SRG/ART-XC all-sky X-ray survey: Catalog of sources detected during the first five surveys

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ABSTRACT

We present an updated catalog of sources detected by the Mikhail Pavlinsky ART-XC telescope aboard the Spektrum-Roentgen-Gamma SRG observatory during its all-sky survey. It is based on the data of the first four and the partially completed fifth scans of the sky (ARTSS1-5). The catalog comprises 1545 sources detected in the 4–12 keV energy band. The achieved sensitivity ranges between $\sim 4 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ near the ecliptic plane and $\sim 7 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ near the ecliptic poles, which is a $\sim 30$–$50\%$ improvement over the previous version of the catalog based on the first two all-sky scans (ARTSS12). There are $\sim 130$ objects, excluding the expected contribution of spurious detections, that were not known as X-ray sources before the SRG/ART-XC all-sky survey. We provide information, partly based on our ongoing follow-up optical spectroscopy program, on the identification and classification of the majority of the ARTSS1-5 sources (1463), of which 173 are tentative at the moment. The majority of the classified objects (964) are extragalactic, a small fraction (30) are located in the Local Group of galaxies, and 469 are Galactic. The dominant classes of objects in the catalog are active galactic nuclei (911) and cataclysmic variables (192).

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

1. Introduction

The Spektrum-Roentgen-Gamma (SRG) orbital observatory\textsuperscript{1} (Sunyaev et al. 2021) was designed to survey the entire sky in X-rays with better sensitivity, angular resolution, and energy coverage compared to its predecessors, such as Uhuru (1970–1973), High Energy Astronomy Observatory 1 (HEAO-1; 1977–1979), and Röntgensatellit (ROSAT; 1990–1991). The spacecraft was launched on July 13, 2019, from the Baikonur Cosmodrome to a halo orbit near the L2 point of the Sun–Earth system, from where it started scanning the sky on December 12, 2019. The observatory is equipped with two grazing incidence telescopes: the extended ROentgen Survey with an Imaging Telescope Array (eROSITA; Predehl et al. 2021) and the Mikhail Pavlinsky Astronomical Roentgen Telescope–X-ray Concentrator (ART-XC; Pavlinsky et al. 2021), which operate in overlapping energy bands of 0.2–8 keV and 4–30 keV, respectively. ART-XC is a key component of the SRG mission because it provides a better sensitivity than eROSITA at energies higher than 6 keV, which is particularly important for the systematic search for and exploration of absorbed X-ray sources. Together, the eROSITA and ART-XC all-sky surveys occupy a unique position in the parameter space of X-ray surveys performed thus far (see a recent review by Brandt & Yang 2022 and in particular Fig. 2 in that paper).

The SRG all-sky survey consists of repeat full scans of the sky, each lasting six months. The original plan was to conduct eight such scans. However, on February 26, 2022, the eROSITA telescope was switched to sleeping mode, and on March 7, 2022, the all-sky survey was interrupted in favor of a deep survey of the Galactic plane region with the ART-XC telescope (the Galactic plane and Galactic center regions had also been observed by SRG during the Calibration and Performance Verification phase in 2019, and the resulting catalogs of sources detected by ART-XC are presented by Karasev et al. 2023 and Semena et al. 2024a). This complementary survey was completed in October 2023, after which ART-XC resumed the all-sky survey. Hence, by early March 2022, the entire sky had been scanned by SRG four times, and about 40% of the sky had also been covered for a fifth time.

After completion of the first two all-sky scans (December 2019–December 2020), we compiled a catalog of sources detected by ART-XC in the 4–12 keV energy band (ARTSS12; Karasev et al. 2023 and Semena et al. 2024a). This complementary survey was completed in October 2023, after which ART-XC resumed the all-sky survey. Hence, by early March 2022, the entire sky had been scanned by SRG four times, and about 40% of the sky had also been covered for a fifth time.

1 The catalog is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/ and at http://srg.cosmos.ru.
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Pavlinsky et al. (2022)\(^2\). It comprised 867 X-ray sources, of which nearly 10% are expected to be spurious due to the design of the catalog.

Here we present an updated version of this catalog, which is based on the entire dataset accumulated by SRG/ART-XC during the first ~ 4.4 all-sky surveys. The ART-XC survey significantly exceeds previous all-sky X-ray surveys carried out in similar energy bands in terms of the combination of angular resolution, sensitivity, and uniformity. Therefore, the presented catalog can be a valuable new source of information for studies of Galactic and extragalactic X-ray source populations.

2. Data analysis

During the all-sky survey, the optical axes of the ART-XC and eROSITA telescopes are rotating with a period of 4 hours around the spacecraft Z-axis, which is always pointed toward the Sun (this regime of observations is called "survey mode"). This provides full sky coverage every 6 months (see Sunyaev et al. 2021 for further details). The catalog of sources presented in this paper is based on the ART-XC data accumulated between December 12, 2019, and March 7, 2022, during the first four and the incomplete fifth all-sky surveys, hereafter referred to as ART-XC sky surveys 1–5, or ARTSS1-5 for short.

We only used ART-XC data that were obtained in survey mode and disregarded data acquired in other (scanning or pointing) observational regimes. We also excised those time intervals when the calibration sources were inserted into the collimators or when high voltage was switched off on the detectors for depolarization (Pavlinsky et al. 2021). As the background of the ART-XC detector has proved to be exceptionally stable (Pavlinsky et al. 2021), virtually no cleaning of the ART-XC X-ray data was necessary for periods of high background. Only events detected in one or two upper detector strips and in one or two lower strips\(^3\) were selected. Events detected in a larger number of strips were not used in the analysis because such events are much more likely to be charged particles than photons.

In constructing the ARTSS1-5 X-ray map and catalog of sources, we adopted largely the same approach as previously for ARTSS12. Therefore, we refer the reader to Pavlinsky et al. (2022) for a detailed description of the different stages of the data analysis. However, we introduced several novel aspects and modifications. In the following subsections, we describe these improvements and briefly outline the components of the analysis that have remained unchanged with respect to the previous version.

2.1. Construction of maps

As in Pavlinsky et al. (2022), to construct all-sky maps, the ART-XC survey data were split into 4,700 overlapping 3.6 × 3.6 deg sky tiles in equatorial coordinates. For each tile, a set of standard maps were prepared, including an exposure map, particle and photon background maps, and sky images. All maps consist of 1024 × 1024 pixels of 12.66′′. The maps were prepared separately for each of the ART-XC surveys (1–5) and then combined. Exposure maps were corrected for vignetting.

Figure 1 shows the all-sky vignetting-corrected ARTSS1-5 exposure map in the 4–12 keV band. Due to the strategy of the SRG all-sky survey (Sunyaev et al. 2021), the accumulated exposure time is lowest near the ecliptic plane, where it varies between ~ 100 and ~ 300 s, and highest near the ecliptic poles, where it reaches ~ 38 ks.

2.2. Background estimation

The SRG/ART-XC data are essentially particle background-limited for sources near the detection threshold. As in Pavlinsky et al. (2022), the particle background was estimated using the data in a hard (30–70 keV) energy band, where the efficiency of the ART-XC X-ray optics vanishes. Because the particle background measured in the SRG orbit is extremely stable, apart from the gradual multiyear trend associated with the solar cycle activity and rare intense solar flares (see Fig. 2, based on data from the SRG Space Weather Monitor\(^4\)), this method of background estimation is highly robust.

The cosmic X-ray background provides a negligible contribution (~ 3.4% in the extragalactic sky) to the total background in the 4–12 keV energy band and, moreover, the cosmic X-ray background is highly uniform over the sky, except near the Galactic plane and within a few degrees of the Galactic center, where there is strong Galactic ridge X-ray emission (Revnivtsev et al. 2006). However, even in the innermost region of the Galaxy, the contribution of diffuse X-ray emission does not exceed 30% of the total background and thus has a small effect on the sensitivity to detection of point sources.

The residual background, associated with the uncertainty in particle background estimation and with large-scale X-ray structures in the sky (in particular, Galactic ridge X-ray emission), was assessed from the X-ray images themselves. To this end, the estimated particle background and the point spread function (PSF) models of all bright sources (with X-ray fluxes higher than ~ 10^{-10} erg s^{-1} cm^{-2}) are subtracted from a given X-ray image, and then all significant details at angular scales smaller than 10′ are eliminated from the X-ray image by wavelet decomposition (wvdecomp; Vikhlinin et al. 1998).

2.3. Detection of sources

We have introduced significant modifications to the source detection procedures compared to the ARTSS12 catalog (Pavlinsky et al. 2022). They are explained below. In constructing the ARTSS1-5 source catalog, we have focused on the detection of point sources, which constitute the vast majority of sources detected by ART-XC during the all-sky survey. We made no attempt to consistently detect extended sources, such as clusters of galaxies or supernova remnants. Nevertheless, many extended sources are still detected with our algorithms designed for the detection of point sources and are thus included in the resulting catalog. However, their estimated X-ray fluxes should be taken with caution.

2.3.1. Optimal matched filtering

In ART-XC X-ray images, the noise statistics is close to the Poisson distribution in most cases, and the PSF and vignetting of a CdTe crystal. The strip width corresponds to an angular resolution of 45′′ (Pavlinsky et al. 2021).
strongly vary across the field of view. We thus adopted the following optimal matched filter, which maximizes the probability of detecting real sources and minimizes the probability of spurious detections of statistical fluctuations:

$$\Phi(x) = \ln \frac{f(e)v(x,e)p_s(g)}{b(x,e)p_b(g)} P(x_0|x) + 1.$$  \hspace{1cm} (1)

Here, $x_0$ are the photon coordinates, $e$ is the photon energy, $f(e)$ is the expected spectral energy distribution of X-ray sources, $v(x,e)$ is the vignetting function, $b(x,e)$ is the spectral brightness of the background as a function of coordinates and energy, $p_s(g)$ and $p_b(g)$ are the probability distributions of observed event grades (see below) for source photons and background events, respectively, and $P(x_0|x)$ is the PSF value at $x_0$ under the assumption that the source is located at $x$.

The optimal matched filter given by Eq. (1) thus depends on the energy of every photon, expected source flux, and estimated background at every position in the image. It is applied to ART-XC data on an event-by-event basis. We derived this filter as a further development of the Poisson optimal matched filter described in previous works (Lynx X-ray Observatory Concept Study Report 2019; Ofek & Zackay 2018; Pavlinsky et al. 2022; Semena et al. 2024b).

The effective energy band of ART-XC in survey observational regime is 4–12 keV, with sensitivity dropping dramatically below 4 keV and above 12 keV. However, because of the finite spectral resolution (FWHM $\sim 1.3$ keV), a significant fraction of photons with intrinsic energies $\sim 4$ keV are registered as events with energies between 3 and 4 keV. For this reason, we used the energy range 3 to 12 keV for the detection of sources.

We adopted the same ART-XC vignetting function, PSF model, and source spectral shape (namely, a power law with photon index $\Gamma = 1.4$) as in our previous work (Pavlinsky et al. 2022). In particular, we refer the reader to Sect. 2.3 of Pavlinsky et al. (2022) as well as to Krivonos et al. (2017) and Pavlinsky et al. (2021) for further details on ART-XC PSF calibration and modeling. In particular, Figs. 12-14 in Pavlinsky et al. (2021) illustrate the behavior of the PSF at different offset angles and energies. We note that the current PSF model does not take into account the dependence on photon energy. This dependence is only significant in the distant wings of the PSF and is thus more important for offset pointing observations than for the all-sky survey. As regards the background spectrum, we adopted an actually measured spectrum, which was obtained by averaging over the whole set of all-sky survey data.
Each event registered by the ART-XC detectors is characterized by a “grade” of 0, 1, 2, 3, and so on, which refers to a particular detection pattern in the 3 x 3 pixel area where the event has been registered. The probability of being detected with a given grade is different for photons and charged particles. For example, an event detected in three pixels is most probably a charged particle. We determined the probability distributions $p_i(g)$ and $p_0(g)$ for X-ray sources and background events based on real data of the ART-XC all-sky survey.

To determine the flux-to-background ratio involved in the calculation of the optimal matched filter (Eq. (1)), we assumed that point sources have a diameter of 90′. This region contains approximately 95% of the photons from a source observed at an offset of less than 10′, whereas source photons detected from larger offsets are included in the background. The PSF large-angular-scale wings of very bright X-ray sources are also added to the background at this stage. We then adopted the source flux within the 90′ diameter aperture that corresponds to a Poisson detection significance of 4.5 for a given background level and substitute this flux for $f(e)$ in Eq. (1). The filter thus defined is close to optimal for detecting faint sources (with Poisson detection significance ≥ 4.5). For brighter sources, this filter is not optimal but such sources will also be detected with confidence with this filter (see section A.3.2 in Lynx X-ray Observatory Concept Study Report 2019). The filter is only weakly sensitive to the choice of a fiducial source flux.

Sources are detected in images that are obtained by convolution of raw photon images with the optimal filter given by Eq. (1) as peaks above some low threshold. Figure 3 shows an example of a raw image and the resulting “convolution image”; the latter clearly reveals the presence of an X-ray source. Specifically, we adopted a threshold that yielded a raw catalog of nearly 7000 sources, most of them presumably being spurious detections. At a later stage of the analysis (see below), we adopted a significantly higher threshold, specified in terms of maximum likelihood detection significance and determined by the desired (low) fraction of spurious detections, to construct the final catalog of sources.

In the case of multiple detections within 52′′ of each other, that is, within a distance smaller than the ART-XC PSF full width at half maximum (FWHM; Pavlinsky et al. 2021), only the highest peak in the convolution image is taken into account (with the corresponding coordinates and amplitude).

### 2.3.2. Maximum likelihood fitting

For all the sources detected with optimal matched filtering technique, we performed a maximum likelihood (ML) fit using the following logarithmic likelihood function (Cash 1979):

$$-2 \ln L = 2 \left( \sum_i \ln m_i - \int m \right),$$

where the sum is taken over all the detected events, and the source plus background model is taken as follows:

$$m(x, e, g) = \sum_j \left[ f(e)v(x, e)p_j(g)P(x_0|x) + b(x, e)p_0(g) \right].$$

Here, the sum is taken over closely located sources, namely within 5.2′′ of each other. To fit the model, we used the data within 2.6′ of each source; for closely located sources, these data regions were merged. We simultaneously fit the fluxes and coordinates of all sources in the given data region. With this likelihood function, the ART-XC PSF and vignetting models as well as information on the event grades are self-consistently taken into account. In reality, the vast majority of sources in the ARTSS-1-5 catalog were fitted separately. The data regions of two or more sources were merged only in a very small number of cases, because the typical flux threshold for the catalog is much higher than the effective confusion limit.

Sources were sorted by their X-ray fluxes. The brighter ones were fitted first, and their PSF model was then added to the background, including the PSF wings at large angular scales, up to ≈ 50′. The significance of source detection, that $S/N$, is calculated from the difference of the logarithmic likelihood function between the best-fit and zero fluxes. The flux and position errors are calculated from the appropriate variation in $-2 \ln L$, by varying the parameter of interest with all other parameters frozen at their best fit values.

### 2.3.3. Monte Carlo simulations

To specify thresholds for source detection in convolution images and validate the detection significance obtained by ML fitting, we carried out Monte Carlo simulations of empty fields. Only the particle background was simulated, because it strongly dominates the ART-XC background. Specifically, we computed the expected number of peaks of a given amplitude per square degree in the convolution image of an empty field for different background levels and obtained ML fits for all detected peaks.

Figure 4 shows the expected number of spurious sources per square degree, $f_{sp}$, as a function of ML detection significance. There is only a weak dependence on the background.

### 2.4. Merging sky tiles and calibration of source fluxes

Using the procedures described above, we obtained catalogs of sources detected in each sky tile. We then merged these individual catalogs into a composite all-sky catalog, taking the overlap of tiles into account. Specifically, sources that are located closer than 3′ to the tile edge were rejected and if a source was detected in two or more tiles, the detection at the larger distance from the tile edge was selected. Figure 5 shows an example of a merged convolution image of a large, crowded region of the sky near the Galactic center.

As was described above, the ML fitting procedure provides the fluxes of detected sources and the corresponding errors. We calibrated the energy flux to count rate conversion factor for the 4–12 keV energy band using the available ART-XC observations of the Crab nebula (see Pavlinsky et al. 2022 for details). This coefficient in general depends on the adopted procedure of selecting various types of ART-XC detector events. For the criteria adopted in this work, a count rate of 1 cnt s$^{-1}$ corresponds to a flux of $4.0 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the 4–12 keV energy band. This takes into account the difference between the slopes of the fiducial source spectrum adopted in this work ($\Gamma = 1.4$) and the Crab spectrum ($\Gamma = 2.1$). The energy flux to count rate conversion factor only weakly depends on the spectral shape, namely it varies by less than 4% for $\Gamma$ between 1.4 and 2.1 and for line-of-sight absorption column densities up to $N_H = 10^{23}$ cm$^{-2}$. This is comparable to current uncertainties in the instrument’s calibration.

### 3. Construction of the final catalog

To construct the final source catalog, we adopted a threshold of $f_{sp} = 7.475 \times 10^{-3}$ spurious sources per square degree, which
Fig. 3. Example of a detection of a faint source using the optimal matched filter given by Eq. (1). Left: Raw photon image in the 4–12 keV energy band. Right: Convolution with the filter. The size of the images is approximately 25′ × 25′.

Fig. 4. Correlation between the S/N and the expected number of spurious source detections per square degree obtained via simulations of empty fields. The observed scatter reflects a weak dependence on the background.

3.1. Identification and classification of ART-XC sources

For identification of ARTSS1-5 sources, we carried out the same kind of analysis as previously for the ARTSS12 catalog (Pavlin-sky et al. 2022). Namely, we cross-correlated the ARTSS1-5 catalog with the SIMBAD Astronomical Database (Wenger et al. 2000), the NASA/IPAC Extragalactic Database (NED), and the X-ray astronomy database provided by the High Energy Astrophysics Science Archive Research Center (HEASARC). We further searched for possible counterparts in catalogs of optical, infrared (IR), and radio all-sky surveys, in particular Gaia Data Release 3 (Gaia DR3, Gaia Collaboration et al. 2023), the Sloan Digital Sky Survey (SDSS; Ahumada et al. 2020), the 6dF Galaxy Survey (Jones et al. 2009), the DECam Plane

\[ S/N \approx 5.3 \] (see Fig. 4). At this threshold, the total number of detected sources is 1545, with 2% of them expected to be spurious.

3 The NASA/IPAC Extragalactic Database is funded by the National Aeronautics and Space Administration and operated by the California Institute of Technology.
survey (DECaPS; Schlaffly et al. 2018, the Wide-field Infrared
Survey Explorer (WISE) observatory’s AllWISE (Cutri et al. 2011) and CatWISE2020 (Marocco et al. 2021) catalogs, the
Very Large Array (VLA) Faint Images of the Radio Sky at
Twenty-Centimeters (FIRST; Helfand et al. 2015), the
National Radio Astronomy Observatory (NRAO) VLA Sky Sur-
vey (NVSS; Condon et al. 1998), the Sydney University Molon-
glo Sky Survey (SUMSS; Mauch et al. 2003), and the Very Large
Array Sky Survey (VLASS; Gordon et al. 2021).

The search for counterparts was conducted within the 98%-confidence error radii (\(R_{98}\)) of ARTSS1-5 sources, which does not exceed 30″ even for the lowest S/N detections, and within some margin outside these regions. In most cases, the positional
precision provided by ART-XC enables a straightforward selec-
tion of a likely counterpart. Often, previous detections in soft
X-rays provide a significantly better localization, which further facilitated this selection. The resulting identifications and clas-
sifications as well as redshifts for extragalactic sources were
adopted from SIMBAD and/or NED in most cases.

In cases of dubious identification or classification and for re-
cently or newly discovered X-ray sources, we used additional
information from the literature, from our multiwavelength cross-
correlation analysis and our optical follow-up campaign (see be-
low). Various photometric (and spectroscopic if available) sig-
natures were taken into account. In particular, the presence of
an extended optical object, an IR source with \(W_1 - W_2 \geq 0.5\)
(the color provided by WISE, Assef et al. 2013), or a radio
source usually indicate an active galactic nucleus (AGN) origin,
whereas the presence of a bright star suggests a Galactic nature.

All nontrivial cases are discussed on a source by source basis in
Appendix A. If the identification and/or classification of a given
ARTSS1-5 source is not robust, we denote such information as
tentative in the catalog.

### 3.2. Follow-up optical program

Since the beginning of the SRG all-sky survey in December
2019, we have been conducting an extensive program of optical
spectroscopy of X-ray sources that have either been discovered
by ART-XC or were known as X-ray sources from previous mis
sions but have remained unidentified so far. This follow-up cam-
paign is focused on the northern sky (Dec \(\geq -25^\circ\)) and is mostly
implemented using two telescopes: the Sayan observatory’s
1.6 m telescope (AZT-331K; Burenn et al. 2016), operated by
the Institute of Solar-Terrestrial Physics of the Siberian branch
of the Russian Academy of Sciences, and the Russian-Turkish
1.5 m telescope (RTT-150), operated jointly by the Kazan Feder-
eral University, the Space Research Institute (IKI, Moscow), and
the TUBITAK National Observatory (TUG, Turkey).

This program has already allowed us to identify and classify
~ 60 AGN and several cataclysmic variables (Zaznobin et al.
2021, 2022; Uskov et al. 2022, 2023, 2024). In addition, the
ARTSS1-5 catalog includes a number of Galactic X-ray tran-
sients that were discovered during the SRG all-sky survey by
eROSITA and/or ART-XC and later followed up in the optical
(e.g., Mereminskiy et al. 2022; Schwope et al. 2022). We took
such information into account when assigning identifications and
classes to ARTSS1-5 sources.

### 4. Source catalog

We provide the following information for each source in the
ARTSS1-5 catalog:

- **Column (1) “Id”**: The sequence number of the source in the
catalog.
- **Column (2) “Name”**: The name of the source in the catalog
(prefix “SRGA” followed by the source coordinates).
- **Columns (3 and 4) “RA, Dec”**: The equatorial coordinates
(J2000).
- **Column (5) “R98”**: The statistical position uncertainty at
98% confidence.
- **Columns (6) “S/N”**: The significance of the detection.
- **Column (7) “Flux”**: The flux in the 4–12 keV energy band
and the corresponding 1σ uncertainty.
- **Column (8) “Conventional name”**: The conventional name
of the source, if available.
- **Column (9) “Redshift”**: The cosmological redshift for extra-
galactic objects if known.

Building on our previous experience of constructing catalogs
of sources detected in all-sky X-ray surveys (e.g., Revnivtsev et al.
2004; Krivonos et al. 2022; Pavlinsky et al. 2022), we re-
stricted ourselves to providing a single conventional name for
previously known ARTSS1-5 sources. To this end, we prefer to
indicate the X-ray observatory and/or survey that discovered a
given source (e.g., 4U or 2RXS). However, this is often diffi-
cult to do, as two or more surveys and/or teams, for example
the Burst Alert Telescope (BAT) on board the Neil Gehrels Swift
Observatory and the Imager on-Board the INTEGRAL Satellite
on board the International Gamma-Ray Astrophysics Labora-
tory (INTEGRAL/IBIS), may have reported the detection of the
same source at about the same time. Moreover, many objects
were originally known from optical or radio observations rather
than from X-ray observations, so in such cases we usually use the
typical or radio name (e.g., NGC or 3C). There are further sub-
tleties. In particular, when referring to a source discovered dur-
ing the ROSAT all-sky survey, we prefer to use the name (2RXS)
from the (latest) second catalog (Boller et al. 2016). However,
ocasionally we use a shorter (RX or RBS) name if a source is
well known under this name from the literature.

Figure 6 shows the positions of the ARTSS1-5 sources on
the sky. The size of the symbols indicates the X-ray brightness
of sources.

1. **4.1. Source counts and survey sensitivity**

Figure 7 shows the cumulative and differential flux distributions of
the ARTSS1-5 sources in the 4–12 keV energy band. The me-
dian flux is \(4.9 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\).

Figure 8 shows the distribution of the ARTSS1-5 sources on the
ecliptic latitude–X-ray flux diagram. This plot highlights
how the sensitivity of the ART-XC all-sky survey monotonically
increases from \(\sim 4 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\) near the ecliptic
plane (at [\(|b_{\text{ ecl}}| < 30^\circ\)] to \(\sim 7 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}\) near the ecliptic
plane.
the ARTSS1-5 catalog. We have managed to identify 1463 out of the 1545 sources. Of these 1463, 174 are tentative identifications, which is to say that for them there is a likely optical/IR counterpart but follow-up observations are needed to ascertain or improve their classification. The majority of the identified objects (66%) are extragalactic, a small fraction (2%) are located in the Local Group of galaxies (namely, in the Large Magellanic Cloud, the Small Magellanic Cloud, M31, and M33), and 32% are of Galactic origin. The largest groups within the Galactic category are CVs (including symbiotic binaries), LMXBs, and HMXBs. The extragalactic objects are dominated by Seyfert galaxies and blazars.

Extended astrophysical objects such as SNRs and clusters of galaxies are expected to be significantly underrepresented in the ARTSS1-5 catalog (for the adopted flux threshold) because our search algorithm is designed for the detection of point X-ray sources. For example, such famous objects as the Coma and Virgo clusters of galaxies are not present in the catalog due to the huge size they subtend on the sky, despite them being bright X-ray sources.

Eighty-four sources in the catalog, or \( \approx 5\% \) of all sources, remain unidentified; of these 84 sources, \( \sim 30 \pm 6 \) are expected to be spurious X-ray detections. The majority of the unidentified sources (62) were discovered by ART-XC. The total number of new X-ray sources in the ARTSS1-5 catalog (including the identified ones) is 158.

Figure 9 shows the redshift distribution of the AGN. The median redshift of the un-beamed (i.e., excluding blazars) AGN is 0.05, and it is 0.25 for the blazars. The redshifts are still missing for 129 AGN and AGN candidates in the ARTSS1-5 catalog.

### 4.3. Localization accuracy

As already mentioned, we evaluated the statistical uncertainties of source positions using ML fitting. Figure 10 shows the resulting \( R_{98} \) uncertainties as a function of \( S/N \) for the ARTSS1-5 sources. There is a clear correlation between these quantities, which can be approximately described as

\[
R_{98} \approx 89'' \left( \frac{S}{N} \right)^{-0.84}
\]

The median statistical position uncertainty is \( R_{98} = 16.1'' \), while for 90% of the ARTSS1-5 sources \( R_{98} < 22.3'' \).

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### Table 1: Statistics of the ARTSS1-5 sources by location in the Universe and by type (including tentative classifications)

<table>
<thead>
<tr>
<th>Category and type</th>
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Fig. 6. Positions in Galactic coordinates of the X-ray sources detected by ART-XC in the 4–12 keV energy band during ARTSS1-5. The size of the symbol reflects the X-ray brightness of a source, as indicated in the legend.
There can also be some systematic uncertainties associated with the determination of source positions. To estimate these, we selected those ARTSS1-5 sources that can be reliably associated with a point-like Galactic object and have an optical counterpart in the Gaia DR3 catalog, and compared their ART-XC and Gaia positions. In total, 346 objects were included in this analysis. Figure 11 shows the X-ray–optical offsets ($S$) versus the 98%-confidence statistical position errors ($R_{98}$) for the test subsample. The fraction of outliers ($S > R_{98}$), 10%, exceeds the 2% expected for the purely statistical uncertainty. Most of these outliers are associated with bright X-ray sources, for which $R_{98}$ is just a few arcseconds. From this comparison, we can estimate a typical systematic positional uncertainty for the ARTSS1-5 catalog at $R_{\text{syst}} \approx 7''$, so that the total error radii of ARTSS1-5 sources can be crudely estimated as $\sqrt{R_{98}^2 + R_{\text{syst}}^2}$.

4.4. Cross-match with external X-ray and gamma-ray source catalogs

Most of the objects in the ARTSS1-5 catalog were known as X-ray sources before. We cross-correlated the catalog with a number of all-sky or nearly all-sky X-ray and gamma-ray surveys: the second ROSAT all-sky survey (2RXS; Boller et al. 2016), the XMM-Newton slew survey (XMMSL2; Saxton et al. 2008, table XMMSLEWCLN in HEASARC), the combined Monitor of All-sky X-ray Image/Gas Slit Camera (MAXI/GSC) 7-year all-sky source catalog (3MAXI; Kawamuro et al. 2018; Hori et al. 2018, table MAXIGSC7YR in HEASARC), the Swift/BAT 105-month all-sky survey (hereafter, Swift105mo; Oh et al. 2018), the INTEGRAL/IBIS 17-year all-sky survey (hereafter, INT17yr; Krivonos et al. 2022), and the Fermi Gamma-ray Space Telescope/Large Area Telescope (Fermi/LAT) 14-year all-sky survey (4FGL-DR4; Abdollahi et al. 2022; Ballet et al. 2023).
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![Graph showing statistical uncertainties and cross-matches for ARTSS1-5 sources.](image1)

**Fig. 10.** Statistical position uncertainties of the ARTSS1-5 sources as a function of their detection significance. The solid line shows the approximate relation between these quantities given by Eq. (4).

![Graph showing offsets between positions of ARTSS1-5 sources and their counterpart sources.](image2)

**Fig. 11.** Offsets between the positions of ARTSS1-5 sources and their counterpart sources in the Gaia DR3 catalogs. The diagonal line shows the 1:1 relation.

We took into account those matches where the angular separation between an ARTSS1-5 source and a source from an external catalog was less than the sum of the corresponding 98% error radii ($R_{98}$). For ARTSS1-5, we added in quadrature a systematic error of 10″ (slightly larger than what was estimated in Section 4.3, to be on the safe side) to the statistical errors of the source position. The $R_{98}$ values for the external catalogs were computed, assuming a two-dimensional Gaussian probability distribution, from the positional uncertainties provided by these catalogs. Specifically, 2RXS reports 1σ positional errors ($σ_x$ and $σ_y$) on image coordinates, while XMMSL2 and 3MAXI provide 1σ error radii ($R_{98}$). For Swift105mo and INT17yr, we estimated $R_{98}$ based on the detection significance of sources, following Oh et al. (2018) and Krivonos et al. (2007), respectively. The 4FGL-DR4 catalog provides the semimajor and semiminer axes of 95%-confidence ellipsoidal localization regions; for simplicity, we converted these into 95%-confidence error radii ($R_{98}$) corresponding to circles of the same area, and also excluded extended 4FGL-DR4 sources.

We have found 4, 4, and 2 cases where two ART-XC sources are blended into one INT17yr, Swift105mo, and 4FGL-DR2 source, respectively. We counted each of these cases as two matches. All of these associations except for two are located in crowded regions of the sky, such as the Galactic plane, Galactic center, and nearby galaxies (Large Magellanic Cloud, M31, and NGC 4945), where high angular resolution is required to resolve individual X-ray sources. Additionally, there are 98 cases where two or more XMMSL2 sources are found within the match region around an ARTSS1-5 source. We regarded each such group as a single match. Most of these cases appear to be caused by imperfect merging of individual XMM-Newton slew detections into “unique sources” in the XMMSL2 catalog.

Table 2 provides the results of the cross-matching analysis. The largest overlap of the ARTSS1-5 catalog is observed with the 2RXS, XMMSL2, and Swift105mo catalogs. The vast majority of these associations must be real. To estimate the number of spurious matches, we shifted the positions of the ART-XC point sources in random directions by 45° and repeated the cross-matching analysis; we ran many such simulations for each external catalog. The chosen offset is small compared to both the effective angular scale height of the Galactic population of X-ray sources and the effective size of the ART-XC deep fields near the ecliptic poles. On the other hand, it is much larger than the positional uncertainties of the vast majority of sources in the external catalogs under consideration, except for a few sources in the 3MAXI and 4FGL-DR4 catalogs. To take these exceptional sources into account, we excluded from the count of spurious matches those few cases where an ARTSS1-5 source was linked with the same 3MAXI or 4FGL-DR4 source before and after applying the positional shift (such associations can be real, rather than spurious). In the last column of Table 2, we provide the estimated numbers of spurious matches with the external catalogs.

Of the 1545 ARTSS1-5 sources, 194 have not been detected in any of the six all-sky surveys on our list. Taking into account that the ARTSS1-5 catalog allows for the presence of ~2% of spurious detections (i.e., ~30±6 sources), we can conclude that ~160 real sources are unique to the ARTSS1-5 catalog among the known all-sky X-ray and gamma-ray catalogs.

No strong trends are apparent in the statistics of cross-identifications with external X-ray source catalogs in terms of celestial position or source class. Specifically, we compared the relative fraction of cross-matches of ARTSS1-5 sources with the 2RXS, XMMSL2, and Swift105mo catalogs (i) near and outside the Galactic plane ($|b| < 10°$ versus $|b| > 10°$) and (ii) for Galactic versus extragalactic sources (according to Table 1), and the resulting numbers differ just by several per cent for each of the mentioned external catalogs. In particular, for 2RXS, the largest difference in the relative (with respect to ARTSS1-5) fraction of cross-matches is found between Galactic and extragalactic sources: 57.4% versus 69.0%, whereas for Swift105mo...
the largest difference is observed between the $|b| < 10^\circ$ and $|b| > 10^\circ$ samples, namely 61.7\% versus 49.8\% (for XMMSL2). The variations are yet smaller. It is difficult to interpret this information, because all these surveys differ significantly in their spectral response and coverage of the sky (expect for 2RXS, whose exposure map is skewed toward the Ecliptic poles as for SRG/ART-XC) and, moreover, XMMSL2 has not covered the whole sky. However, intrinsic variability, spectral hardness, and line-of-sight absorption (both intrinsic and Galactic) certainly play key roles in this statistics.

We note that all of the surveys considered here, except for 2RXS, were conducted over periods of at least 8 years but some of them (in particular, XMMSL2) are characterized by a low duty cycle. For comparison, the ARTSS1-5 catalog is based on a relatively short period of 2.3 years of nearly continuous scanning of the sky, characterized by a duty cycle of more than 97\%.

4.5. Ecliptic poles

Longer exposures were carried out for the regions around the ecliptic poles compared to other fields during the ART-XC all-sky survey (see Fig. 1), and it is interesting to examine the composition of the X-ray source samples detected in these “deep surveys.” Specifically, we focus our attention on the regions $b_{\text{ ecl}} > 82^\circ$ and $b_{\text{ ecl}} < -82^\circ$, with an area of $\approx 200$ square degrees each, around the north and south ecliptic poles (NEP and SEP), respectively. For the adopted detection significance threshold, the expected number of spurious sources in the combined NEP–SEP sample is $\sim 0.3$ (i.e., this sample is expected to be highly pure).

There are 49 ARTSS1-5 sources, with fluxes down to $\sim 2 \times 10^{-13} \text{erg s}^{-1} \text{cm}^{-2}$, in the NEP field. The majority of them (44) were known as X-ray sources before and 5 sources have been discovered by ART-XC. These five sources proved to be AGN, based on our follow-up optical spectroscopy program (in addition, we identified via optical spectroscopy 3 AGN among the previously known X-ray sources). Most of the NEP sample are extragalactic sources: 3 galaxy clusters and 41 AGN (including candidates). There are also 5 Galactic objects: 3 CVs and 2 coronally active stars.

The SEP region contains 60 ARTSS1-5 sources, with fluxes down to $\sim 3 \times 10^{-13} \text{erg s}^{-1} \text{cm}^{-2}$, including nine X-ray sources discovered by ART-XC. One-third of the SEP sample (20 objects) are X-ray binaries and SNRs residing in the Large Magellanic Cloud. Most of the remaining sources are extragalactic: one galaxy cluster and 33 AGN (including candidates). There are also five Galactic objects (three CVs and CV candidates, one HMXB, and one star), and one unclassified object. As expected, the AGN detected in the NEP and SEP fields are on average more distant than those found elsewhere, with the most distant un-beamed AGN located at $z \sim 0.9$.

5. Discussion and summary

We have updated the catalog of sources detected by the ART-XC telescope during the SRG all-sky survey by adding data from the third, fourth, and the $\sim 40\%$ complete fifth half-year scans of the sky to the data of the first two scans on which the previous version of the catalog (ARTSS12, Pavlinsky et al. 2022) was based. The new catalog comprises 1545 sources detected in the $4$–$12$ keV energy band. The achieved sensitivity ranges between $\sim 4 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$ near the ecliptic plane and $\sim 7 \times 10^{-13} \text{erg s}^{-1} \text{cm}^{-2}$ near the ecliptic poles. The new ART-XC catalog is $\sim 1.3$–$1.5$ times deeper than the previous one. The sensitivity as a function of celestial coordinates will be evaluated more accurately elsewhere (Burenin et al., in prep.), based on extensive numerical simulations of the survey.

Just a few all-sky or nearly all-sky surveys have been conducted in similar medium X-ray bands (i.e., at energies $\sim 2$–$20$ keV). In particular, the HEAO-1 experiment A2 performed a survey of the extragalactic sky ($|b| > 20^\circ$) in the $2$–$10$ keV energy band (Pizzolotto et al. 1982), the Rossi X-ray Timing Explorer (RXTE) slew survey (XSS) covered the $|b| > 10^\circ$ sky in the $3$–$20$ keV band, and the MAXI/GSC all-sky survey (3MAXI) covered the entire sky in the $4$–$10$ keV band (Kawamura et al. 2018; Horii et al. 2018). All these surveys had much lower angular resolutions ($\sim 1^\circ$) compared to ARTS1-5, which led to source confusion in crowded regions of the sky and complicated the identification of X-ray sources. The median sensitivities of the HEAO-1 A2 survey, XSS, and 3MAXI, converted to the $4$–$12$ keV energy band, are $\sim 1.8 \times 10^{-11}$, $\sim 1.1 \times 10^{-11}$, and $\sim 8 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$ (for spectra not very different from those of the Crab), which is significantly worse than the sensitivity achieved during ARTS1-5 in its shallowest part near the ecliptic plane.

The XMM-Newton slew survey (XMMSL2; Saxton et al. 2008) covered $\sim 84\%$ of the sky. The median flux of the sources detected in its hard band of $2$–$12$ keV is $9.3 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$, which corresponds to $\sim 5.7 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$ in the $4$–$12$ keV band for Crab-like spectra. This should be compared to the median flux of $\sim 4.9 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$ of the ARTS1-5 sources. Therefore, XMMSL2 (hard band) and ARTS1-5 are comparable in sensitivity, but the latter provides a more regular coverage of the sky and is done in a slightly harder energy range.

As a result of the increased depth compared to the first year of the ART-XC all-sky survey (Pavlinsky et al. 2022), the dominance of AGN among the classified sources has strengthened, with $\sim 60\%$ of the ARTS1-5 catalog sources being AGN or AGN candidates. The catalog includes 158 objects that were not known as X-ray sources before. Given that $\sim 30$ of them are expected to be spurious detections (for the adopted detection significance threshold), there are $\sim 130$ truly new X-ray sources, which corresponds to $\sim 8\%$ of the entire catalog. This fraction has increased with respect to ARTSS12, as anticipated.

The ARTS1-5 catalog has a significant added value in terms of the identification and classification of sources. Nearly $83\%$ of the sources are already reliably classified and another $\sim 11\%$ have tentative classifications. We are pursuing the goal of achieving a nearly $100\%$ identification completeness. To this end, we have been carrying out a follow-up optical spectroscopy program, which has already allowed us to identify and classify $\sim 60$ AGN and $\sim 10$ Galactic objects (mostly CVs). So far, this campaign has been focused on the northern sky (Dec $> -25^\circ$), and we urge its extension to the southern hemisphere. Our ultimate objective is to provide statistically complete samples of different classes of objects, in particular AGN and CVs, selected in the $4$–$12$ keV energy band, which is largely unique to the ART-XC survey. The current samples of AGN and CVs in the ARTS1-5 catalog comprise $\sim 900$ and $\sim 200$ objects, respectively. We are now developing an ARTS1-5 web database\footnote{https://www.cosmos.esa.int/web/xmm-newton/xmmsl2-ug} that will provide additional information on the counterparts of the ARTS1-5 sources.

The SRG/ART-XC all-sky survey has recently been resumed after a 1.5-year pause. Four new scans of the sky are to be conducted by the end of 2025. The next official release of the ART-
Table 2. Cross-match of the ARTSS1-5 sources with selected X-ray and gamma-ray source catalogs.

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<th>Spurious matches$^a$</th>
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<td>ROSAT (2RXS) 1 year</td>
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<td>4.5 (2–7)</td>
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<td>MAXI/GSC 7 years</td>
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<td>Kawamuro et al. (2018); Hori et al. (2018)</td>
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<td>5.6 (3–9)</td>
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<td>Swift/BAT 105 months</td>
<td>14–195 keV</td>
<td>Oh et al. (2018)</td>
<td>785</td>
<td>5.8 (3–8)</td>
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<td>INTEGRAL 17 years</td>
<td>17–60 keV</td>
<td>Krivonos et al. (2022)</td>
<td>504</td>
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<td>Fermi/LAT 14 years</td>
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<td>Abdollahi et al. (2022)</td>
<td>222</td>
<td>23.8 (18–30)</td>
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$^a$ Expected value of spurious matches and the corresponding 90% confidence interval.

Acknowledgements. The Mikhail Pavlynski ART-XC telescope is the hard X-ray instrument on board the SRG Observatory, a flagship astrophysical project of the Russian Federal Space Program realized by the Russian Space Agency in the interests of the Russian Academy of Sciences. The ART-XC team thanks the Russian Space Agency, Russian Academy of Sciences, and State Corporation Rosatom for the support of the SRG project and ART-XC telescope. We thank Kovochkin Association (NPOL) with partners for the creation and operation of the SRG spacecraft (Navigator). We thank Accroard Co., Ltd. (Japan), which manufactured the CdTe dies, and Integrated Detector Electronics AS – IDEAS (Norway), which manufactured the ASICs for the X-ray detectors. SS, RB, EF, RK, IM, GU, EZ, and LZ acknowledge the support of this research by the Russian Science Foundation (grant 19-12-00396). We are grateful to the referee for the helpful comments and suggestions.

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Uskov, G. S., Sazonov, S. Y., & Zaznobin, I. A. e. a. 2024, Astronomy Letters
Appendix A: Notes on individual sources

Here⁹, we provide additional comments on the identification and classification of a number of sources from the ARTSS1-5 catalog, namely those with dubious identification or classification as well as recently or newly discovered X-ray sources. In addition to the databases and catalogs already mentioned in Section 3.1, we acquired this information from the literature and from our ongoing follow-up optical spectroscopy campaign.

For a few of the objects discussed below, we obtained a tentative Seyfert classification (class “Seyfert?” in the catalog) by inspecting their optical spectra available from the SDSS or 6dF surveys. To this end, we used the standard criteria based on the widths and intensities of emission lines (Osterbrock 1981; Baldwin et al. 1981) following our previous work on the classification of AGN from the SRG/ART-XC all-sky survey (e.g., Uskov et al. 2023, 2024).