SRGA J124404.1–632232/SRGU J124403.8–632231: a new X-ray pulsar discovered in the all-sky survey by SRG

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ABSTRACT

Ongoing all-sky surveys by the eROSITA and the Mikhail Pavlinsky ART-XC telescopes on-board the Spectrum Roentgen Gamma (SRG) mission have already revealed over a million of X-ray sources. One of them, SRGA J124404.1–632232/SRGU J124403.8–632231, was detected as a new source in the third (of the planned eight) consecutive X-ray surveys by ART-XC. Based on the properties of the identified optical counterpart it was classified as a candidate X-ray binary (XRB). We report on the follow-up observations of this source with Nuclear Spectroscopic Telescope Array (NuSTAR), Neil Gehrels Swift Observatory (Swift), and the Southern African Large Telescope (SALT), which allowed us to unambiguously confirm the initial identification and establish SRGU J124403.8–632231 as a new X-ray pulsar with a spin period of \(-538\) s and a Be-star companion, making it one of the first Galactic X-ray pulsars discovered by SRG.

Key words. pulsars: individual; (SRGA J124404.1–632232/SRGU J124403.8–632231) – stars: neutron – stars: binaries

1. Introduction

The Spectrum Roentgen Gamma (SRGA) mission was launched on July 13, 2019 from Baikonur, and started the all-sky survey on Dec 12, 2019. In total, eight complete scans of the celestial sphere, each lasting six months are foreseen to be conducted with each of the two instruments on board SRGA, i.e. eROSITA (Merloni et al. 2012; Predehl et al. 2021) operating in the 0.2–10 keV, and the Mikhail Pavlinsky ART-XC (Pavlinsky et al. 2021) operating in the 4–30 keV energy range. Both instruments produce standard X-ray event data and produce not only images, but also spectra and light-curves for each point on the sky. At the end of the survey, the eROSITA surveys are expected to be a factor 20–40 more sensitive than the ROSAT All-Sky Survey in common energy band (\(~2.5 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}\) for eROSITA (Predehl et al. 2021) compared to \(~10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}\) for ROSAT). Moreover, SRG will also conduct first ever true imaging all-sky surveys above the ROSAT pass band.

A large majority of the several millions of new X-ray sources detected in the survey are expected to be extra-galactic objects (i.e. active galactic nuclei and galaxy clusters), and ordinary stars (Merloni et al. 2012; Predehl et al. 2021). However, a significant expansion of the sample of the Galactic X-ray binaries can also be anticipated and will help to obtain important constraints on their luminosity function (Lutovinov et al. 2013; Doroshenko et al. 2014). Of particular interest here are properties of the faint Be X-ray binaries (BeXRBs) which up to now have been mostly discovered with all-sky monitors during their strong outbursts. It is quite clear, however, that the population of known BeXRBs is potentially only the tip of an iceberg as objects exhibiting fainter outbursts or no outbursts at all were likely missed due to the low sensitivity of all-sky monitors (Doroshenko et al. 2014). In comparison with available wide-field instruments both eROSITA and ART-XC are significantly more sensitive and are expected to unveil at least a part of this hidden population and thus facilitate advances in understanding of origin and evolution of the Galactic X-ray binaries.

On 2021 Jan 27, during the third consecutive all-sky survey, the Mikhail Pavlinsky ART-XC telescope on board the SRG observed a bright X-ray source SRGA J124404.1–632232 with a flux of \(~10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}\) in the 4–12 keV energy band (Semena et al. 2021). Inspection of the ART-XC data from previous two surveys in 2020 (see i.e. Table 1 for summary of the observations) revealed no excess at this position, so the source appeared to be new. However, it was found that an object was actually detected by eROSITA in all three surveys, which allowed to refine its X-ray position and identify a tentative optical counterpart of the X-ray source (Semena et al. 2021). Near infra-red and X-ray colours, the X-ray flux, and an estimated X-ray luminosity of \(~\mathcal{10}^{34} \text{ erg s}^{-1}\) implied by the Gaia distance of \(-5.8 \text{ kpc}\) (Bailer-Jones et al. 2021), strongly suggested that the object may be a new high-mass X-ray binary (HMXB). The variability of...
the counterpart, in particular a weak periodic, ~138 d, optical flux variations revealed by the Optical Gravitational Lensing Experiment (OGLE, Mroz & Udalski 2021) commonly observed also in other high-mass X-ray binaries with Be-star counterparts, strongly supported this suggestion. To confirm this identification, we observed the counterpart with the Southern African Large Telescope (SALT, Buckley et al. 2006), revealing a prominent H$\alpha$ line in emission (Buckley et al. 2021), which is typical for Be X-ray binaries and also strongly supports the BeXRB nature of the source which motivated us to conduct follow-up observations of this X-ray source with NuSTAR.

In this paper we report in detail on the analysis of the observational data of NuSTAR, SALT, and the SRG survey. The paper is organized as follows. In Sect. 2 we first briefly discuss observations used, and then discuss in detail analysis steps which led to identification of the near-infrared counterpart of X-ray source, and details of analysis for the follow-up NuSTAR and SALT observations. We then discuss our findings in context of properties of other BeXRBs in Sect. 3, and finally summarize the results in Sect. 4.

2. Observations and data analysis

As already mentioned, there are two telescopes on board SRG, i.e. eROSITA and ART-XC described in detail in Predehl et al. (2021) and Pavlinsky et al. (2021), respectively. Due to the comparatively low exposures achieved up to now in the survey, data from both instruments were mostly used to obtain a precise position of the X-ray source, and measure flux variations between the three consecutive surveys, whereas NuSTAR data were used for detailed spectral and timing analysis. Considering the non-detection of the source by ART-XC in the first two surveys, we only use data from the third survey for this instrument. For eROSITA, data from all three surveys are used.

eROSITA data were processed using the current (c946) eSASS (Brunner et al., submitted) pipeline configuration (used to characterize both software and calibration files version), which was also used to derive the source position and to extract X-ray spectra which were modeled jointly with NuSTAR data to improve the low-energy coverage and constraints on the absorption column. Details on calibration and in-orbit background of eROSITA are reported in Dennerl et al. (2020) and Freyberg et al. (2020) respectively. The data from the three all-sky surveys were analyzed independently, although spectrum of the source was assumed to be the same in all of them as described below.

ART-XC data were processed with the analysis software ARTPRODUCTS v0.9 with the calibration files version 20200401. A description of the ART-XC telescope and the analysis software can be found in Pavlinsky et al. (2021). Taking into account the faintness of the source and the significant amount of shorter effective exposure for ART-XC due to its smaller field of view, it was only possible to detect the source and estimate the number of counts above the background. Thus we use ART-XC data mostly to improve constraints on the source flux by eROSITA in the third survey. In practice, we attributed all counts detected by ART-XC to two broad energy bins covering 4-12 keV band, and modeled the ART-XC data using the current response. Here we note also that even if ART-XC and eROSITA observed the source at about the same time, difference in field of view of the two instruments and scanning pattern of the all-sky survey implies that the observations are not strictly simultaneous, so source flux measured by ART-XC was estimated independently.

In addition to SRG data, a deep (55 ks, obsid. 80660301002) observation of the source with NuSTAR (Harrison et al. 2013) was obtained to characterize the broadband spectrum of the source and search for possible pulsations. The data reduction for this observation was done using HEASOFT v6.28 and caldb version 20210210 as described below. Soon after that, the Neil Gehrels Swift Observatory also observed the object with XRT telescope (obsid. 00041978002), so we also use that observation.

Furthermore, as part of a transient identification and characterisation program being undertaken at SALT (Buckley 2015), we observed the optical counterpart on 2021 January 29 using the Robert Stobie Spectrograph (RSS) in low resolution mode ($R = 420$). In particular, two spectra, each with 1 ks exposure covering the region 3300–9000 Å were obtained starting 23:34:05 UTC. The summary of all observations is presented in Table 1.

Finally, to study properties of the optical counterpart, we used the archival OGLE I-band light curve published by Mroz & Udalski (2021) available via the OGLE XROM service.

2.1. X-ray position and near-infrared counterpart

To determine the X-ray position of the source, we considered the rectified source positions from three eROSITA surveys as independent measurements and combined them following the procedure described in Doroshenko et al. (2020). This allowed to fix the final X-ray position as $a_{2000.0} = 12^h 44^m 03^s 57.5, \delta_{2000.0} = -63^\circ 22' 28''$ with an uncertainty of about 1"/4 at 1σ or ~3"7 at 3σ confidence level (not accounting for potential systematic uncertainties (up to 5") of individual eROSITA measurements). As evident from Fig. 1 the estimated X-ray position coincides with the near-infrared source 2MASS J12440380−6322320, which was thus suggested as the tentative optical counterpart of the X-ray source (Semena et al. 2021). Considering the variability reported by Mroz & Udalski (2021), we observed the object with SALT (Buckley et al. 2021) to finally confirm this identification.

In particular, the proposed optical counterpart was observed using the low resolution 3001 mm−1 transmission grating, typically used for spectral classification of transients. The RSS spectra were reduced using the PvSALT primary data reduction pipeline (Crawford et al. 2012), which corrects for bias, gain and detector mosaic amplifier cross-talk. We then used iraf for the remaining data reduction steps, namely wavelength calibration, background subtraction extraction of the one-dimensional spectra and relative flux calibration (absolute flux calibration is impossible with SALT, due to its design).

The combined SALT spectrum presented in Fig. 1 shows a strong H$\alpha$ emission line, a weaker H$\beta$ emission line and a largely featureless red continuum, rising to longer wavelengths. It is thus consistent with a highly reddened early-type Be star located in the Galactic plane at ~6 kpc (Semena et al. 2021) and strongly

| Instrument | $T_{\text{start}}$, MJD | $T_{\text{stop}}$, MJD | Exposure, ks |
|------------|------------------------|------------------------|-------------|
| eROSITA    | 58883.36               | 58885.86               | 0.501       |
|            | 59068.27               | 59070.43               | 0.380       |
|            | 59239.92               | 59241.59               | 0.289       |
| ART-XC     | 59240.59               | 59241.42               | 0.172       |
| NuSTAR     | 59244.48               | 59245.53               | 54          |
| Swift/XRT  | 59248.17               | 59248.77               | 1.7         |
| SALT       | 59243.98               | 59244.01               | 2           |

1 http://ogle.astrouw.edu.pl/ogle4/xrom/srga_j124404.1-632232.html
2 Image Reduction and Analysis Facility: iraf.noao.edu
suggests that the X-ray source is likely indeed a Be X-ray binary (Buckley et al. 2021).

The Hα line is single peaked, but shows a slight asymmetry, with the peak flux on the red side of the line centre. The equivalent width (EW) and FWHM of the line are measured as $-54.2 \pm 2.7 \AA$ and $17.55 \pm 0.48 \AA$, respectively. The Hβ line EW is approximately $-5 \AA$, although this is hard to measure precisely due to the lower S/N at the blue end of the spectrum. The Hα EW is large compared to most other BeXRBs. Based on the proposed orbital period of 138 days (Mroz & Udalski 2021) and the well-known correlation between orbital period and Hα EW in BeXRBs (Reig 2011), the expected EW would be around $-35 \AA$, so our measurement suggests that the disc has grown to be larger than expected for this orbital period so the system indeed can be expected to be active in X-rays.

2.2. NuSTAR data analysis

In this paper we mainly focus on the NuSTAR observation of the source obtained as part of the approved guest observer program targeting X-ray binaries discovered by SRG. The observation was triggered following the SALT observation and was specifically optimized to mitigate potential stray light contamination from the bright nearby X-ray pulsar GX 301−2. In particular, it was scheduled to occur outside of the regular “pre-periastron” flares observed from this X-ray binary (Doroshenko et al. 2010).

Unfortunately, as illustrated in Fig. 2 it was not possible to avoid contamination completely. This resulted in a low signal to noise ratio for SRGU J124403.8−632231, particularly in the hard band above 20 keV. Therefore, for spectral and timing analysis in the hard band an optimized extraction region of $32''$ was chosen to achieve the optimal signal to noise ratio in the 20−80 keV energy band as described by Vybornov et al. (2018). However, taking into account that most of the photons are actually detected below 20 keV, for timing analysis in the soft band a larger region ($72''$) was selected using the same procedure. Considering the apparent stray light contamination from GX 301−2, the background was also extracted from a contaminated area on the same chip away from the source using a circular region with radius of 100″. We verified that the choice of the location of the background region (as long as it is extracted from a stray light contaminated region) does not affect any of our conclusions.

Timing analysis To search for possible pulsations, we extracted a background-subtracted light curve in the 3−20 keV energy band with a time resolution of 16 s, combining the events extracted from both NuSTAR units. We applied barycentric correction and then searched for pulsations using the generalized Lomb-Scargle periodogram (Zechmeister & Kürster 2009). The result is presented in Fig. 3 where a strong peak corresponding to a period of $\sim 538.56 \text{ s}$ is obvious (false detection probability as defined in Zechmeister & Kürster 2009) is $\log P \sim -87$.

We note that this peak is not associated with the pulsations from the nearby GX 301−2, which has a longer period of $\sim 670 \text{ s}$ that is clearly detected in the periodogram.
of the background light curve, but not for the background-subtracted light curve. The detected pulsations imply that the X-ray source is an accreting neutron star, so we conclude SRGA J124404.1−632232/SRGU J124403.8−632231 is likely indeed a new Be X-ray pulsar.

In order to refine the period value and in order to estimate its uncertainty, we used the phase-connection technique (Deeter et al. 1981). This approach allowed us to determine the final pulse period value as \( P = 538.70(5) \) s. Note that this value does not account for Doppler delays associated with the orbital motion of the pulsar, as its orbital parameters are not yet known and cannot be estimated using our comparatively short duration of NuSTAR observation (with respect to the expected orbital period).

To investigate the dependence of the pulse profiles of the source with energy, we extracted light curves in the 3–5, 5–10, 10–20, and 20–80 keV energy bands, and folded those with the determined period using 32 equally spaced phase bins. Again, the light curves from the two NuSTAR units were co-added and background was subtracted. As is evident from Fig. 3, the pulse profile is single peaked, sinusoidal, and exhibits no strong variations with energy. The pulsed fraction, defined here as \( \text{max}(r) - \text{min}(r) / \text{max}(r) + \text{min}(r) \), where \( r \) is the count rate, is high at all energies at \( \sim 55\% – 90\% \) and, as illustrated in Fig. 5, exhibits no clear increasing trend typical for X-ray pulsars (Lutovinov & Tsygankov 2009) or other features apart from a slight drop in the 5–10 keV band which is likely related to the chosen binning of the pulse profile and comparatively large measurement uncertainties.

Spectral analysis

Taking into account that the stray light contamination is mostly relevant in the hard band, the broadband NuSTAR spectrum was extracted using the region optimized for the hard band, i.e., using the extraction radius of 32′′. The SRG spectra were extracted as described above. The Swift/XRT spectrum of the source was extracted using the online tools provided by UKSSD (Evans et al. 2009). Considering the low statistics in all spectra with the exception of NuSTAR, we modeled six data sets (i.e., eROSITA spectra extracted using srctool task separately for the three surveys, the ART-XC spectrum for the third survey, the NuSTAR spectra extracted separately from the two units, and the spectrum from the Swift/XRT pointing carried out soon after NuSTAR) using the same model including a cross-normalization constant to account for differences in flux. As already mentioned, this includes contemporary observations by eROSITA and ART-XC which are, in fact, not strictly simultaneous due to the different field of view resulting in different length of scans over the source for the two instruments. All spectra were grouped to contain at least one count per energy bin and modeled using Xspec v12.11.1 using the Cash (Cash 1979) and Anderson-Darling (Anderson & Darling 1952) as fit and test statistics. This necessitated also the use of Monte-Carlo sampling for the final estimates of parameter uncertainties and the goodness of fit (using the chain and goodness commands in Xspec).

We considered several phenomenological models typically used to describe the spectra of X-ray pulsars to model the broadband spectrum of SRGA J124404.1−632232/SRGU J124403.8−632231. In particular, we first attempted to model the spectrum with absorbed cutoff power-law models, i.e. cutoffpl and hihecut models multiplied by a cross-normalization constant to account for differences in absolute flux calibration of individual instruments and flux variations between observations and TBars (Wilms et al. 2000) to account for absorption. However, in both

![Fig. 3. Lomb-Scargle periodogram for source (black) and background (red) light curves. Note that the ~670 s and ~335 s peaks from GX 301–2, which are visible in the background light curve are not present in the source light curve and do not overlap with the pulsed signal from SRGA J124404.1−632232/SRGU J124403.8−632231.](https://www.swift.ac.uk/user_objects/index.php

![Fig. 4. Normalized, background-subtracted pulse profiles of SRGA J124404.1−632232/SRGU J124403.8−632231 as function of energy as observed by NuSTAR.](https://www.swift.ac.uk/user_objects/index.php)
cases the cutoff energy was not constrained effectively reducing both models to a simple power law, which is unexpected for an X-ray pulsar. Nevertheless, the best-fit parameters for the absorbed power-law model are listed in Table 2. We note that the goodness of fit assessed using a set of spectra simulated based on the best-fit power-law model using the goodness command turned out to be not acceptable (with over 95% simulations yielding lower statistics than the data), so other models need be considered.

We note that the estimated broad-band un-absorbed source flux for the power-law model of ∼ 2.3 × 10^{-11} erg cm^{-2} s^{-1} implies a luminosity of ∼ 10^{35} erg s^{-1} for the assumed distance of 5.8 kpc (Bailer-Jones et al. 2021), i.e., SRGA J124404.1–632232/SRGU J124403.8–632231 appears to be more similar to the low-luminosity pulsars like X Persei than to classical Be transients. We considered, therefore, also a model consisting of two comptonization components represented by the Comptonization model (Titarchuk 1994) with linked seed temperatures used to describe spectra of X Persei and other similar sources (Doroshenko et al. 2012; Tsygankov et al. 2017). As a result, a relatively stable luminosity of X Persei is expected to proceed from the “cold” non-ionized accretion disk regularly replenished by the wind of the primary (Tsygankov et al. 2017), suggesting that the pulsar probably is indeed far from the companion and thus unlikely to cross the circum-stellar disk.

At first sight SRGU J124403.8–632231 appears to be variable by a factor of six between the observations. We emphasize, however, that due to the short duration of the individual scans compared to spin period of the source, and high pulsed fraction revealed by NuSTAR, most of this variability is likely associated with the short-term variability over the pulse period rather than long-term flux changes. We conclude, therefore, that long-term flux of the source remains comparatively stable with no clear outbursts typical for BeXRBs detected up to now.

### 3. Discussion

As discussed above, the observed properties of the newly discovered BeXRB pulsar SRGA J124403.8–632231 are rather similar to those of other long-period pulsars observed at low luminosities. In particular, similar spectra were reported from the transient XRBs 1A 0535+262 (Tsygankov et al. 2019b) and GX 304–1 (Tsygankov et al. 2019c) when observed in quiescence. Another object where a similar X-ray spectrum was observed is the only persistent BeXRB known, i.e. X Persei, which historically was only observed in the low-luminosity state, presumably due to the longer orbital period and wider separation between the neutron star and the donor.

Finally, comparison of spectra normalization obtained by various instruments also allows to assess variability of the source on long timescales. As illustrated in Table 2, the source flux appears to be variable by a factor of six between the observations.

| energy, keV | powerlaw | CompTT2 |
|------------|----------|----------|
| 0.12(3)    | 1.08(3)  | 1.08(4)  |
| 0.6(1)     | 0.6(1)   | 0.6(1)   |
| 1.3(4)     | 1.3(3)   | 1.3(3)   |
| 3.3(7)     | 2.9(3)   | 2.9(3)   |
| 4.1(7)     | 2.6(3)   | 2.6(3)   |
| 2.11(4)    |          |          |
| 3.26(3)    | 1.6(2)   | 0.08(1)  |
| 10^{-11}   | 2.6(3)   | 1.6(2)   |
| 1.1426     | 1.0/1.3  |
| -8.81/1432 | -9.89/1427 |           |
| 46         | 64       |

Table 2. Broadband spectral modeling results for SRGA J124404.1–632232/SRGU J124403.8–632231 using absorbed power law (powerlaw) and two-component comptonization models (CompTT2).

Notes. Test statistics probability (log P(>T)) and Bayesian information criterion (BIC) values are quoted.

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Fig. 5. Pulsed fraction of SRGA J124404.1–632232/SRGU J124403.8–632231 as function of energy as observed by NuSTAR.
will eventually undergo an outburst. Indeed, the suggestion of the orbital period by Mroz & Udalski (2021) is based on the detection of several short episodes when the companion brightened by ~0.1 mag (illustrated in Fig. 7). However, considering that only five such episodes can be identified in the light curve, one can not be fully sure that those are periodic and associated with orbital motion. A search for periodicity in the raw OGLE light curve reveals several marginally significant peaks, and the peak at ~140 d, i.e., slightly longer than the period suggested by Mroz & Udalski (2021), is only one of them. In particular, the longer period of ~225 d also appears to be consistent with most of the brightening episodes (see i.e. Fig. 7). Furthermore, the 225 d period also better fits the correlation between Hα EW and orbital period (discussed in Sect. 2.1). This period corresponds to the expected EW of ~50 Å (Reig 2011), consistent with our measurement with SALT. Both suggested values are also consistent with expectations based on the relation between spin and orbital periods for X-ray pulsars (Corbet 1986) as illustrated in Fig. 5 (here shown based on the data reported in the catalog of the Galactic HMXBs by Liu et al. 2006). Further monitoring of the source in X-ray and optical bands is, therefore, required to clarify the long-term behaviour of the source.

4. Conclusions

SRGA J124404.1−632232/SRGU J124403.8−632231 is one of the first new Galactic X-ray pulsars identified in the all-sky X-ray survey of SRG (Lutovinov et al., submitted), and the first confirmed Galactic Be X-ray binary (note that several such objects also have been already detected in the Large Magellanic Cloud where longer exposures are available, see e.g. Maitra et al. 2021b; Haberl et al. 2020; Maitra et al. 2020). Although it is not yet fully clear whether the source is a persistent low-luminous pulsar similar to X Persei or a low duty cycle transient Be X-ray binary. The non-detection of a strong outburst with peak luminosity of ~10^{36–37} erg s^{-1} typical for other BeXRBs despite the observed prominent Hα emission line from the companion, which indicates the presence of an expanded decretion disk (Reig et al. 2016) around the donor suggests, however, that the former is more likely. We note that pre-launch estimates indicate that several tens of objects like this one are expected to be detected in the eROSITA survey (Doroshenko et al. 2016), and SRGA J124404.1−632232/SRGU J124403.8−632231 might be the first of them. In fact, only SRG can unveil the population of such faint persistent objects and we are searching for more of those in the survey.

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Fig. 8. Orbital period - spin period (Corbet 1986) diagram for wind accreting (blue) and Be (red) high-mass X-ray binaries. The position of SRGA J124404.1−632232/SRGU J124403.8−632231 is indicated with the yellow line assuming the orbital period from 138 to 225 d.

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