogue.

3.2.2. Extended Galactic radio sources

Among the seventeen remaining sources, eleven hard X-ray sources do show extended radio morphology within the position error circle. The available X-ray spectra on a few of these sources suggest their binary nature and galactic origin (Table 1). No known extragalactic radio sources from the NED catalogue lie in the position error circle of these *INTEGRAL* sources and in coincidence with the GMRT position. The observed radio emission with morphology different from the radio galaxies and with no known extragalactic identification from NED therefore suggests that these extended sources are most probably associated with the radio emitting regions within the galaxy. From the GMRT data, based on their radio morphology, the eleven *INTEGRAL* hard X-ray sources can be grouped into two classes: (a) an extended Galactic source and (b) an extended source typical of the diffuse emission regions. In Figs. 6 and 7 we plot representative radio images for the two groups. The image shown in Fig. 7 is similar to reminscent of the molecular clouds. Information from other wavelengths are necessary to interpret the true nature of these sources.

Five hard X-ray sources, namely, IGR J16207−5129, IGR J16558−5203, IGR J17285−2922, IGR J17460−3047, and IGR J18450−0435 belong to group (a). Except for IGR J17285−2922, all sources are located in the direction of the Norma Arm region and have a high probability of being galactic in nature. The X-ray spectrum of IGR J17285−2922 shows XB characteristics (Barlow et al. 2004); however, the nature of remaining sources has not yet been identified. Positive detection of extended radio emission at low frequencies, associated with the galactic X-ray sources seen in the GMRT data, suggests the presence of a new class of galactic extended radio sources.

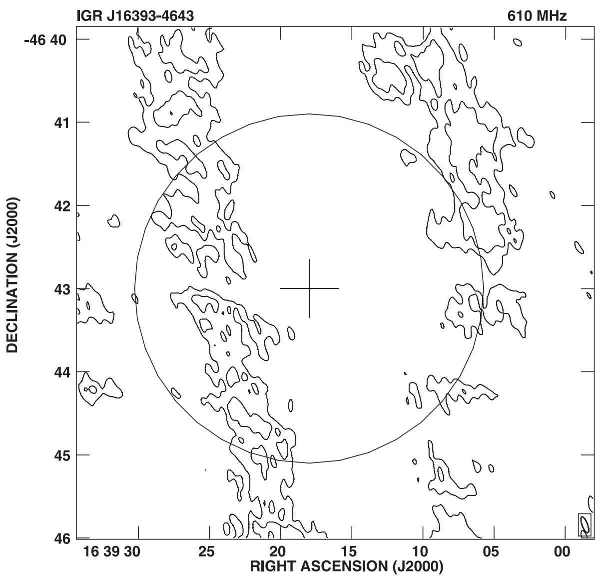

Fig. 7. GMRT image of IGR J16393−4643 at 0.61 GHz with the *INTEGRAL* position marked with a +. The circle show the *INTEGRAL* uncertainty error circle of 1.6σ. The countour levels are 2.0 mJy × 1, 2, 4, 18, 16, 32, 64.

Six sources, i.e. IGR J16167−4957, IGR J16195−4945, IGR J16393−4643, IGR J17252−3616, IGR J17254−3257, and IGR J17475−2822, belong to group (b). Most of the sources in this group were detected in the direction of Norma Arm region (Table 1).

As seen from Fig. 7, due to the large extent of the radio emission, it is difficult to associate a single region with the X-ray source, even though the radio emission lies within the position error circle of the X-ray source. The sources IGR J16393−4643, IGR J17456−2901, IGR J17460−3047, and IGR J17475−2822 have crowded fields with a large number of field sources >20, as expected from the diffuse regions. Therefore, we conclude that none of these radio sources may be associated with the *INTEGRAL* sources.

3.3. X-ray sources with no radio counterpart

Six sources, i.e. IGR J00370+6122, IGR J01363+6610, IGR J16358−4726, IGR J17488−3253, IGR J18027−2016, and IGR J18490−0000, have no GMRT counterpart. It has been suggested that IGR J00370+6122 and IGR J01363+6610 are HMXB systems (Reig et al. 2005). Hence, either these sources are not REXBs or they are synchrotron self-absorbed at the low frequencies at which our observations were made or they are highly variable in the radio band. Follow-up observations in the radio window are necessary to confirm the variable nature of these sources.

4. Summary and conclusion

The results of our radio survey of the newly discovered *INTEGRAL* hard X-ray sources are presented in this paper. Few of these sources are possible X-ray binaries (Table 1). The identification of AGNs, radio galaxies, X-ray novas, CVs, and pulsars was the important results achieved by the follow up observations at various wavelengths. Among the twenty-three sources observed at radio wavelengths, seventeen have a possible radio counterpart detected within the position error circle. The position offset of the possible radio counterparts with respect to the *INTEGRAL* position is of the order of a few arc minutes.

The consistent position provided by the GMRT will enable the search for infrared/optical counterparts for these sources to be detected. Based on the radio morphology of these sources, we have grouped them further into:

(a) Galactic point source;
(b) extended Galactic sources and sources in diffuse Galactic emission;
(c) extragalactic sources.

Three sources belong to group (a). We carried out a detailed study of these three sources and their possible counterparts at other wavebands. Based on the variability in the radio and X-ray windows, we infer that IGR J17303−0601, IGR J17464−3213, and IGR J18406−0539 are possibly REXBs. However, devoted radio observations are necessary to confirm the jet emission from these sources. We also detected a variable compact radio source within the field of IGR J17464−3213. Eleven sources can be associated with group (b), the diffused Galactic region, while three sources satisfy the radio morphology of extragalactic sources, group (c). No radio counterpart was detected for the remaining sources.

To conclude, we highlight that our observations were very important for pinpointing the possible counterparts from the list of forty *INTEGRAL* sources observed at radio wavelength. We performed repeated observations of a couple of these sources due to our interest in Cycle 7 when looking for the radio variability. The data still need to be analyzed and the results will be presented in a future paper.

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