Wide-field X-ray observations of the supernova remnant Puppis A with the SRG/ART-XC telescope

R. Krivonos,1* V. Arefiev,1 I. Lapshov,1 E. Filippova,1 R. Burenin,1 A. Semena,1 S. Grebenev,1 S. Sazonov,1 A. Shtykovsky,1 A. Tkachenko,1 and A. Lutovinov1

1Space Research Institute (IKI), Profsoyuznaya 84/32, Moscow 117997, Russia

ABSTRACT
The Spectrum-Roentgen-Gamma (SRG) observatory is currently conducting its 4-year all-sky X-ray survey, started on December 12, 2019. The survey is periodically interrupted for technological operations with the spacecraft. These time intervals are usually used by the Mikhail Pavlinsky ART-XC telescope to perform calibrations. In this context, SRG carried out scanning observations of the Puppis A supernova remnant (SNR) with the aim to check the imaging performance of ART-XC and to optimize the technique of image reconstruction for extended objects. Using the unique imaging capabilities of ART-XC and its uniform coverage of the entire Puppis A region, we attempted to investigate the morphology of this SNR at energies ≥ 4 keV, and to search for previously unknown X-ray sources. Puppis A was observed in 2019–2020, conducting coverage of the entire Puppis A region, we attempted to investigate the morphology of this SNR at energies ≥ 4 keV, and to search for previously unknown X-ray sources. Puppis A was observed in 2019–2020, conducting 1.5° × 1.5° shallow surveys with an exposure of 36 hours. Additional deep pointed observations of the central part of Puppis A were carried out in 2021 lasted 31 hours to highlight the morphology of the extended emission. The X-ray emission of the Puppis A was significantly detected as an extended structure in the 4–6 keV energy band. The morphology of the emission is in general agreement with that observed in soft X-rays previously. The deep sky image of Puppis A obtained with the ART-XC telescope is characterized by a typical SNR shell rim morphology, an extended emission and a bright emission knot in the north-eastern part of the supernova shell. Also, four point X-ray sources have been detected, including three objects identified in catalogs, and one newly discovered X-ray emitter.

Key words: ISM: supernova remnants – X-rays: general – surveys

1 INTRODUCTION
Puppis A is one of the best studied Supernova Remnants (SNRs) in our Galaxy, which shows a strong evidence of the shock-cloud interaction. The distance to Puppis A is estimated to be around 2.2 kpc based on neutral hydrogen observations (Reynoso et al. 2003). At this distance, the 50′ visible diameter of Puppis A corresponds to about 30 pc. Near the geometric center of Puppis A, a central compact object (CCO) RX J0822–4300 is located, which has been identified as a stellar remnant left after the supernova explosion (Petre et al. 1996; Zavlin et al. 1999). The observed proper motion of the CCO and optical filaments suggests the age of Puppis A to be 4450 ± 750 years (Becker et al. 2012). Early X-ray observations recognised two bright emission knots inside Puppis A: the “bright eastern knot” (BEK) and another one to the north (Petre et al. 1982). The X-ray spectral studies provided evidence that the expanding SNR shell has interacted with dense molecular clouds in a relatively late phase of its evolution (Hwang et al. 2005; Katsuda et al. 2010, 2012), rendering Puppis A the first X-ray-identified example of a cloud-shock interaction. No dense molecular cloud is found to be adjacent to the BEK, suggesting that the molecular clumps have been completely destroyed by the shock (Paron et al. 2008; Arendt et al. 2010).

Since Puppis A is the archetypal SNR interacting with dense molecular clouds, it is expected to be a strong emitter of γ-rays. Based on seven years of Fermi LAT observations, Xin et al. (2017) revealed a noticeable non-thermal γ-emission located in northeastern and eastern quadrants of the SNR, which is well correlated with the thermal X-ray and IR spatial morphology rather than with the radio emission. This may indicate that some dense clouds are present in Puppis A providing the target material for interaction with cosmic rays.

Puppis A is one of the brightest SNRs in X-rays. Different areas of its extended emission have been observed with several orbital X-ray telescopes, including Einstein (Petre et al. 1982), ROSAT (Aschenbach 1993), Chandra (Hwang et al. 2005), Suzaku (Hwang et al. 2008) and XMM-Newton (Hui & Becker 2006; Katsuda et al. 2010, 2012). The observed X-ray emission is thermal in origin, mostly originated in the shocked interstellar medium (Hwang et al. 2005), also showing evidence for the supernova ejecta. Dubner et al. (2013) presented the most complete and detailed X-ray view of Puppis A, confirming that this SNR evolves in an inhomogeneous, probably knotty interstellar medium. The HaloSat CubeSat mission recently provided the first soft X-ray (0.4–7 keV) observation of the entire Vela SNR and Puppis A SNR region with a single pointing and moderate spectral resolution (Silich et al. 2020). After this manuscript has been prepared, Mayer et al. (2021) presented the large-scale distribu-
tion of absorption, plasma temperature and emission lines of Puppis A, using field-scan data acquired by the SRG/eROSITA telescope during its calibration and performance verification phase.

Due to its relatively large spatial size, Puppis A is a complicated target for X-ray focusing telescopes, since many pointings with different observational configurations have to be combined, which usually requires non-trivial modeling of the astrophysical background. The 36′ field of view (FOV) of the Mikhail Pavinsky ART-XC telescope, on board the recently launched SRG observatory, is well suited for mapping large parts of the Puppis A region. Moreover, the scanning mode observations enable covering even larger regions of the sky with the uniform exposure. The ART-XC working 4–30 keV energy band allows previous observations of Puppis A carried out in the similar (medium X-ray) energy bands to be complemented.

In this work, we present the first results of a series of wide-field observations of Puppis A with ART-XC telescope, performed in 2019–2021. The paper is organized as follows. Observations of the Puppis A region with SRG are described in Sect. 2. Sect. 3 briefly outlines the data reduction. Sect. 3.1 describes the construction of different sky maps of Puppis A. The detected point X-ray sources are discussed in Sect. 3.2. Discussion and summary are presented in Sect. 4.

2 ART-XC OBSERVATIONS OF Puppis A

The region of the Puppis A SNR was observed in 2019–2021 (Table 1) with the Mikhail Pavinsky Astronomical Roentgen Telescope – X-ray Concentrator (ART-XC, Pavlinsky et al. 2021), one of two X-ray telescopes on board the SRG observatory (Sunyaev et al. 2021), launched on July 13, 2019, from the Baikonur Cosmodrome. SRG is surveying the sky from its halo orbit near the Sun–Earth L2 point. ART-XC is a grazing incidence X-ray telescope containing 7 independent modules with their own X-ray mirror assemblies and focal plane CdTe detectors. ART-XC energy coverage of 4–30 keV in hard X-rays complements the soft energy response of the other instrument of the SRG observatory, eROSITA (Predehl et al. 2021), which is sensitive in the 0.2–8 keV energy band.

SRG is currently conducting its planned 4-year all-sky survey, which is periodically interrupted by technological operations with the spacecraft, mainly associated with orbit corrections. Both the ART-XC and eROSITA telescopes normally perform in-flight ongoing calibration before and after an orbital maneuver to check the instrument performance.

Table 1. List of scanning and pointed observations of Puppis A with SRG/ART-XC.

| ObsID    | Date           | Exposure | Step |
|----------|----------------|----------|------|
| 70019900100 | 29-11-2019 20:35 (MSK) | 18 hr    | 10′  |
| 00003058001 | 24-11-2020 00:50 (MSK) | 18 hr    | 4′   |
| 121100510XX | 24-05-2021 00:30 (MSK) | 19 hr    | 4′   |
| 121100520XX | 24-05-2021 20:15 (MSK) | 12 hr    | 4′   |

* Two-digit numbers “XX” denote indexes of grid nodes. The full list of observations is available on SRG website http://srg.cosmos.ru

2.1 Scanning observations

The first scan pattern (hereafter “scanning”) observation of the Puppis A region with a total exposure of 18 hrs was carried out during the SRG Performance Verification phase in 2019. This scanning observation was done with a scan step of 10′ optimized for the vignetting function of the eROSITA telescope.

The second observation with a comparable exposure was performed in 2020 after a planned correction of the SRG orbit with the aim to calibrate X-ray imaging of an extended object with an angular size greater than the field of view (FOV) of the ART-XC telescope. The scan step size of 4′ was optimized for the vignetting function of the ART-XC X-ray mirrors in order to obtain highly uniform exposure. Fig. 1 shows the scanning observation, which was carried out on November 24, 2020. The eROSITA telescope was not operating during this period.

2.2 Grid observations

Scanning mode observations allow one to obtain very uniform exposure coverage, but their implementation with the SRG platform requires exposure losses in some turning points, referred to as “parking positions”, which are normally removed from the analysis. The optimal size of the scanning region is found to be from ~1.5′ to several degrees. In order to cover smaller regions with angular sizes less than ~1.5 degrees, the grid of ART-XC pointed observations of step 4′ proves to be more effective. In this case, nearly uniform exposure is concentrated in the central part of the selected sky region.

To cover the brightest part of Puppis A, we initiated two sets of pointed observations in May 2021 arranged over 6 × 6 (ObsID’s 121100510XX) and 5 × 5 (ObsID’s 121100520XX) grids with a 4′ node separation. These grid patterns where shifted by 2′ with respect to each other, so that the combined data set provides a quasi-uniform exposure of 90–110 ks within ~24′ in a diameter. Note that the pointing direction is centered at the maximum of the ART-XC

Figure 1. Scanning mode observations of the Puppis A SNR performed on November 24, 2020 (Galactic coordinates). The scanning step is 4 arcmin. The size of the scanning region, shown as a blue snake-like pattern, is 1.5′ × 1.5′. The circle indicates the ART-XC FOV size (36′ in diameter). The image in the background is taken from the ROSAT All-Sky X-ray Survey (0.4–2.4 keV).
analysis tools developed in IKI center (Pavlinsky et al. 2021). The exposure levels of the combined vignetting function, which is shifted by $\sim -2'$ with respect to the FOV center (Pavlinsky et al. 2021). The exposure levels of the combined data set in 2021 are shown by black contours in Fig. 2.

3 DATA ANALYSIS

We reduced raw telemetry data of the ART-XC telescope using data analysis tools developed in IKI, as briefly described in Pavlinsky et al. (2021). Using the pipeline software (ARTPIPELINE), we produced clean calibrated event lists for each of the telescope modules and spacecraft attitude data. The cleaned science data were then processed (ARTPRODUCTS) to obtain exposure and particle background maps as well as sky images.

Fig. 2 shows the exposure map of the Puppis A scanning observations in 2020. It can be seen that the ART-XC scanning observations provide a highly uniform coverage of a wide $1.5^\circ \times 1.5^\circ$ region around Puppis A with an exposure of $\sim 2600$ seconds in each point (averaged over all 7 telescope modules). A slightly displaced position of the 2019 scanning observations is shown with green contour levels.

3.1 X-ray images of Puppis A

We combined ART-XC cleaned event lists for all 7 telescope modules into sky mosaics in different energy bands from 4 to 12 keV. Figure 3 (right) shows the sky image of Puppis A in the full 4–12 keV band, which is the most sensitive energy range for detection of point-like X-ray sources, given the energy dependence of the ART-XC effective area (Pavlinsky et al. 2016). Due to the sparseness of the photon image, we applied an adaptive smoothing to this image. The image reveals an extended structure of low surface brightness and a number of point-like X-ray sources. We analyzed ART-XC sky images of Puppis A in different energy bands from 4 to 12 keV and found that the extended emission of the supernova remnant is most pronounced in the 4–6 keV energy range, as shown in Fig. 3 (right). At higher energies $\geq 6$ keV, we do not detect any significant excess of the Puppis A extended emission above the background. In general, the 4–6 keV emission of Puppis A is consistent with the brightest part of the SNR known from ROSAT observations (Aschenbach 1993).

Figure 4 shows the combined 2019–2020 image of the full region of the Puppis A SNR. In order to reveal faint features, the image was processed with a simple low-pass filter with a cutoff frequency $\sim 0.1$ arcminute$^{-1}$. Among the extended structures consistent with ROSAT contours, the image reveals a bright emission knot in the northeastern part of the SNR centered approximately at RA=08:23:46, Dec=–42:53:38 (J2000). This bright knot is not spatially consistent with the bright eastern knot revealed previously in soft X-rays (Petre et al. 1982) and shown by the highest ROSAT contour level.

Figure 5 shows the deepest low-pass filtered image of the central part of the Puppis A SNR obtained with ART-XC in the 4–6 keV band using all available observations carried out in 2019–2021. The image reveals four point X-ray sources: S1, S3, S4 and the CCO region around 2600 seconds in each point (averaged over all 7 telescope modules). A slightly displaced position of the 2019 scanning observations is shown with green contour levels.

To explore the arc-shaped shock front of the SNR, we constructed radial profiles in four sectors centered at the remnant’s optical expansion center at RA=08h22m27.5s, Dec.=-42d57m29s (Winkler et al. 1988; Becker et al. 2012), as shown in Fig. 5. Sectors A1–4 were chosen to highlight the SNR emission as a function of the angular offset from the center out to the distance where it dims below the background level (Fig. 6). All the profiles demonstrate a drop of the emission at the same angular offset of $\sim 20'$. Only the radial profile A3 reveals a strong excess of the emission knot in the eastern part of the shell.

3.2 Point-like X-ray sources

We performed a search for point X-ray sources on the combined 2019–2021 image of Puppis A. The source detection was done by the wavelet decomposition method (wvdecomp, Vikhlinin et al. 1998), along with matched filter and maximum likelihood fitting algorithms. The method uses a probabilistic approach for detection of X-ray sources from non-negative counts following the Poisson statistics (see e.g., Hong et al. 2016), and taking the ART-XC vignetting and point spread function (PSF) into account. Figure 7 shows the source detection probability map based on a given estimate of background counts. This map provides a direct indicator of how likely or unlikely it is to have a new point-like source. The map reveals a significant detection of four X-ray sources. In addition, Fig. 7 reveals extended emission from Puppis A, including the aforementioned bright knot. However, it is not properly described by the method since it is optimized only for point-like sources.

Table 2 shows the list of four detected sources with a signal-to-noise ratio greater than $5\sigma$. The S1 source is spatially consistent with 4XMM J082226.8–431027. According to the XMM-Newton catalog (Zolotukhin et al. 2017), this source has a relatively hard spectrum.

\footnote{Space Research Institute of the Russian Academy of Sciences, Moscow, Russia}

3 \footnote{http://xmm-catalog.irap.omp.eu}
Figure 3. ART-XC image of the Puppis A region in the 4–12 keV (left) and 4–6 keV energy bands (right) obtained in 2020. The images were smoothed with task `dmimgadapt` from CIAO-4.13 using a tophat kernel. The color bar is in units of counts s$^{-1}$ pixel$^{-1}$, and the angular size of the image pixel is 6.33". The white grid indicates Equatorial coordinates in degrees. Green contours demonstrate X-ray surface brightness measured in the ROSAT All-Sky X-ray Survey (corresponds to the background image in Fig. 1).

Figure 4. ART-XC 4–6 keV image of the full Puppis A SNR region based on SRG/ART-XC data acquired in 2019–2020. The white circles show the positions of the detected pointed X-ray sources listed in Table 2. The yellow dashed circle denotes the position of CCO RX J0822–4300.

Figure 5. ART-XC 4–6 keV zoomed-in image of the Puppis A region based on the combined SRG/ART-XC data set acquired in 2019–2021. The magenta circle with 50" in diameter denotes the region with the ART-XC exposure greater than 30 ks.

spectrums with $\Gamma \sim 1.5$ and a flux of $(8.7 \pm 0.2) \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the 4.5–12 keV band, which agrees well with our ART-XC measurement. The S2 source does not have any known X-ray counterpart within 1′ from the ART-XC position. The S3 source, located in the bright rim of the supernova shell, can be identified with 2CXO J082303.0–423901 from the Chandra source catalog Release 2.0 (Evans et al. 2010), located ~15″ away from the ART-XC position. The last source, S4, is consistent with the position of the 4XMM J082224.9–425811 source as well as with its 4.5–12 keV flux of $(9.2 \pm 1.3) \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ which renders it a likely counterpart. We finally note that for the exposure of 6–7 ks in these ART-XC observations, the typical sensitivity is $\sim 1.5 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ (4–12 keV). But it is higher in several regions, which allows us to detect fainter sources, like S4.

The CCO RX J0822–4300, which emits thermal X-rays, is not detected with ART-XC in the full 4–12 keV band. However, it is revealed in the 4–6 keV image (see Fig. 5) at the position of RA=08°21′59″, Dec.=−43°00′16″ (uncertainty ~30″), which is spatially consistent with the position of the CCO determined by Becker et al. (2012) us-
We have presented wide-field observations of the SNR Puppis A region with the Mikhail Pavlinsky ART-XC telescope on board the SRG observatory. The Puppis A supernova remnant has been significantly detected in the 4–6 keV energy band as a spatially extended inhomogeneous emission. In general, the X-ray map of Puppis A obtained by ART-XC (see Fig. 5) demonstrates the morphology consistent with that observed in previous soft X-ray studies. Among the most noticeable features one can mention a typical shell rim morphology of the SNR and the bright emission knot in the northeastern part of the remnant. The shell-like morphology of the SNR is consistent with the ROSAT contours as well as with later XMM-Newton (Katsuda et al. 2010; Dubner et al. 2013) and Chandra (Hwang et al. 2005) observations. The overall 4–6 keV ART-XC morphology of Puppis A is consistent with that simultaneously observed by SRG/eROSITA in 3.00–3.25 keV band (Mayer et al. 2021).

The bright extended knot observed by ART-XC is located inside the SNR shell and is spatially consistent with the region of highest plasma temperature (~0.75 keV) observed with SRG/eROSITA in Puppis A (Mayer et al. 2021), which indicates that the 4–6 keV bright emission knot seen by ART-XC belongs to hard tail of high temperature thermal emission. It is interesting to note that this region is also spatially consistent with the non-thermal γ-emission detected by Fermi in the northeastern quadrant of the remnant (Xin et al. 2017), which raises open question of the presence of a non-thermal emission component in Puppis A for future studies.

Among the four X-ray point sources significantly detected in the 4–12 keV band, three are associated with known XMM-Newton and Chandra sources and one has been detected in X-rays for the first time. The central compact object RX J0822–4300 is detected only in the 4–6 keV energy band, with a flux of \((6.6 \pm 2.4) \times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\).

In the forthcoming paper, we will present a spectral study of Puppis A based on the SRG/ART-XC observations reported here.

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DATA AVAILABILITY

The data of the ART-XC telescope used in this paper, as well as data analysis software is not available for public. However, there are plans to provide public access to the ART-XC scientific archive in the future.

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