Hard X-ray surveys with the *INTEGRAL* observatory

A.A. Lutovinov, R.A. Krivonos, I.A.Mereminsky, S.Yu.Sazonov
Space Research Institute (IKI), Moscow, Russia

S.S. Tsygankov
Tuorla Observatory, Department of Physics and Astronomy, University of Turku, Finland

E.M. Churazov, R.A. Sunyaev
Max-Plank Institute für Astrophysics, Garching, Germany
Space Research Institute (IKI), Moscow, Russia

The *INTEGRAL* observatory demonstrates a great success in surveying the sky at energies above 20 keV both in the Galactic plane and extragalactic areas. The observatory provides a significant scientific outcome to the astrophysical community and triggered a large number of new studies and observational campaigns in other wavelengths. The latest results of the surveys, performed with *INTEGRAL* are reviewed, including the deepest Galactic plane surveys in hard X-rays (from 17 to 150 keV) to detect new sources and study their populations and in ^{44}Ti lines to search for the emission of the supernovae remnants, the deep surveys of three extragalactic fields (in the direction to M81, LMC and 3C273/Coma), etc.

1 Introduction

The main project of the last decade in the hard X-ray and gamma-ray astronomy *INTEGRAL* (INTErnational Gamma Ray Astrophysical Laboratory)[1] is devoted to the study of different Galactic and extragalactic classes of objects as well as the diffuse emission. The *INTEGRAL* project was developed by the European Space Agency (ESA) in a cooperation with the Russian Space Agency and NASA and launched on 17 October 2002 with the Proton launcher from the Baikonur cosmodrome. The launch of the observatory was performed with an accuracy much better (by more than an order of magnitude) than was guaranteed. This allowed to significantly reduce the fuel consumption when forming the ultimate orbit by the spacecraft engines resulted in increasing the operational time of the observatory from 2 years to more than 20 years and obtaining the outstanding scientific results.

The *INTEGRAL* payload consists of a set of four complimentary instruments with detectors operating at various energy ranges: (1) SPectrometer on Integral (SPI), dedicated to high-resolution spectroscopy in a wide energy band from 15 keV to 8 MeV; (2) Imager on Board Integral Sattelite (IBIS), providing fine imaging in gamma-rays and covering the energy band from 15 keV to 20 MeV; (3) Joint European X-ray Monitor (JEM-X), supplementing SPI and IBIS in the 3-35 keV energy band; and (4) Optical Monitoring Camera (OMC), providing measurements in the optical band. All instruments except the OMC use the method of coded aperture for the image reconstruction.

An excellent performance of the *INTEGRAL* instruments and health of the satellite, as well as its long operation on the orbit enabled not only to study the spectral properties of individual sources, but also provided a great ability to survey different regions of the sky with an unprecedented sensitivity and accuracy in the hard X-ray and gamma-ray energy bands. Among the most prominent results of *INTEGRAL* it is necessary to mention next ones: deep all-sky surveys leading to the discovery of several hundreds of new hard X-ray sources both galactic and extragalactic nature[2,3,4,5,6]; population studies of different types of objects[7,8,9]; discovery of gamma-ray lines from radioactive decay of ^{44}Ti and ^{56}Co from supernovas SN1987A[10] and SN2014J[11], respectively; high-accuracy measurements of the energy of nuclear gamma-ray lines at 511 keV[12,13,14] and 1.8 MeV[15], originated from the annihilation of electron-positron pars and the radioactive decay of ^{26}Al, respectively; mapping of the Galactic plane in these lines[16,17,18,19]; discovery of the past activity of a supermassive black hole Sgr A* in the center of our Galaxy[20].

Below we briefly review some of *INTEGRAL* results, concentrating on the most recent surveys.

2 Survey of the Galactic plane in hard X-rays

X-ray surveys play a key role in our understanding of energetic phenomena in the Universe. Detailed investigations of the physics and evolution of X-ray sources are usually based on systematic studies of their properties. Observations in recent decades have revealed a variety of X-ray point sources beyond the solar system in the Milky Way and Magellanic Clouds. Although the bright X-ray sources in the Milky Way can be effectively studied in soft X-rays, many of them are not observable due to the heavy obscuration by the Galactic disk and interstellar dust.

X-ray observations of our Galaxy at energies above 10 keV are free from this obscuration bias. However, due to the large extent of the Milky Way across the sky, a systematic survey of the Galactic X-ray source population and discovery of new X-ray emitters require wide-angle instruments. This makes the IBIS coded-mask telescope[21] onboard the *INTEGRAL* observatory unique and most suitable for surveying the Galaxy in the hard X-ray domain.

The *INTEGRAL* observatory has been successfully operating in orbit more than 15 years and acquired a huge data set, which allowed us to construct high quality X-ray catalogs in the Galactic Plane (GP), starting from our early papers by [22,23,24] to more recent surveys [3,25,4,6]. These works were subsequently used for many relevant studies, including systematic discoveries of strongly absorbed high-mass X-ray binaries (HMXBs) and the study of their luminosity function and distribution in the Galaxy[26,27,28], the statistics of low mass X-ray binaries (LMXBs)[7] and cataclysmic variables (CVs)[8].

The recent analysis of 14-year averaged sky images of the Galactic plane ($|b| < 17.5^o$) led to the detection of 522 hard X-ray sources[6] at significance $S/N > 4.7\sigma$, which is ∼30% more compared to the previous 9-year survey[3] with the same detection threshold. Among 134 newly added sources, authors identified 62 previously known X-ray emitters, including 17 known sources that experienced transient events last years. Other 72 (out of 134) sources are newly detected hard X-ray ones, i.e. those sources whose detection is mainly determined by the increased *INTEGRAL* survey sensitivity.

The peak sensitivity of the 14-year *INTEGRAL* survey is 2.2×10^{-12} erg s^{-1} cm^{-2} (∼0.15 mCrab in the 17-60 keV energy band) at a 4.7σ detection level. The survey covers ∼ 11400 squared degrees down to the flux limit of 1.3×10^{-11} erg s^{-1} cm^{-2} (∼0.93 mCrab) and ∼ 1300 squared degrees down to the flux limit of 3.8×10^{-12} erg s^{-1} cm^{-2} (∼0.26 mCrab). The improvement in sensitivity with respect to the 9-year survey makes it possible to probe deeper into the Galaxy. Fig. 1 shows a face-on schematic view of the Galaxy and the distances at which we can detect a hard X-ray source of a given luminosity $L_{\rm X}$ in the $17-60$ keV band. One can see that (i) we can now detect all sources with the luminosity $L_{\rm X} > 2 \times 10^{35}$ erg s^{-1} at the far end of the Galaxy in the direction towards the Galactic Centre (GC), (ii) the distance range for the luminosity $L_{\rm X} > 10^{35}$ erg s^{-1} covers most of the Galactic stellar mass, and (iii) the Galactic central bar is fully reachable at luminosities $L_{\rm X} > 5 \times 10^{34}$ erg s^{-1} (see details in Krivonos et al.[6])

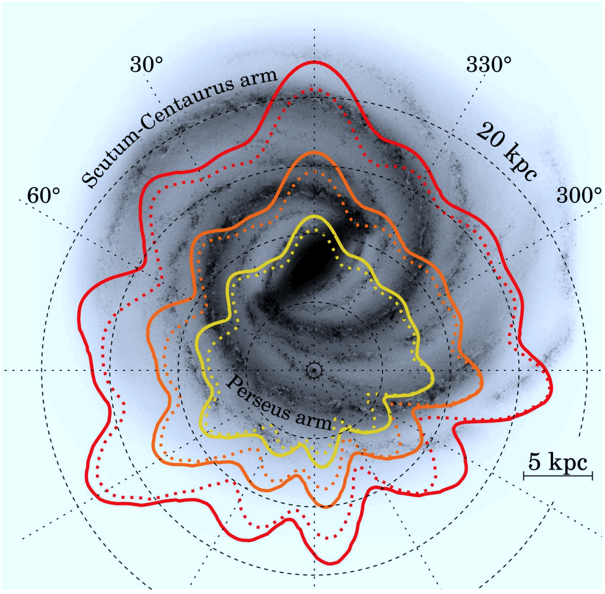

Figure 1 – Face-on view of the Galaxy shown along with the distance range at which an X-ray source of a given luminosity L_X (or more) can be detected according to the $17-60$ keV sensitivity of the 14-year *INTEGRAL* survey (solid lines), compared to the 9-year GP survey (dotted lines). Red, orange and yellow contours correspond to $L_X = 2\times10^{35}$, 10^{35} and 5×10^{34} erg s^{-1}, respectively. The background image is a sketch of the Galaxy adopted from Churchwell et al.

3 Survey of the Galactic plane above 100 keV

As it was shown above the *IBIS/INTEGRAL* telescope has demonstrated a great success in surveying of the hard X-ray sky at energies above 15 keV, especially in sky areas with a high surface density of sources – near the Galactic plane and Galactic Center. While the best sensitivity of this instrument is achievable at lower energies (typically $\sim 17-60$ keV), the harder energy band $> 100-200$ keV might be potentially interesting due to study of a possible appearance of new mechanisms of the photons generation. The *IBIS/INTEGRAL* telescope is only instrument which can build the sky maps at these energies[30,25] and reconstruct spectra of sources. Fig. 2 shows the Galactic bulge and disk map in the $100-150$ keV energy band in comparison with the map acquiring in the softer $17-60$ keV range.

A whole catalogue of detected sources includes 132 objects[25] (Fig. 3). The statistical sample detected on the time-averaged $100-150$ keV map at a significance above 5σ contains 88 sources: 28 AGNs, 38 LMXBs, 10 HMXBs and 12 rotation-powered young X-ray pulsars. The catalogue includes also 15 persistent sources, which were registered with the significance $4\sigma \leq S/N < 5$ in hard X-rays, but at the same time were firmly detected ($\geq 12\sigma$) in the $17-60$ keV energy band. All sources from these two groups are known X-ray emitters, that means that the catalogue has 100% purity in respect to them. Additionally, 29 sources were found in different time intervals.

It is clearly seen that the sky at energies $100-150$ keV is dominated by galactic sources (60 out of 88). Compared to the *INTEGRAL* Galactic 9-year $17-60$ keV survey[3], the number of LMXBs and HMXBs drops by a factor of ~ 3 and ~ 8 correspondingly. Such a dramatic difference is indeed expected as HMXBs have softer spectra than LMXBs. Indeed, the vast majority of high mass X-ray binaries, seen by *INTEGRAL*, are magnetic neutron stars (NS), accreting matter from their binary companions[31,32]. The emergent spectra of these sources are generated by a hot plasma, heated in an accretion column near the neutron star surface, and usually demonstrate an exponential cutoff at high energies[33,34]. In several cases a hard X-ray component was found in spectra of HMXBs[35,36,37], that allows one to detect them above 100 keV in the persistent state.

An emission of low mass X-ray binaries is formed in the innermost regions of the accretion flow around typically non-magnetic sources. Extensive studies of these sources show that they demonstrate different spectral states[38,39]. Typically LMXBs have hard spectra (both black holes and neutron stars) during low level of their mass accretion rate and soft spectra at high mass accretion rates. The total number of LMXBs in *INTEGRAL* Galactic nine-year survey is mainly

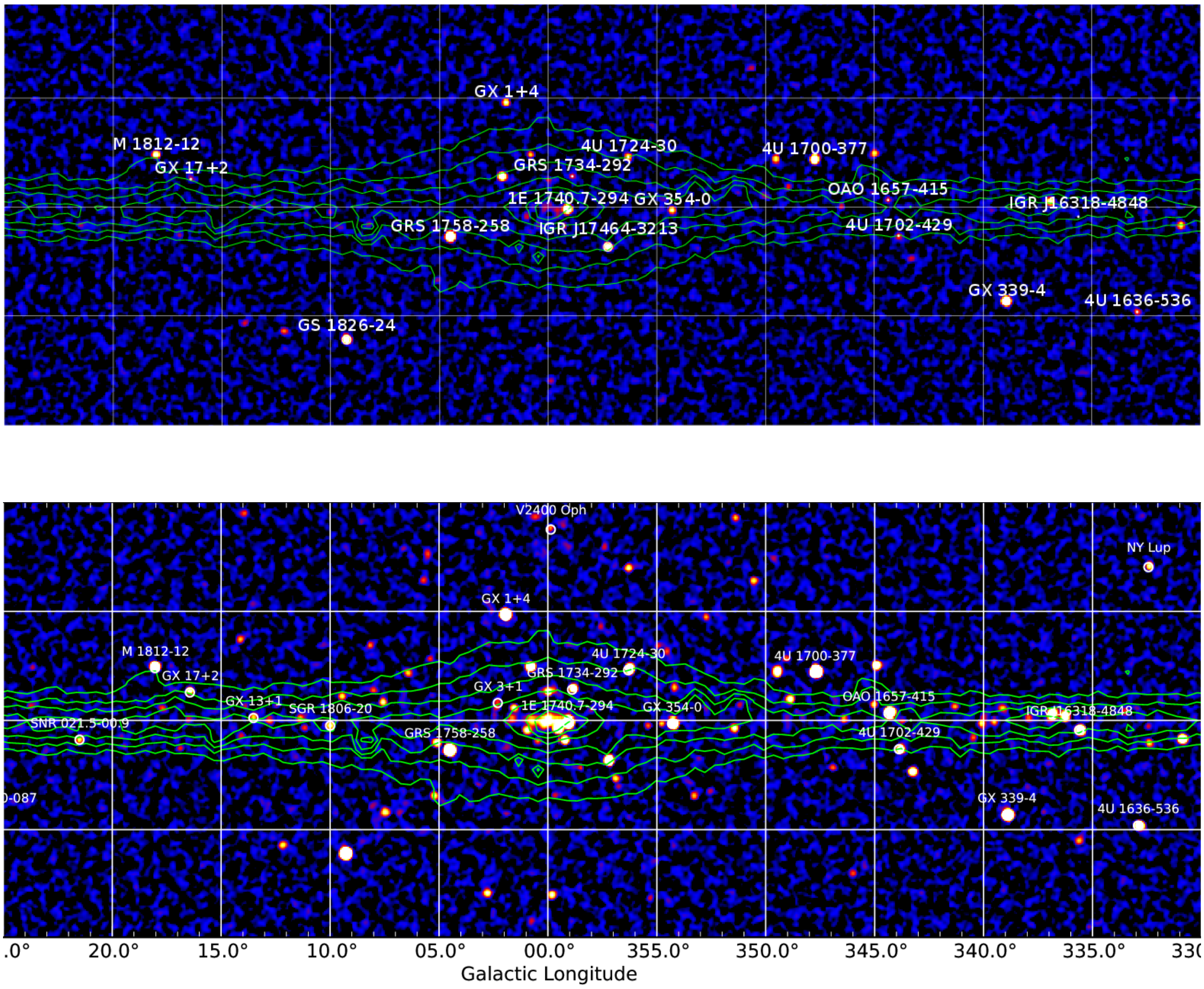

Figure 2 – INTEGRAL/IBIS γ-ray ($100-150$ keV, upper panel) and hard X-ray ($17-60$ keV, bottom panel) maps of the Galactic bulge and (partially) disk. The most brightest sources are indicated. The green contours are isophotes of the 4.9 micron surface brightness of the Galaxy (COBE/DIRBE) revealing its bulge/disk structure.

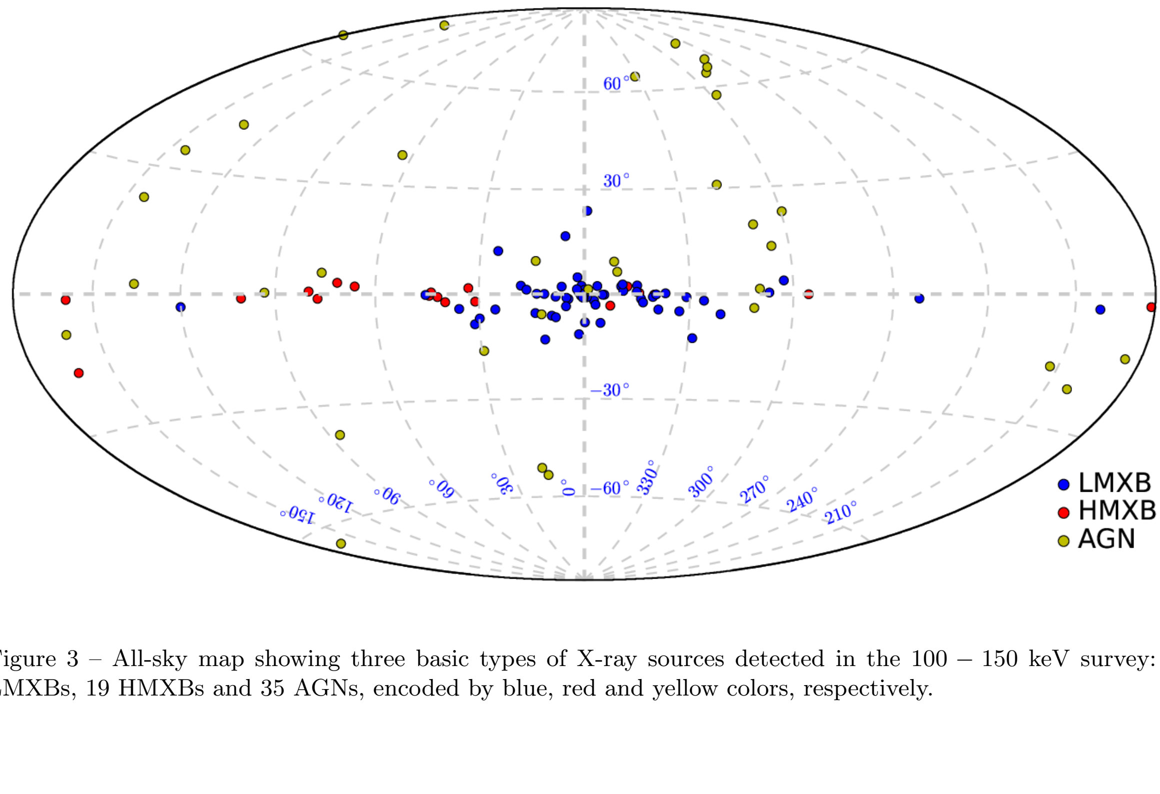

Figure 3 – All-sky map showing three basic types of X-ray sources detected in the $100-150$ keV survey: 64 LMXBs, 19 HMXBs and 35 AGNs, encoded by blue, red and yellow colors, respectively.

Table 1: Catalogue of hard X-ray sources detected by *INTEGRAL* in the 150 − 300 keV band

No.	Name	Ra deg	Dec deg	$Flux_{150-300\ keV}$ erg $cm^{-2}s^{-1}$	Type
1	Crab	83.63	22.02	657.7 ± 1.2	PSR/PWN
2	NGC 2110	88.05	-7.46	13.7 ± 2.3 (5.9)	AGN
3	NGC 4151	182.63	39.41	17.9 ± 1.5	AGN
4	NGC 4388	186.45	12.66	6.3 ± 1.1 (5.9)	AGN
5	3C273	187.28	2.05	15.7 ± 1.0	AGN
6	Cen A	201.36	-43.02	47.0 ± 2.0	AGN
7	PSR B1509-58	228.48	-59.14	13.3 ± 1.5 (8.8)	PSR
8	XTE J1550-564	237.76	-56.46	14.0 ± 1.3	LMXB
9	4U 1630-47	248.52	-47.39	7.7 ± 0.9 (8.4)	LMXB
10	GX 339-4	255.71	-48.79	33.0 ± 0.9	LMXB
11	4U 1700-377	255.98	-37.84	10.6 ± 0.8	HMXB
12	IGR J17091-3624	257.29	-36.41	5.3 ± 0.8 (6.5)	LMXB
13	GX 354-0	262.99	-33.83	4.7 ± 0.7 (6.6)	LMXB
14	1E 1740.7-294	265.98	-29.73	23.1 ± 0.7	LMXB
15	Swift J174510.8-262411	266.30	-26.40	14.3 ± 0.8	LMXB
16	IGR J17464-3213	266.56	-32.23	10.0 ± 0.7	LMXB
17	SWIFT J1753.5-0127	268.37	-1.45	63.4 ± 1.5	LMXB
18	GRS 1758-258	270.30	-25.74	40.8 ± 0.7	LMXB
19	M 1812-12	273.78	-12.09	8.6 ± 1.0 (8.7)	LMXB
20	GS 1826-24	277.37	-23.80	12.5 ± 0.9	LMXB
21	GRS 1915+105	288.80	10.95	32.9 ± 1.0	LMXB
22	Cyg X-1	299.59	35.20	416.1 ± 1.1	HMXB
23	Cygnus A	299.87	40.74	7.2 ± 1.2 (6.2)	AGN
24	Cyg X-3	308.11	40.96	11.2 ± 1.1	HMXB
25	3C 454.3	343.49	16.15	15.9 ± 2.2 (7.2)	AGN

provided by faint sources (i.e. sources with low level of mass accretion rate). It means that their spectra are hard (harder than those of HMXBs) and thus we should expect that the ratio of number of LMXBs in 17-60 keV and 100-150 keV should be smaller than that for HMXBs.

Another class of galactic sources detected above 100 keV are rotation-powered young X-ray pulsars. They typically demonstrate hard power-law spectra with photon indexes of 1.5-2.0 at energies above 20 keV. It is widely accepted that their hard X-ray emission is dominated by the extended pulsar wind nebula (PWN) emitting synchrotron photons and Compton upscattering of softer photons on relativistic electrons. The *INTEGRAL* 100 − 150 keV survey includes 13 PSRs, one of which – PSR 0540-69 – the pulsar and supernova remnant in the Large Magellanic Cloud. Thus PSRs becomes a second dominant class of galactic hard X-ray sources (after LMXBs) above 100 keV. This clearly demonstrates that a non-thermal emission mechanisms start to play an important role at these energies.

Finally, we also investigated a sky map in the harder energy band 150−300 keV and found 25 significantly detected sources of a different nature[25]: 7 AGNs (one Seyfert type 1, 4 Seyfert type 2 galaxies, 2 blazars at high redshifts), 13 LMXBs, 3 HMXBs (Cyg X-1, Cyg X-3 and 4U 1700-377), and 2 rotation-powered pulsars (PSRs: Crab and PSR B1509-58). Among LMXBs and HMXBs we identified 12 black hole candidates, the neutron star binary system 4U 1700-377 and three X-ray bursters (GX 354-0, M 1812-12 and GS 1826-24). All these sources have been detected in the 100 − 150 keV energy band as well and therefore present in the catalogue. Table 1 lists all the sources detected in the 150 − 300 keV band with corresponding fluxes and source types.

4 The Galactic survey in ^{44}Ti radioactive lines

An understanding of mechanisms of supernova (SN) explosions is the keystone of many branches of the modern astrophysics, primarily the chemical and physical evolution of the Universe. However, there is no way to observe directly physical processes during the first stages of the

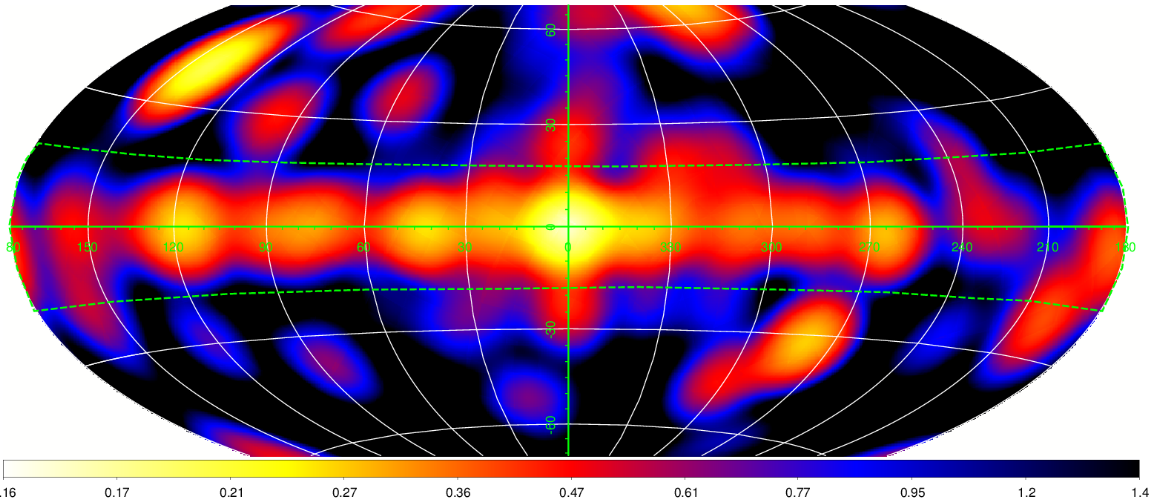

Figure 4 – The map shows 1σ flux sensitivity in the 64.6–82.2 keV energy band ranging from 0.16 to 1.4 mCrab. Two dashed green lines comprise geometrical area of the survey ($|b| < 17.5°$).

explosion due to a very high opacity. The most promising solution of this problem is to measure the amount of radioactive elements synthesised during the SN explosion and based on that to verify the existing models [40].

One of the best candidate to such an explosion tracer is radioactive isotope of titanium-44 (^{44}Ti). It has a lifetime of about 85 years [41], that is long enough to guarantee the substantial fraction of the synthesised titanium to remain active after the envelope become transparent. Such a lifetime permits to associate the measured flux with a specific supernova remnant (SNR), thus increasing chances to detect young (few hundred years) SNR. From the observational point of view the signatures of titanium decay can be observed in broad range of energies – it produces on average ∼0.17, ∼0.88, ∼0.95 and ∼1 photons per one decay in the lines at energies 4.1, 67.9, 78.4, and 1157 keV, respectively. The latter three lines are well inside of the working energy range of the *INTEGRAL* observatory.

Until recently the SNR Cas A was the only confidently detected source of ^{44}Ti emission [42]. Thanks to a significant exposure collected by the IBIS/*INTEGRAL* telescope, the emission in ^{44}Ti lines was discovered from SNR 1987A[10]. Based on the deep *INTEGRAL* observations of the GP we performed a systematic survey for ^{44}Ti sources to search for new and previously unknown SNRs, serendipitous detections of which could provide us information about SN activity in the Milky Way within the last few centuries. Note, that last similar survey in the MeV domain was conducted by the COMPTEL experiment more than twenty years ago[43].

The new survey can improve our knowledge about a SN activity by the model independent and systematic-free imaging at better angular resolution ($12'$) in comparison to COMPTEL(∼1°). Moreover the peak sensitivity of our survey reached an unprecedented level of 4.8×10^{-6} ph cm^{-2} s^{-1} (3σ) that improves the sensitivity of the survey done by *CGRO*/COMPTEL by a factor of ∼ 5[44]. Strictly speaking the source detection sensitivity of our ^{44}Ti survey is not completely uniform over the Galactic Plane (Fig. 4) and achieved in the region of the Galactic Center. To illustrate the improvement of sensitivity in the current survey in comparison to the COMPTEL one, we constructed the age-distance diagram for several known SNRs assuming a ^{44}Ti yield of $Y_{44} = 1 \times 10^{-4}$ M$_\odot$ (Fig. 5).

Even with the improved sensitivity we did not detect any other sources of titanium emission in the Galactic Plane, excepting Cas A, at significance level higher than 5σ confirming previous claims of the rarity of such ^{44}Ti-producing SNRs. The Cas A shows significant detection with a flux $F_{68} = (1.3 \pm 0.3) \times 10^{-5}$ ph cm^{-2} s^{-1} in agreement with most of previously published measurements. This flux corresponds to $(1.1 \pm 0.3) \times 10^{-4}$ M$_\odot$ of ^{44}Ti that is at the upper

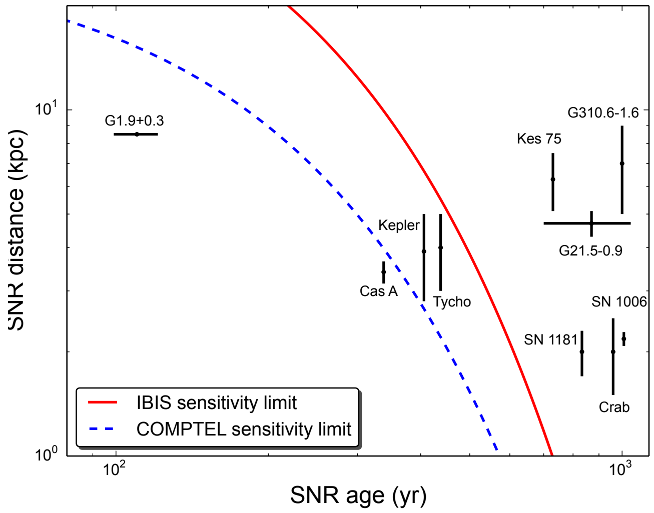

Figure 5 – Age-distance diagram showing the capability of ^{44}Ti emission detection using the COMPTEL and *INTEGRAL*/IBIS surveys. The red solid line and blue dashed line show 1σ peak sensitivity reached in the *INTEGRAL*/IBIS survey ($\sim 1.7 \times 10^{-6}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$) and COMPTEL survey ($9 \times 10^{-6}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$), correspondingly. A ^{44}Ti lifetime of 85.0 yr and a yield of 1×10^{-4} $M_\odot$ were assumed.

boundary of the theoretical predictions for core-collapse SNe [45].

We put also strong upper limits on the detection of ^{44}Ti emission for all Galactic SNRs reported in the catalog by [46], including other historical SNRs: Vela Jr, Tycho (SN1572), Per OB2 and G1.9+0.3. The obtained upper limits can be used to estimate the exposure times needed to detect ^{44}Ti emission from any known SNR using existing and prospective X- and gamma-ray telescopes. Moreover, more or less homogeneous coverage of the Galactic Plane with *INTEGRAL* (see Fig. 4) permits to estimate an upper limit on the titanium emission from any potentially interesting place in the Galaxy: starburst regions, high-absorption regions such as the spiral arm tangents, and to revisit the issue about the main sources of Galactic ^{44}Ca[44].

5 Deep surveys of extragalactic fields

Deep X-ray surveys of extragalactic fields with focusing X-ray telescopes[47] are essential for studying the evolution of active galactic nuclei (AGN) and physical processes powering their activity, but have a number of limitations. In particular, their small covered areas prevent finding a sufficient number of bright objects, whereas the soft X-ray energy band ($E < 10$ keV) used in most surveys introduces a strong bias against obscured (i.e. those with substantial intrinsic absorption) AGN. These drawbacks was partially overcame with the IBIS/*INTEGRAL* telescope, which was able to achieve a high sensitivity in extragalactic fields. In general, the IBIS sensitivity grows nearly proportionally to the square root of exposure showing no significant contribution of systematic noise and allowing to find sources at the tenths-of-mCrab flux level with a low number of false detections. In combination with the IBIS large field of view, this opens up a possibility to collect a significantly large sample of hard X-ray emitting AGN with fluxes down to a few 10^{-12} $\mathrm{erg\,s^{-1}}$ $\mathrm{cm^{-2}}$.

As it can be understand from previous Sections the observational program of *INTEGRAL* has been mainly dedicated to Galactic source studies, whereas the high Galactic latitude sky has been observed less intensively and very inhomogeneously. Nevertheless, on-going extragalactic surveys carried out with IBIS expand significantly our knowledge about populations of extragalactic hard X-ray sources [2,48,49,4,5].

The deepest extragalactic fields, observed with *INTEGRAL*, are regions around M81 (exposure of 9.7 Ms), Large Magellanic Cloud (6.8 Ms) and 3C 273/Coma (9.3 Ms). Such exposures allowed to reach a 4σ peak sensitivity of 0.18 mCrab (2.6×10^{-12} erg s^{-1} cm^{-2}) in the 17-60 keV energy band in the current survey[5] and to detect in total 147 sources in all three fields, including 37 sources observed in hard X-rays for the first time.

Fig. 6 shows the mosaic images along with exposure contours for the three studied fields.

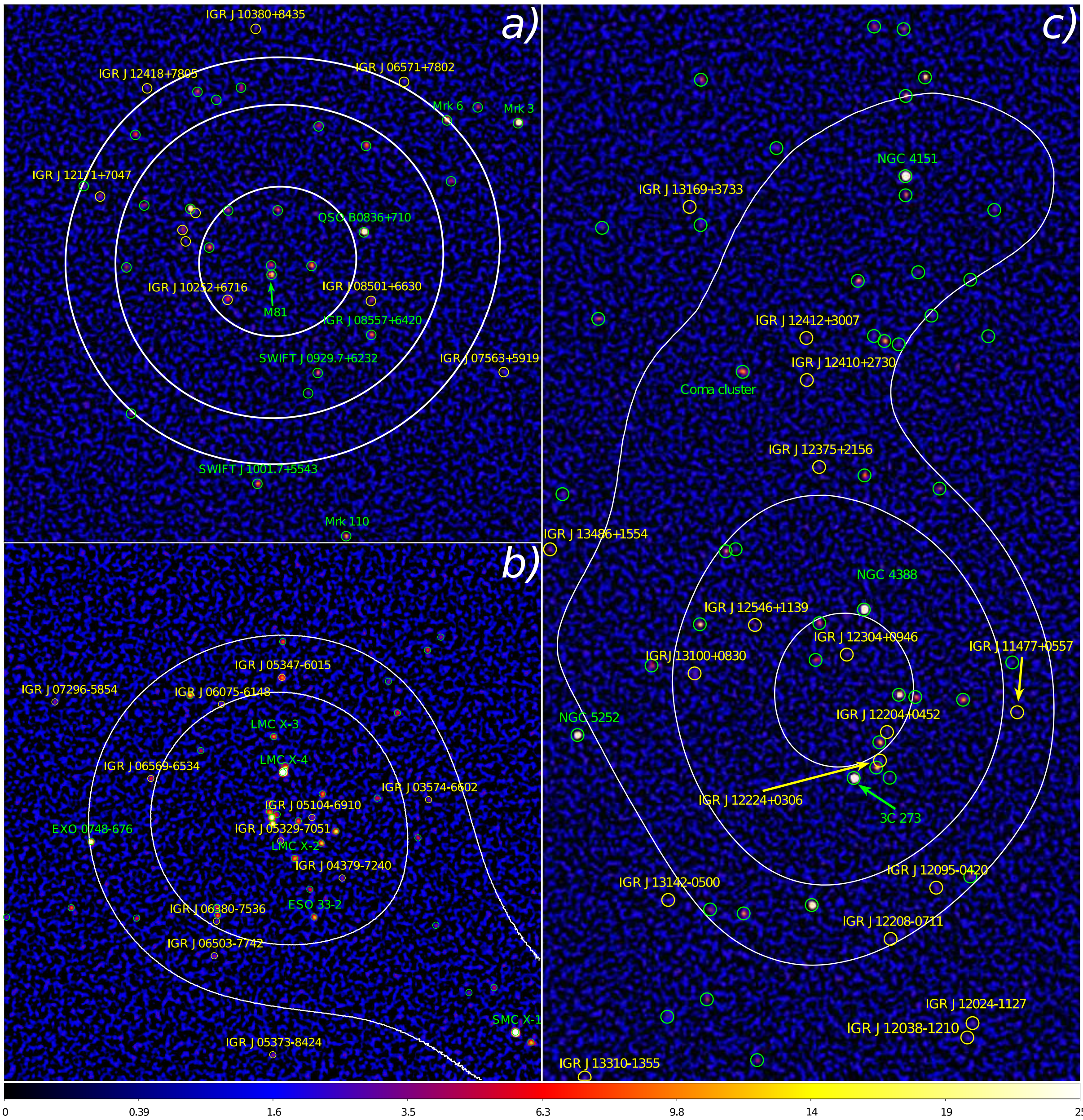

Figure 6 – Hard X-ray maps of the M81, LMC and 3C 273/Coma fields. Yellow circles denote new sources and green circles already known ones. Some of the brightest sources are marked for easy navigation. *a) M81 field.* The peak exposure 9.7 Ms, contours show exposures of 2, 4 and 8 Ms. *b) LMC field.* The peak exposure 6.8 Ms, contours drawn at 2 and 4 Ms. *c) 3C 273/Coma field.* The peak exposure 9.3 Ms, contours drawn at 2, 4 and 8 Ms.

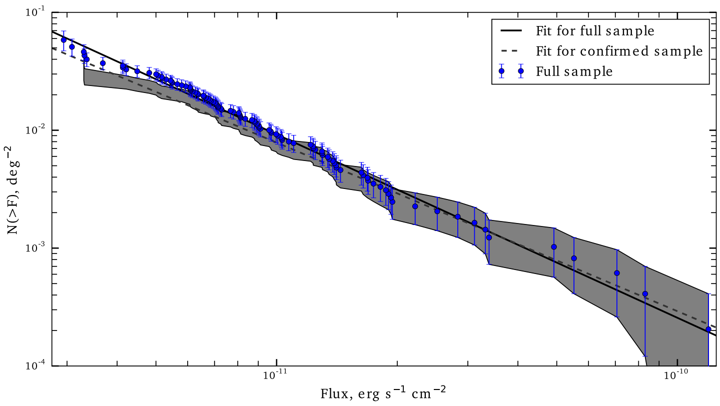

Figure 7 – Number–flux (17–60 keV) relation for AGN. Blue points represent the full AGN sample, while the black solid line shows the corresponding best-fitting power law model. The shaded area represents the 1σ error region for the confirmed AGN sample composed of 80 non-blazar AGN. The power-law fit for this sample is shown by the gray dashed line.

It is important to note that the M81 and 3C 273/Coma fields do not show any systematic noise, which suggests that the IBIS/*INTEGRAL* telescope can be used to perform even deeper extragalactic surveys in the future.

The survey is dominated by extragalactic sources, mostly by active galactic nuclei (AGN). The sample of identified sources contains 98 AGN (including 64 Seyfert galaxies, 7 LINERs, 3 XBONGs, 16 blazars and 8 AGN of unclear optical class), two galaxy clusters (Coma and Abell 3266), 17 objects located in the Large and Small Magellanic Clouds (13 high- and 2 low-mass X-ray binaries and 2 pulsars), three Galactic cataclysmic variables, one ultraluminous X-ray source (ULX, M82 X-1) and one blended source (SWIFT J1105.7+5854). The nature of 25 sources remains unknown, so that the surveys identification is currently complete at 83%.

The cumulative $\log N$–$\log S$ distribution of non-blazar AGN (Fig. 7) is consistent with a power law down to fluxes $\simeq 3\times10^{-12}$ erg s^{-1} cm^{-2}, which is deeper by a factor of two compared to the previous (all-sky) measurement[50]. The AGN number counts for the M81 and 3C 273/Coma fields are consistent with each other, while the LMC field demonstrates a steeper number-flux distribution (2σ deviation from the expected $-3/2$ slope) and a lack of bright AGN with flux higher than 2×10^{-11} erg s^{-1} cm^{-2}.

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