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Recent results from the INTEGRAL hard X-ray surveys

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Abstract. The INTEGRAL observatory has been successfully operating in orbit since 2003. On the basis of the data obtained, many studies have already been done on the study of the properties of X-ray sources in our Galaxy and beyond. Using the dataset of the INTEGRAL, accumulated over 14 years, we managed to build the most ever sensitive X-ray maps of the Galactic plane, which allows us to detect either nearby low-luminosity sources or bright objects in more distant parts of the Galaxy. In this short review we summarize follow-up observations of the newly detected hard X-ray sources and provide hard X-ray maps of the Galactic center region not included in the original paper.

Key words. Surveys – Catalogs – X-rays: general – Galaxy: center

1. Introduction

Since the beginning of X-ray astronomy, when the first X-ray satellite was launched (*Uhuru*, Giacconi et al. 1971), a large number of X-ray surveys has been made in both the soft and hard X-ray energy bands, providing systematic approach for studying astrophysical objects often triggering extensive follow-up observational campaigns at different wavelengths. The catalog of X-ray sources observed with the Uhuru X-ray observatory in the $2 - 20$ keV energy band included 339 objects of known source types – binary stellar systems, supernova remnants, Seyfert galaxies and clusters of galaxies (Forman et al. 1978). Later, the X-ray and gamma-ray instrument HEAO-A4 onboard the HEAO 1 satellite, conducted all-sky survey in the $13 - 180$ keV range providing catalog of 77 hard X-ray sources (Levine et al. 1984).

The majority of soft X-ray surveys of the last decades have been condacted in standard X-ray band $2 - 10$ keV with grazing incidence X-ray telescopes. These surveys are characterised by a high sensitivity and angular resolution, however limited sky coverage area. Soft X-ray surveys also suffers from detection bias against photoelectric X-ray absorption, when even luminous X-ray emitters can avoid detection due to strong intrinsic or interstellar absorption.

Compared to the soft X-ray band, hard X-ray surveys ($E > 10$ keV) are less affected by the detection bias mentioned above, because energetic X-ray photons can penetrate large columns of gas and dust without interaction even in Compton-thick environment ($N_H > 10^{24}$ cm^{-2}).

Currently, two main orbital X-ray telescopes survey the entire sky in hard X-rays – the Burst Alert Telescope (BAT, Barthelmy et al. 2005) onboard Neil Gehrels Swift Observatory (Gehrels et al. 2004) and the

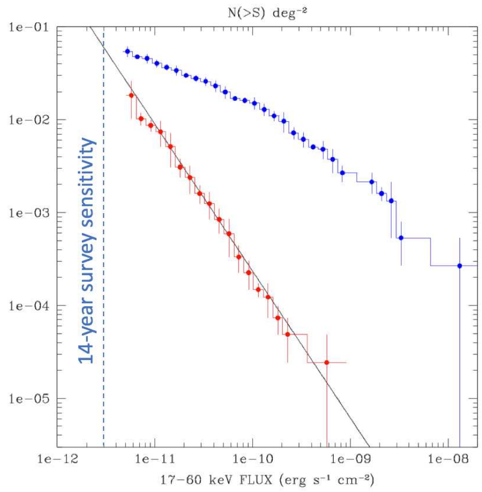

Fig. 1. Cumulative log$N$−log$S$ distribution in the energy band 17−60keV of all sources in the Galactic plane region ($|b| < 5°$, blue histogram) in comparison with that of AGNs at high latitudes ($|b| < 5°$, red histogram) taken from INTEGRAL all-sky survey based on four years of observations with the IBIS telescope (Krivonos et al. 2007). The solid black line represents the best-fitting power law to the number-flux relation of AGNs. The vertical dashed line shows current sensitivity of the INTEGRAL survey in the Galactic plane (Krivonos et al. 2017).

IBIS telescope (Ubertini et al. 2003) onboard INTEGRAL observatory (Winkler et al. 2003). Both telescopes are designed as coded mask imagers working in similar energy bands: 15 – 150 keV (BAT) and 15 – 1000 keV (IBIS – ISGRI detector layer, Lebrun et al. 2003). The *Swift*/BAT survey provides very homogeneous sky coverage with a current maximum sensitivity of 8.4×10^{-11} erg s^{-1} cm^{-2} at 90% all-sky coverage (Oh, et al. 2018). In contrast to *Swift*, the INTEGRAL observatory provides an all-sky survey with exposure more concentrated in the Galactic plane, having a typical limiting flux of less than 1.3×10^{-11} erg s^{-1} cm^{-2} in 17 – 60 keV at 90% coverage of the Galactic plane ($|b| < 17.5°$, Krivonos et al. 2017).

2. INTEGRAL Galactic plane surveys

The on-going INTEGRAL observations of the Galactic plane allows us to continiously gain exposure available for the hard X-ray survey. Thanks to the improved sky reconstruction method for the IBIS telescope (Krivonos et al. 2010), we can significantly supress systematic noise seen on the sky maps, which makes sensitivity limited by photon statistics only. As a result, low detection threshold of $4 - 5\sigma$ allows us to register weak X-ray sources without a large number of false detections. This is confirmed by a high value of the survey completeness, e.g. Krivonos et al. (2012) report on ∼ 92% completeness which is improving with time thanks to intensive follow-up observations (Karasev et al. 2012; Landi, Bassani, Bazzano, Fiocchi & Bird 2013; Masetti et al. 2013; Lutovinov et al. 2013; Revnivtsev et al. 2013; Bassani et al. 2014; Tomsick et al. 2015, 2016; Clavel et al. 2016; Rahoui et al. 2017; Fornasini et al. 2017; Potter & Buckley 2018) and now reaches ∼ 95%.

As seen from the catalogs of identified sources, the fraction of extragalactic obgects within the Galactic plane grows with the increased sensitivity. This is quite expected due to the fact that active galactic nuclei (AGN) number-flux relation has steeper slope compared to the Galactic population. Fig. 1 shows cumulative extragalactic and Galactic log$N$-log$S$ distributions from early four-year INTEGRAL survey (Krivonos et al. 2007) constructed within $|b| < 5°$. As seen from the figure, the extragalactic surface number density should exceed the Galactic log$N$-log$S$ at sensitivity of the current 14-year INTEGRAL survey (Krivonos et al. 2017). The work on the Galactic 14-year survey is still in progress, however, many follow-up studies of the unidentified INTEGRAL sources show that newly detected sources are mostly AGNs and cataclysmic variables (CVs) (e.g., Tomsick et al. 2015, 2016; Karasev et al. 2018). Latter, is an emerging population of numerous Galactic low-luminosity binary systems in which a white dwarf accretes matter from a late-type main sequence companion via Roche-lobe overflow (Mukai 2017).

The improved 14-year sensitivity of the INTEGRAL survey allows us to extend the horizon of the accessible volume of the Galaxy in hard X-rays. The face-on sketch view of

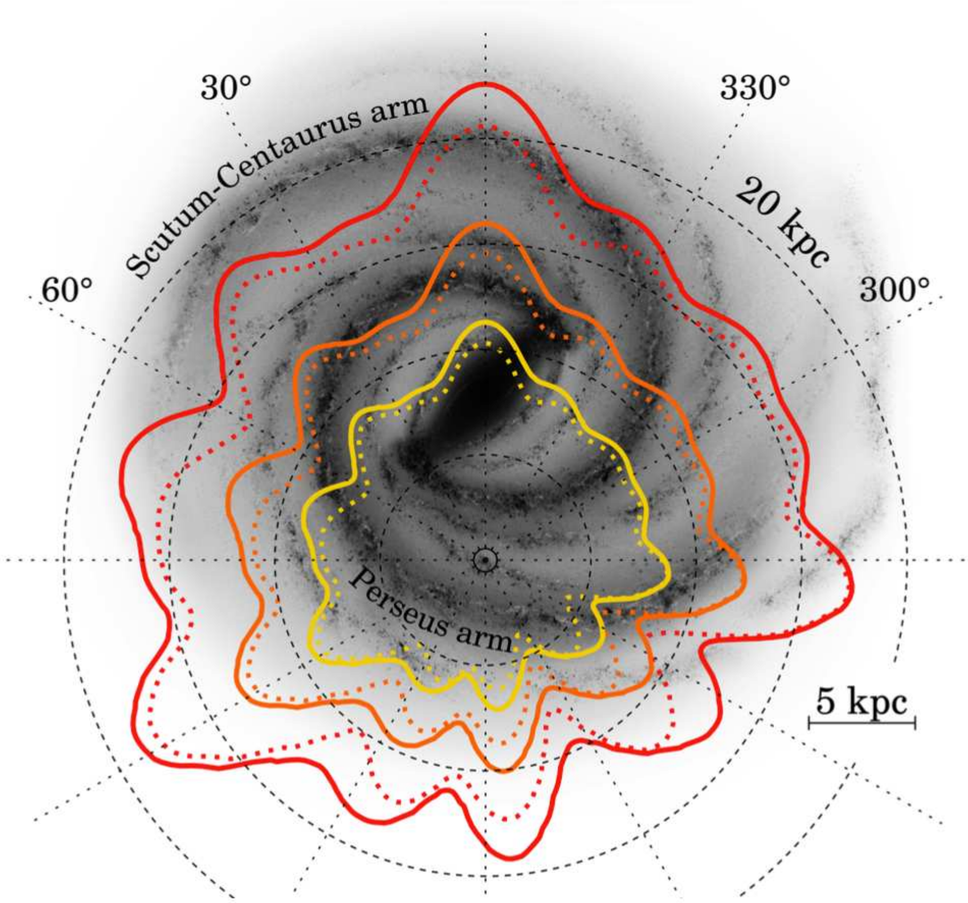

Fig. 2. Face-on view sketch of the Milky Way (Churchwell et al. 2009) shown along with the distance at which an X-ray source of a given luminosity $L_{\rm HX}$ (or more) can be detected according to the 17 – 60 keV sensitivity of the 14-year INTEGRAL survey (solid lines, Krivonos et al. 2017), compared to the 9-year survey (dotted lines, Krivonos et al. 2012). Red, orange and yellow contours correspond to $L_{\rm HX} = 2\times10^{35}$, 10^{35} and 5×10^{34} erg s^{-1}, respectively.

the Milky Way shown in Fig. 2 illustrates the distance out to which INTEGRAL can detect sources of given luminosity $(0.5-2)\times10^{35}$ erg s^{-1} in comparison with the previous 9-year survey. We can now probe deeper into the Galactic center for weak sources, and cover most of the Galactic stellar mass for bright distant objects located at the far end of the Galaxy.

The peak sensitivity of the survey is 2.2×10^{-12} erg s^{-1} cm^{-2} (~0.15 mCrab, 17−60 keV) at a 4.7σ detection level. The survey covers 90% of the geometrical area of the extended Galactic plane (12680 degrees) down to the flux limit of 1.3×10^{-11} erg s^{-1} cm^{-2} (~0.93 mCrab) and 10% of the total area down to the flux limit of 3.8×10^{-12} erg s^{-1} cm^{-2} (~0.26 mCrab).

The catalogue of 72 hard X-ray source candidates is presented in the original paper (Krivonos et al. 2017). Fig. 3 shows 17 – 60 keV sky map of the central part of the Galaxy with positions of the detected sources located in this region.

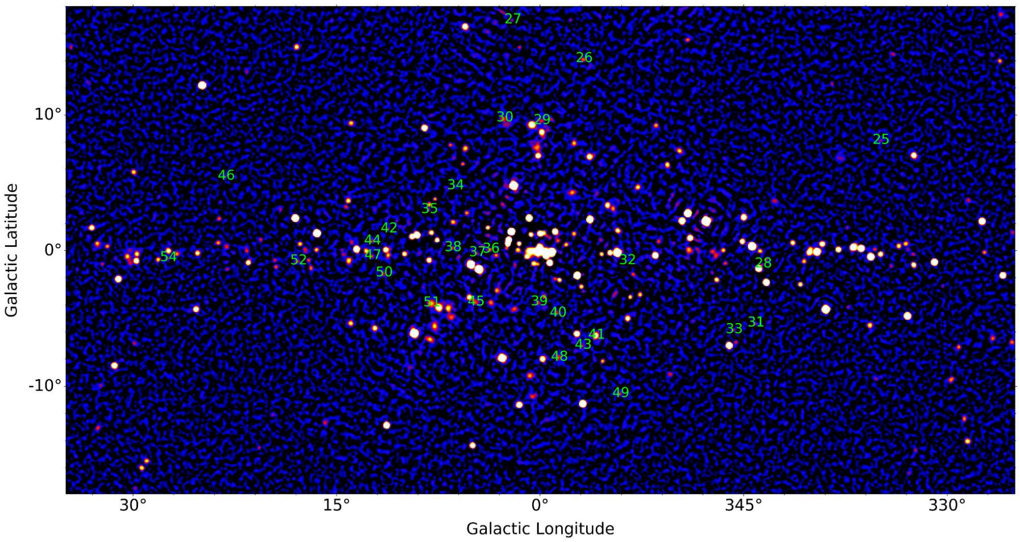

Fig. 3. INTEGRAL/IBIS/ISGRI 17 − 60 keV sky map of the central Galactic plane region. The total exposure is about 40 Ms in the Galactic center region. The image is shown in terms of S/N pixel values with the color map ranging between 0 and 25. Red, yellow and white colors correspond to S/N pixel values of $4-9\sigma$, $12-20\sigma$ and $> 20\sigma$, respectively. The selected color scheme is used to emphasize sky background variations (black to blue colors). Green labels mark position of 72 new hard X-ray sources detected in 14-year Galactic plane survey by Krivonos et al. (2017) with the corresponding source ID number.

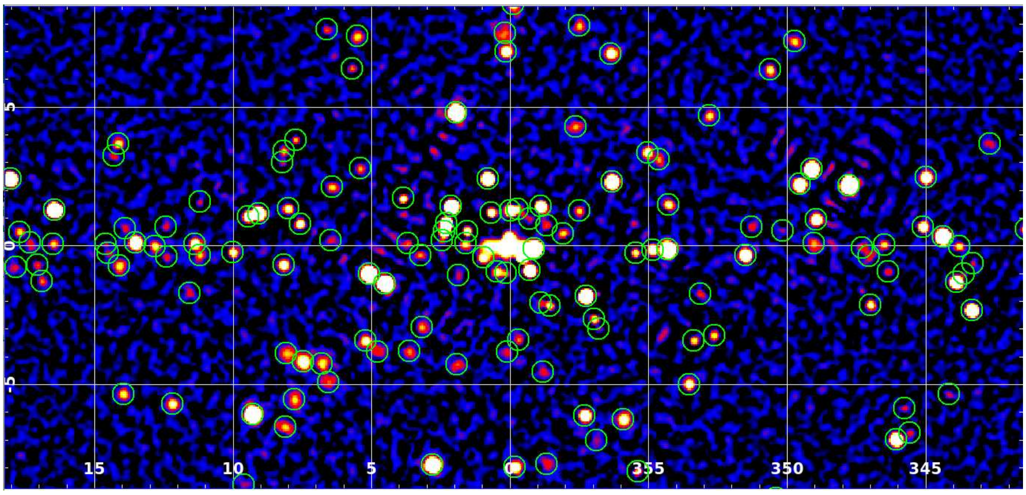

Fig. 4. Zoom-in sky map of the Galactic center region shown in Fig. 3. Green circles mark position of known hard X-ray sources.

3. Future INTEGRAL surveys

Since the launch in 2002, the INTEGRAL observatory has been continiously demonstrating a great success in surveing the hard X-ray sky, including taking long-term high-quality snapshot of the whole Milky-Way. This progress is possible thanks to unique properties of the

IBIS telescope, which is well-suited to carrying out imaging surveys in hard X-rays: a wide field of view of $28^\circ \times 28^\circ$ and moderate angular resolution of $12'$. The localization accuracy of $< 2-3'$ is sufficiently good for searches of soft X-ray and optical counterparts and subsequent optical identification of newly discovered hard X-ray sources.

Hopefully, INTEGRAL will continue to make observations for the next years, and new data acquired will improve sensitivity of the on-going hard X-ray survey. The coded-mask design of the IBIS telescope is known to have sky reconstruction issues, which introduce systematic noise in the images (e.g. not well known model of the mask). Krivonos et al. (2010) demonstrated that this noise can be effectively suppressed, which opens a path for very deep future surveys limited by photon statistics only.

The future INTEGRAL surveys will not be strongly limited by source confusion, even in the crowded field of the Galactic center. Fig. 4 shows zoom-in map of the Galactic center (Fig. 3). The density of sources in the Galactic bulge region is so high, that the total number of sources in a 40 Ms deep field is about 100 within the IBIS field of view, which is at the limit for the coded mask telescope, however, still feasible for observations. Less crowded Galactic spiral arm regions and extragalactic deep fields M81, LMC and 3C 273/Coma (Mereminskiy et al. 2016) are mostly free from source confusion effects and have enough capacity for the future data.

4. Conclusions

Systematic observations of the Galactic plane with INTEGRAL are continiously improving the sensitivity of the hard X-ray survey, which helps to extend our knowledge of the Galactic and extragalactic X-ray source populations. Using the dataset, accumulated over 14 years with IBIS telscope, we managed to build the most ever sensitive X-ray maps of the Galactic plane, which allows us to detect either nearby low-luminosity sources or bright objects in more distant parts of the Galaxy.

The obtained X-ray sky maps are mostly limited by photon statistics and not strongly affected by the systematic noise and source confusion effects, which allows to add new observational data for the future INTEGRAL surveys.

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