SRG/eROSITA discovery of an extremely radio-faint iron-rich X-ray candidate supernova remnant SRGe J003602.3+605421=G121.1-1.9

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ABSTRACT

We report the discovery of a candidate X-ray supernova remnant SRGe J003602.3+605421=G121.1-1.9 in the course of SRG/eROSITA all-sky survey. The object is located at (l,b)=(121.1°,-1.9°), is ≈ 36 arcmin in angular size and features nearly circular shape. Clear variations in spectral shape of the X-ray emission across the object are detected, with the emission from the inner (within 9′) and outer (9′-18′) parts dominated by iron and oxygen/neon lines, respectively. The non-equilibrium plasma emission model is capable of describing the spectrum of the outer part with the initial gas temperature 0.1 keV, final temperature 1.8 keV, and the ionization age ~ 2 × 10^{10} cm^{-3} s. The observed spectrum of the inner region is more complicated (plausibly due to the contribution of the outer shell) and requires substantial overabundance of iron for all models we have tried. The derived X-ray absorption equals to (4 – 6) × 10^{21} cm^{-2}, locating the object at the distance beyond 1.5 kpc, and implying its age ~ (5 – 30) × 1000 yrs. No bright radio, infrared, H_α or gamma-ray counterpart of this object have been found in the publicly-available archival data. A model invoking a canonical 10^{51} erg SN Ia explosion in the hot and tenuous medium in outer region of the Galaxy ~9 kpc away might explain the bulk of the observed features. This object might be a rare example of an old SN Ia remnant in our Galaxy still bearing signatures of the ejecta enrichment and probing the thermal and non-thermal properties of the hot phase of the ISM above the cold disc. This scenario can be tested with future deep X-ray and radio observations.

Key words: ISM: supernova remnants – Interstellar Medium (ISM), Nebulae, radiation mechanisms: thermal – Physical Data and Processes, X-rays: general – Resolved and unresolved sources as a function of wavelength, Galaxy: halo – The Galaxy

1 INTRODUCTION

Strong shock waves driven into the interstellar medium by supernova explosions are believed to be the primary acceleration sites responsible for the populations of cosmic ray protons and ions up to 10^{15} eV in our Galaxy (Ginzburg & Syrovatskii 1969). The direct observation of this acceleration process, however, comes from the observation of the gamma-ray radiation and radio synchrotron emission produced by the relativistic particles (e.g. Berezhko & Völk 2004).

Indeed, the wide area surveys of the Galactic plane at radio frequencies not only allowed to discover a few hundred supernova remnants (SNR) to date (Green 2019), but also derive insightful scaling relations (e.g. between the size of the remnant and its surface brightness, Clark & Caswell 1976; Lozinskaya 1981; Berkhuijsen 1986; Green 1984; Urošević 2020), as well as reveal intricate properties of individual objects.

Although many of the general properties of this emission are in agreement with the basic predictions of the diffuse shock acceleration (DSA) scenario, the exact mechanism and efficiency of electrons acceleration at collisionless interstellar shock waves still remains a matter of the debate, and observations of the objects at different evolution stages or environment conditions offer a possibility to look for certain relations revealing underlying physical processes (e.g. dependence on the shock Mach number or strength and orientation of the ambient magnetic field). On the other hand, it is expected that at the late stage of their evolution, SNRs must become increasingly fainter, severely limiting and biasing the currently available samples.

There is a growing number of the supernova remnants identified at other wavelengths and featuring very weak or non-detectable (at the current sensitivity level) radio emission. These, for instance, include supernova candidates identified in optical, X-ray and gamma-ray surveys (Long 2017). Further increase in the size of radio-blind SNR samples is vital to understand whether such objects are rare examples failing to accelerate relativistic particles due to some particular reason, or there is a large population of such events missed in the previous samples because of the selection criteria.

The unprecedentedly deep and uniform maps provided by the all-sky survey by the eROSITA telescope (Predehl et al. 2021) onboard the SRG observatory (Sunyaev et al. 2021) offer unique opportunities to look for extended objects of relatively low surface brightness, in particular in the soft X-ray band, from 0.4 to 2.3 keV. As a result, such faint and extended X-ray structures, like eROSITA bubbles (Predehl...
et al. 2020), Hoinga supernova remnant (Becker et al. 2021), and the candidate Ia supernova remnant in the Galactic Halo SNR G116.6-26.1 (Churazov et al. 2021a, hereafter Paper I) have already been discovered. For the latter object in particular only very weak radio emission was recently discovered (Churazov et al. 2022, hereafter Paper II) in the data of LOFAR Two-metre Sky Survey (LoTTS-DR2, Shimwell et al. 2022), possibly because this supernova exploded in the hot and tenuous medium of the Galactic Halo, reducing the shock Mach number and the efficiency of particle acceleration.

Here we report SRGe/eROSITA discovery of an X-ray bright and extremely radio-faint candidate supernova remnant located in the Galactic disc. Based on the interstellar absorption value inferred from the X-ray spectra we place it at a distance of >1 kpc at 90% confidence level and >3 kpc at the 1σ level, making this object an excellent candidate for the evolved SNR located in the “normal” Galactic disc environment. No counterpart of this object is observed at other wavelengths, including radio, optical and gamma-ray bands.

2 X-RAY OBSERVATIONS

Orbital observatory SRG (Sunyaev et al. 2021), featuring two focusing X-ray telescopes, eROSITA (Predehl et al. 2021) and ART-XC (Pavlinsky et al. 2021, 4-30 keV) was launched in July 2019 and started to perform the all-sky survey mission in December 2019. By now four complete all-sky snapshots have been obtained, resulting in the unprecedentedly deep and uniform X-ray maps of the whole sky being obtained.

Here we use the data accumulated over 4 consecutive scans, with the total effective exposure amounting to 1225 seconds (i.e. = 8600 s in equivalent exposure for one telescope module). For the imaging analysis we use the data of all seven telescope modules (TM), while TMs 5 and 7 are excluded from the spectral analysis due to possible impact of the optical light leak on their signal (e.g. Predehl et al. 2021). Initial reduction and processing of the data were performed using standard routines of the eSASS software (Brunner et al. 2018; Predehl et al. 2021), while the imaging and spectral analysis were carried out with the background models, vignetting, PSF and response function calibrations built upon the standard ones via slight modifications motivated by results of calibration and performance verification observations (e.g. observations of the Coma cluster, Churazov et al. 2021b).

2.1 X-ray imaging

After correction for the vignetting and background subtraction, the obtained maps are routinely processed in terms of detecting point and mildly-extended sources and creating their catalogues. By means of proper modelling and subtraction of these sources, maps of the unresolved diffuse emission are obtained, consisting mainly of the unresolved cosmic X-ray background and Galactic (genuinely) diffuse emission. Already a visual inspection of these residual emission maps allows one to spot previously unknown relatively faint extended structures.

Inspection of an image in soft X-ray band (from 0.4 to 2.3 keV) centred on the position near Galactic coordinates (l, b) = (121.1°, −1.9°) (i.e. (RA,Dec)= (9.1°, 60.9°) in the equatorial coordinates) revealed a faint diffuse emission of nearly circular shape half of the degree in diameter, hereafter SRGe J003602.3+605421=G121.1-1.9. Figure 1 shows the image in the 0.4-2.3 keV band, obtained by masking point-like and mildly extended sources down to 0.5-2 keV flux $3 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ and smoothing with a 30 arcsec gaussian window to enhance visibility of the discovered diffuse emission.

Figure 2 shows the corresponding radial profile of the X-ray surface brightness centred on (RA,Dec)= (9.0196°, 60.9140°). One can see that the excess emission extends to ≈18 arcmin from the geometrical center, has rather flat radial profile and varies between 1 and 2 times of the background level in amplitude. The latter is estimated to be equal to $1.5 \times 10^{-6}$ photons s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$ from the 20’-30’ annulus region around the object.

No significant excess emission is visible at energies above 2.3 keV, suggesting that the spectrum of the object’s emission is soft.

The estimated 1σ upper limit on the 2.3-4 keV surface brightness is $3 \times 10^{-8}$ ph s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$, i.e. ~10% of the measured background level, corresponding to the total 2.3-4 keV flux $>10^{-13}$ erg s$^{-1}$ cm$^{-2}$.

Indeed, splitting of the standard 0.4-2.3 keV into three sub-bands, 0.4-0.7, 0.7-1.3 and 1.3-2.3 keV shows no significant excess emission already in the 1.3-2.3 keV band. A pseudocolor image combining emission in 0.4-0.7 and 0.7-1.3 keV bands is shown in Figure 3, where original pixel size resolution was degraded to 1.5’ size and $σ = 90’$ gaussian smoothing was applied in order to suppress low counts noise. Spectral colour variations are clearly visible on this image and in the simplest approach, we can separate harder from softer emission by $r=90’$ radius.

A possible reason for that might be the difference in the foreground absorption, causing more absorbed regions having harder spectra. In order to verify this we check the maps of the dust emission at 100 μm in the same region from the Improved Reprocessing of the IRAS
Figure 2. A radial profile of the X-ray surface brightness of the diffuse emission in the 0.4 to 2.3 keV band extracted with 1 arcmin linear without (black) and with (blue) subtraction of the estimated astrophysical background level. The errorbars show purely statistical (i.e. photon counts) 1σ uncertainty, the red horizontal dashed line marks the estimated level of the background emission. The vertical dashed lines mark 9’ and 18’ radii used as boundaries of the spectral extraction regions.

Figure 3. A pseudo-two-colour image showing surface brightness distribution in 0.4-0.7 keV (red) and 0.7-1.3 keV (green) bands. The images were downgraded to 1.5’ pixel size and smoothed with a σ=90” gaussian filter after masking point sources in order to suppress the noise and enhance visibility of the 'colour' variations across the region of G121.1-1.9. The white circles show the 0’-9’, 9’-18’, 18’-27’ concentric regions used for the spectra extractions.

Figure 4. IRIS map of emission at 100 μm in the region of G121.1-1.9 with the contours of X-ray emission in 0.4-0.7 keV (red) and 0.7-1.3 keV (blue) bands overlaid. The dashed black contours correspond to three levels of the 100 μm emission, namely the mean one within the G121.1-1.9 region and ±25% of it.

2.2 X-ray spectroscopy

We extract spectra, calculate corresponding response functions and estimate particle background signals for three concentric annulus regions: 0’-9’, 9’-18’ and 18’-27’ in radius (shown as white circles in Figure 3). The latter ring is used for estimation of the local astrophysical background, taking into account significant variations in the foreground absorption on a scale of ~ 1 degree in this region close to the Galactic plane. The resulting particle background-subtracted, effective area-corrected spectra are shown in Figure 5, re-normalised to 1 arcmin$^2$ surface area. Strong excess of the emission above the background level (black points) is present only in the band from 0.5 to 1.3 keV, with the spectrum of the inner part (green points) peaking around 0.8 keV, while the spectrum from 9’-18’ arcmin having relatively flat shape between 0.5 and 1 keV.

We fit the background emission with the standard three-component model TBabs*apec+TBabs(apec+powerlaw) in the XSPEC X-ray fitting package (Arnaud 1996). The first component stands for the Local Hot Bubble emission, and it was fitted with the fixed temper-
ature, $kT = 0.1$ keV, and metallicity, $Z = 1$ (the Solar abundance set of Anders & Grevesse 1989 is used throughout the paper). The second component describes (in a phenomenological way) the emission of the Galactic Halo, with $kT \sim 0.3$ keV, and solar metallicity. The latter component stands for the Cosmic X-ray Background radiation, with the fixed slope $\gamma = 1.41$. The absorbing column density for the last two components was a free parameter and turned out to be $(6 \pm 0.1) \times 10^{21} \text{ cm}^{-2}$.

This value is consistent with the total line-of-sight absorbing column density in this direction estimated at the level $\approx 6.1 \times 10^{21} \text{ cm}^{-2}$ based on the method of (Willingale et al. 2013), which accounts for contributions of the atomic ($\approx 4.7 \times 10^{21} \text{ cm}^{-2}$, Kalberla et al. 2005) and molecular gas ($\approx 1.4 \times 10^{21} \text{ cm}^{-2}$ derived from the reddening value of $E(B-V) \approx 0.91$, Schlegel et al. 1998) to it.

For the source regions, the emission was fitted with the same background model complemented with the additional component standing for the source emission. We have tried the collisional ionisation equilibrium plasma model apec, but it provided poor fits to the spectra. Instead, we used non-equilibrium plasma ionisation model with variable heavy metal abundances vrnei (Borkowski et al. 2001). The starting temperature was $kT_1$ was fixed at 0.1 keV for the both source regions, while the final temperature $kT_2$ was allowed to vary. The initial gas temperature was fixed, because it was only very poorly constrained from the low side when kept as a free parameter, reflecting the fact that at moderate values of the ionization parameter $\tau \sim 10^{10} - 10^{11} \text{ cm}^{-3} \text{ s}$ there is already no strong influence of the initial temperature as far as it is high enough to ensure dominance of the helium-like ion in the ionization state of oxygen. After the fit with the solar abundance of the all elements, some residuals were obvious in the region of the neon lines for the outer region and iron lines for the inner region. Motivated by that, we allowed abundances of these elements to vary freely during the fits and found that neon overabundance at the level of $\approx 1.6$ and iron overabundance at the level of $\approx 3$ can indeed improve the fit significantly. The final models overlaid over the astrophysical-background subtracted spectra in the 0.4-1.3 keV is shown in Figure 6, with positions of the most important lines marked and labelled correspondingly.

The robustness of the fitting procedures was checked with an extensive survey of the parameter space over the highly non-linear parameters, namely the ionisation parameter $\tau = n_e t$, where $n_e$ is the local gas number density and $t$ is the ionisation time scale (see Borkowski et al. 2001, for details), and the total absorbing column density $N_H$. Results of these surveys were used for error estimation of the model parameters. Figure 8 shows the $\chi^2$ maps on the $\tau - N_H$ plane for both of the source regions. The resulting parameters of the fits are listed in Table 1.

First of all, no significant difference in the value of $N_H$ is required between the inner and the outer region, both are consistent with $N_H = (5 \pm 1) \times 10^{21} \text{ cm}^{-2}$, which is only slightly smaller than the total absorbing column density in that direction. This implies that the source is located further away than the bulk of the absorbing gas along the line-of-sight. We exploit this information to estimate the distance to the object from the 3D absorption maps in Section 2.3.

Second, the best fit parameters imply that the inner and outer regions differ mostly in the value of the ionisation parameter $\tau$, and not in the final temperature $kT_2$. The latter turns out to be $\sim 0.5$ keV for both regions, while the former differs by a factor of 2.5, which is not inconsistent with the assumption that the gas in the inner region was shocked earlier and had more time to equilibrate. On the other hand, the difference in $\tau$ might come from the higher density in the inner region. Indeed, if we combine the derived model normalisations $N_{\text{inner}} = 3.1^{+2.8}_{-1.8} \times 10^{26}$, $N_{\text{outer}} = 1.8^{+3.8}_{-1.8} \times 10^{26}$ for the surface brightness within the inner and outer regions with their areas and approximate estimation of their volumes, we get

$$\frac{N_{\text{outer}}}{N_{\text{inner}}} = \sqrt{\frac{R_{\text{outer}}^2}{R_{\text{inner}}^2}} \frac{R_{\text{inner}}^3}{R_{\text{outer}}^3} \frac{1}{1 + 1} \approx 0.5$$

for $R_{\text{outer}}/R_{\text{inner}} = 18'/9' \approx 2$ and $N_{\text{outer}}/N_{\text{inner}} \approx 0.6$. Thus a large portion of the difference in $\tau$ might be attributed to the difference in the gas densities. Given the large uncertainties and degeneracies between the parameters of the fits, it is hard to draw a more quantitative conclusion on that, however. Also, a single-zone model for these regions might be an oversimplification, possibly biasing the derived parameters towards values reflecting conditions in the regions of higher emissivity. Unfortunately, low count statistics of the data does not allow us to perform more spatially-resolved spectral analysis.

Finally, the fits for the inner and outer regions require overabundance in iron ($3.3 \pm 1.2$) and neon ($1.6 \pm 0.5$), respectively. Since at the temperatures of $kT \sim 0.1-0.5$ keV the continuum emission is rather weak, this over abundances mostly reflect the ratio of the corresponding lines to the lines of helium- and hydrogen-like oxygen at 574 eV and 654 eV (see Figure 6). The required overabundance of neon, however might be connected to the particular choice of the standard Solar abundance set (e.g. using the set of Feldman (1992) instead of Anders & Grevesse (1989) results in slightly smaller best fit value which is consistent with unity within the error bar) and imperfections of the single-zone modelling of the emission from this region. Indeed, the ratio of neon to oxygen lines might be strongly boosted in the regions of higher electron temperature due to exponential sensitivity in excitation efficiencies for the corresponding transitions (e.g. Paper I). Although, the vrnei naturally accounts for this, the single-zone assumption might lead to substantial deviations from the spectrum observed in reality.

The derived overabundance of iron in the inner region cannot be fully explained by any of these effects, however. Indeed, using another set of standard abundances, e.g. Anders & Grevesse (1989), would result in even higher values, $Z_{Fe,inner} \approx 5$. Also, the iron ions responsible for the observed lines correspond to significantly higher temperatures, than the lines of oxygen and neon, indicating that not only a boost in the collisional excitation but also the real change in the ionization state should have occurred.

Given the clear signatures of radial gradients, a-de-projection technique is needed in order to avoid a contamination of the SNR inner regions spectra by the emission of the outer shells. However, the statistical significance of the currently available data allows at most a two-shell approximation, which is sensitive to the choice of the boundary between the shells. We, therefore, defer reporting the results of the deprojected spectral analysis for future publications and show instead a set of radial profiles in narrow energy bands centered at the most prominent emission lines.

We have built the radial profiles of the X-ray emission in narrow energy bands, containing the oxygen lines (O VII and O VIII, 0.4-0.7 keV), iron lines (Fe XVII, 0.7-0.9 keV) and neon lines (0.9-1.1 keV). The resulting profiles (after subtraction of the constant level different radial shells can contribute, especially when the inner region is considered. It is, therefore, possible that the failure of the APEC model is caused by the projection effects.
estimated from the ring outside the object) are shown in top panel of Figure 7. One can easily see the difference in the radial behaviours of the emission in these bands - for the 0.4-0.7 keV, the radial profile is edge-brightened; for the 0.7-0.9 keV, it is centrally-peak. The major contribution to the edge-brightening in the oxygen band is provided by the O VII line, as can be seen in the radial profiles built for even narrower energy bands, 0.52 to 0.61 and 0.61 to 0.7 keV, centred on the O VII and O VIII lines, respectively (middle panel in Figure 7). Similar behaviour is observed for the lines of helium- and hydrogen-like neon, Ne IX and Ne X in 0.87-0.96 and 0.96-1.05 keV bands (bottom panel in Figure 7).

Some part of the centrally peaked emission profile for iron might in principle be attributed to the direct contribution and gas enrichment by the iron-rich ejecta, but the observed behaviour of different lines can also be affected by the ionisation state gradient across the object, as shown by results of the spectral fitting presented above (see also the discussion in Section 4). Once again, in order to disentangle these possibilities the de-projected spectra must be considered, which requires a robust model for the radial emission measure distribution.

### 2.3 Distance estimate from the 3D absorption profile

The measured value of the interstellar absorbing column density $N_H$ allows us to estimate the distance to the object based on the 3D maps of the Galactic extinction. Namely, we took advantage of the maps of (Sale et al. 2014) based on the photometric data of the IPHAS/IGAPS surveys, and (Chen et al. 2019), STILISM (Capitanio et al. 2017; Lallement et al. 2019), and Bayestar19 (Green et al. 2019), all based on the Gaia (Gaia Collaboration et al. 2016) parallax measurements. All these maps differ in the probed distance range and accuracy of the reconstruction, as well as in the zero-point offset and conversion to the $E(B-V)$ values. Since we are interested mostly in the shape of the cumulative distribution of the absorption, i.e. the way how it is accumulated over the line-of-sight, we start by checking that the IPHAS profile is consistent with the LOS-integrated value of absorption from Schlegel et al. 1998 at its furthest end. After that, by slight adjustment in normalisations, we match all other profiles around 1.5 kpc, where all of them appear to be well constrained. The resulting combined profile for a $R = 18'$ aperture centred on G121.1-1.9 is shown in Figure 9.

We convert the measured X-ray absorption $N_H = (5.0\pm1.1)\times10^{21}$ cm$^{-2}$ to the $E(B-V)$ value by rescaling the total $E(B-V)$ value in that direction down to by the factor $N_{H,tot}/N_H \approx 1.3 \pm 0.3$.

### Table 1. Main observed parameters of the X-ray emission from the newly found SNR candidate G121.1-1.9, namely equatorial and Galactic coordinates of its centre, angular size(radius), the total observed background-subtracted 0.4-2.3 keV flux and the intrinsic 0.4-2.3 keV after correction for the interstellar absorption. The spectral parameters are given for emission from the 0.4-2.3 keV flux and the intrinsic 0.4-2.3 keV after correction for the interstellar absorbing column density $N_H$.
Khabibullin et al.

Figure 7. Same as Fig. 2 but for the narrow energy bands centred on various emission lines. Top panel - 0.4-0.7 keV (O VII and O VIII, red) and 0.7-0.9 keV (Fe XVII, blue). Middle panel - 0.52-0.61 keV (O VII, red) and 0.61-0.7 keV (O VIII, blue). Bottom panel - 0.87-0.96 keV (Ne IX, red) and 0.96-1.05 keV (Ne X and Fe XXI, blue). The dashed horizontal lines indicate the levels of the subtracted background emission, vertical lines mark 9’ and 18’ radii.

Figure 8. Results of the regular parameter space mapping in \( N_H \) and \( \tau \) coordinates for the 0’-9’ (squares) and 9’-18’ (crosses) regions. The colour shows the difference \( \Delta \chi^2 \) in the \( \chi^2 \) value with respect to the minimum value \( \chi^2_{\text{min}} \), demonstrating the shape of the confidence contours around the best fit values. The grey and black contours correspond to the \( \Delta \chi^2 \) values of 1 and 2 for the inner and outer regions, respectively.

resulting in \( E(B-V) \approx 0.75 \pm 0.15 \), meaning that \( E(B-V) \approx 0.6 \) is a 1\( \sigma \) lower limit. Taken at face values, \( E(B-V) \approx 0.75 \) would locate G121.1-1.9 at the distance of 4-6 kpc, and the 1\( \sigma \) lower limit at 2.5 kpc. If we consider 90% confidence level for the measured \( N_H \), we get the lower limit for the distance around 1 kpc, meaning that it should be located far enough so that the bulk of the local gas absorption is already accumulated (see the discussion in Section 3).

3 DATA AT OTHER WAVELENGTHS

Since the newly discovered object is located in the Galactic plane with \( b \approx -2 \) deg, a plenty of publicly available data exist for this region, including those which have been commonly used for identification of the supernova remnants.

3.1 H\( \alpha \)

We have used the data of the INT Galactic Plane Survey (IGAPS) in order to construct a mosaic image of the 1.4\( \times \)1.4 deg\(^2\) region surrounding G121.1-1.9 in the narrow-band centred on H\( \alpha \) emission line (Greimel et al. 2021). The resulting image, built after iterative background matching and co-adding of the individual images, performed using MONTAGE software\(^3\), is shown in Figure A1 in Appendix.

The image was convolved with a 20" filter with 3\( \sigma \)-clipping applied in order to suppress contribution of the numerous point point source present in the field. In addition, we have also constructed a continuum-corrected H\( \alpha \) map based on the data of the Virginia Tech Spectral-Line Survey (VTSS) (Dennison et al. 1998), featuring poorer angular resolution but more uniform coverage across the

\(^3\) http://montage.ipac.caltech.edu
3.2 Radio

Radio emission is ubiquitously detected from the supernova remnants in our Galaxy (Green 2019; Vukotić et al. 2019) and in external galaxies (e.g. Urošević et al. 2005). Moreover, there is a relation connecting the physical size and surface brightness of the radio emission, i.e. the so-called \( \Sigma \sim D \) relation (Clark & Caswell 1976; Lozinskaya 1981; Berkhuysen 1986; Green 1984; Urošević et al. 2005; Arbutina & Urošević 2005; Vukotić et al. 2019), which possibly reflects evolutionary track of the remnants located in some “typical” Galactic environments (e.g. Berezhko & Völk 2004; Asvarov 2006; Urošević 2020).

Thanks to the location in the Galactic disc, the position of G121.1-1.9 falls into footprints of a number of sensitive radio surveys at various frequency bands. Namely, we constructed maps of the 1.4×1.4 deg\(^2\) regions surrounding the position of G121.1-1.9 based on the data of the VLA Low-Frequency Sky Survey Redux (VLSSr) at 74 MHz (Cohen et al. 2007; Lane et al. 2012), the TIFR GMRT Sky Survey (TGSS) Alternative Data Release 1 (ADR1) at 150 MHz (Intema et al. 2017), the Westerbork Northern Sky Survey (WENSS) at 92 cm (326 MHz, Rengelink et al. 1997), the Canadian Galactic Plane Survey (CGPS) at 408 MHz and 1.4 GHz (Taylor et al. 2003), the NRAO VLA Sky Survey (NVSS) 1.4 GHz (Condon et al. 1998), Effelsberg Radio Continuum Survey of the Galactic Plane at 11 cm (2.7 GHz, Reich et al. 1984; Forst et al. 1990), the Green Bank 6cm (4.85 GHz) survey (Condon et al. 1994), the Arcminute Microkelvin Imager Galactic Plane Survey (AMIGPS) at 15.7 GHz (Perrott et al. 2013, 2015). Some of them were generated using services provided by the Centre d’Analyse de Données Etendues (CADE)

4 http://cade.irap.omp.eu

3.3 Global gas environment and search for cavities

Thanks to the data of Gaia (Gaia Collaboration et al. 2016), the distribution of gas within a few kpc around the Sun can be now reconstructed with high accuracy (e.g. Lallement et al. 2019). In Figure 10 we show two projections of the global gas distribution centred on the direction of G121.1-1.9 extracted from the 3D maps of the STILISM project (Lallement et al. 2019). Namely, the X-Y projection shows a view “from top” on a 200 pc-thick slice of the Galaxy, i.e. it shows distribution of the gas in plane of the Galactic disc, with the X axis being directed towards the center of G121.1-1.9. The dashed lines illustrated the angular extent of the object. Correspondingly, Z-R projection shows the projection of a 1-deg
In agreement with the radial profiles of absorption considered in Section 2.3, we see that the bulk of the gas in this direction is concentrated within 1.5 kpc, corresponding to the Local Arm of the Galaxy. Further gas condensations start to appear at a distance of ~ 3.5 kpc, corresponding to the Perseus Arm (Xu et al. 2021). Location of the object beyond 1.5 kpc would indeed imply relatively low density environment, corresponding to the inter-arm region at the height of ~ 100 pc below the Galactic plane.

Cavities in the distribution of atomic and molecular gas associated with old supernova remnants can also be searched for in the velocity-resolved data on atomic hydrogen and molecular species. In order to do so, we used the velocity-resolved HI data from the Canadian Galactic Plane Survey (Taylor et al. 2003).

Figure 11. Line-of-sight velocity profile of the HI emission from the 30×30 arcmin region centred on G121.1-1.9 (red line) in comparison to the averaged profile from the six surrounding rectangular regions of the same size (black line). The blue shaded region shows the range from the averaged value minus standard deviation to the averaged value plus standard deviation, while the shaded grey region shows the span from the minimum to the maximum value among all background regions in every velocity channel. The dashed vertical lines mark three velocity regions (around -68.2, -25.4 and -7.2 km/s), where the surface brightness within the source region falls beyond the range charted by the minimum and maximum values.

Figure 10. 3D maps of the dense gas distribution based on STILISM. Top panel shows projection of 200-pc thick slice in the Galactic plane, with the X axis being directed towards G121.1-1.9. Bottom panel shows gas distribution in a 1-deg wide wedge perpendicular to the Galactic plane and centred on G121.1-1.9. The white dashed lines illustrate the angular extent of the object.

3.4 Massive stars

The distribution of massive star formation regions which are might be birth place for a SN II progenitor is closely related to the distribution of the dense gas (e.g. Lallement et al. 2019). For the direction of G121.1-1.9, the main star-formation regions (e.g. Reid et al. 2019)
and massive individual O-type stars (Xu et al. 2021) are indeed concentrated within the two main arms, the Local Arm and the Perseus Arm. A progenitor star with the initial velocity of $v \sim 10 \, v_{10}$ km/s can travel $d \sim 100$ pc $v_{10} \, t_{10}$ in $10 \, t_{10}$ Myrs. This distance is in principle enough to escape denser regions of the spiral arm and enter the inter-arm medium. On the other hand, 100 pc displacement in the picture plane implies a shift by $\sim 1.9 (d/3kpc)$ deg, so that original birth site of the progenitor star is difficult to identify.

Indeed, we have searched SIMBAD database (Wenger et al. 2000) for all objects within $\sim 3$ degrees of G121.1-1.9, and selected only stars and star clusters with the parallax measurements. The resulting sky distribution of them is shown in Figure 12. The nearest star clusters, NGC 189, is located 0.45 deg away and has the distance estimate 1.3 kpc, i.e likely at the furthest edge of the Local Arm. The second one, NGC 136, is located at 5.5 kpc, instead, likely corresponding to the Perseus Arm. There is a number of other clusters being present in this field as well, with the nearest one located at 0.7 kpc and the median value for the distance being close to 3 kpc. Thus, location of the progenitor star somewhere in the inter-arm region from 1.3 kpc to 5.5 kpc away from the Sun and 50-200 pc away from the Galactic plane is not unlikely.

### 3.5 X-rays

The latter argument is further confirmed by the presence of High Mass X-ray binary, IGR J00370+6122, in the same field (0.46 deg to the North of G121.1-1.9 center) at the estimated distance of 3-4 kpc (e.g. Uchida et al. 2021). Also the spectral analysis of this system shows that the likely value of the interstellar absorbing column density is $\sim 6 \times 10^{21}$ cm$^{-2}$, consistent with the value inferred by us for G121.1-1.9 (the same is true for the inferred reddening of the optical companion, BD+60 73 = HIP 2930, Brandt 2021). Moreover, the measured proper motion of this star, $\mu_{RA} = -1.644 \pm 0.034$ mas yr$^{-1}$ and $\mu_{Dec} = -0.804 \pm 0.036$ mas yr$^{-1}$, implying in plane velocity $\approx 30$ km/s at the distance of 3.5 kpc, indeed allowing to travel at least 30 pc ($\approx 0.5$ deg) in 1 Myr.

It is also interesting to look for a possible remnant of the supernova explosion, i.e. a central compact object (CCO), among the X-ray sources observed in the field. In the case of an isolated neutron star it is expected to have very soft X-ray spectrum and lack an optical counterpart, akin CCO discovered in the Cas A (Tananbaum 1999; Pavlov et al. 2000) and Puppis A (Petre et al. 1996) SNRs.

There is a number of other point sources with the 0.5-2 keV fluxes above $3 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ within this radius, with the majority of them having relatively soft spectrum and probably associated with stars within 1 kpc (see Figure 13). For instance, the brightest ($F_{X,0.4-2.3} = 2.4 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$) source inside the extend of G121.1-1.9, SRGe J003545.0+604955, is probably associated with a nearby (~ 200 pc) star Gaia EDR3 430106477517090560 (Brandt 2021). The HMXB IGR J00370+6122 clearly stands out in this image thanks to its relative brightness and very blue emission.

Another remarkable source is 1RXS J003817.1+605815, which is to the East located right at the boundary of the diffuse emission. It is detected by eROSITA as SRGe J003816+605730 with the flux of $\approx 4 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. It could be associated with a Gaia source Gaia EDR3 427131306439799296 (=PS1 181150095671982153) with the measured parallax value 0.33±0.05 and proper motions $\mu_{RA} = -2.310 \pm 0.044$ mas yr$^{-1}$ and $\mu_{Dec} = -0.111 \pm 0.053$ mas yr$^{-1}$ (Gaia Collaboration et al. 2021). There is also a radio source CGPS J003816+605634 (= NVSS J003816+605635) in 50” away from it, which is however much larger then the positional accuracy for both X-ray and radio location (Taylor et al. 2017). The measured proper motion implies velocity of $\sim 30$ km/s, while X-ray flux corresponds to the 0.4-2.3 keV luminosity at the level of 4$x10^{32}$ erg/s. This source however is unlikely to be a remnant, since in order to be at the SNR boundary, it has to move with the same mean velocity as the shock, i.e at least a few hundreds km/s, which is apparently not the case.

The cross-correlation of X-ray detections down to the flux $10^{-14}$ erg s$^{-1}$ cm$^{-2}$ with the CGPS catalogue of radio sources (Taylor et al. 2017) gave no probable matches within 15 arcmin from the center.

### 3.6 Gamma-rays

We have searched the Fermi Large Area Telescope Fourth Source Catalog (4FGL, Abdollahi et al. 2020) for the sources that might be associated with G121.1-1.9. The two nearest sources are 4FGL J0041.3+6052 and 4FGL J0035.8+6131, both being $\approx$38 arcmin from the centre of G121.1-1.9 and $\approx$20 arcmin from its boundary, which is well above the positional uncertainties of these sources, $\approx$6 arcmin. The detected 1-100 GeV gamma rays from 4FGL J0041.3+6052 might be produced by cosmic rays accelerated in G121.1-1.9 escaped the source and illuminating a nearby dense cloud as it is the case in some other SNRs. However, the gamma ray energy flux detected from 4FGL J0041.3+6052 is larger than the detected thermal X-ray flux and this is not typical for many other SNRs (see e.g. Slane et al. 2015). 4FGL J0035.8+6131 is in fact a variable gamma-ray source with unclear identification so far (Pandel & Kaaret 2018). We conclude that these sources are unlikely to be a diffuse gamma-ray counterpart of the newly discovered SNR candidate.
From the consideration presented in the previous sections, it seems reasonable to assume that G121.1-1.9 is located in the distance range from 1.5 to 6 kpc, so that we can take the fiducial value of the distance instead.

The observed X-ray properties of G121.1-1.9 listed in Table 1 can be briefly summarised as follows: 1) the object has nearly circular shape and surface brightness comparable to the X-ray background level; 2) the integral X-ray spectrum is soft, with no significant emission above 1.3 keV (in excess of the background level); 3) X-ray emission in the bands dominated by O VII and Ne IX lines show edge-brightened morphology, while emission in the bands dominated by O VIII, Ne X and Fe XVII lines is radially flat or even centrally-peaked; 4) the spectral shape of the emission from the inner and outer halves of the object can be described by non-equilibrium plasma emission models with the ionisation parameter $\tau$ in the range from $10^{10}$ to $2 \times 10^{11}$ cm$^{-3}$ s, initial electron temperature $kT_1 \sim 0.1$ keV and final temperature $kT_2 \sim 0.5$ keV; 5) the inferred value of X-ray absorption locates object beyond the Local Arm; 6) no counterpart is visible on radio, infrared, optical or gamma-ray images.

4 DISCUSSION

The observed X-ray properties of G121.1-1.9 listed in Table 1 can be summarised as follows: 1) the object has nearly circular shape and surface brightness comparable to the X-ray background level; 2) the integral X-ray spectrum is soft, with no significant emission above 1.3 keV (in excess of the background level); 3) X-ray emission in the bands dominated by O VII and Ne IX lines show edge-brightened morphology, while emission in the bands dominated by O VIII, Ne X and Fe XVII lines is radially flat or even centrally-peaked; 4) the spectral shape of the emission from the inner and outer halves of the object can be described by non-equilibrium plasma emission models with the ionisation parameter $\tau$ in the range from $10^{10}$ to $2 \times 10^{11}$ cm$^{-3}$ s, initial electron temperature $kT_1 \sim 0.1$ keV and final temperature $kT_2 \sim 0.5$ keV; 5) the inferred value of X-ray absorption locates object beyond the Local Arm; 6) no counterpart is visible on radio, infrared, optical or gamma-ray images.

4.1 Derived physical properties

From the consideration presented in the previous sections, it seems reasonable to assume that G121.1-1.9 is located in the distance range from 1.5 to 6 kpc, so that we can take the fiducial value of $d = 3$ kpc and allow a factor of 2 variation in it. In fact, somewhat smaller ($\sim 1$ kpc) and larger ($\sim 9$ kpc) distances also cannot be excluded, given the systematic uncertainties in the X-ray spectral modelling and 3D absorption profiles, so we conservatively allow a factor of 3 uncertainty in the distance instead.

The object’s apparent radius, 18 arcmin, translates into the physical size of $R = 16$ (d/3kpc) pc, ranging from $\sim 5$ pc at $d = 1$ kpc to $\sim 50$ pc at $d = 9$ kpc.

From the X-ray spectral fitting, we measured the post-shock temperature at the level of 0.5 keV, which implies the shock velocity $v_{sh} = \sqrt{\frac{16 kT}{5 \mu m_p}} \approx 650-715$ km/s for the mean molecular weight of the fully ionized gas $\mu = 0.5 - 0.6$.

From the Sedov-Taylor solution, we can approximately estimate the age to be $t_{age} = \frac{3}{2} \frac{R}{v_{sh}} \approx 3 \times 10^{11}$ s (d/3kpc) $\approx 9000$ yrs (d/3kpc). Combining the age estimates with the values of the $\tau$ inferred from the fit, we get estimates for the gas densities in the emitting regions: $n_{e,inner,\tau} = 0.3 \pm 0.15$ cm$^{-3}$ (d/3kpc)$^{-1}$ and $n_{e,outer,\tau} \sim 0.15 \pm 0.05$ cm$^{-3}$ (d/3kpc)$^{-1}$, where we have assumed the twice smaller age for the outer region.

On the other hand, the gas number densities can be estimated from the normalizations of the emission components obtained by the fit. From the definitions of the normalisation $N$ in the vrn@ model (Borkowski et al. 2001), we get

$$n_e^3 \times L = \frac{4 \pi X_e N}{10^{-14} d^2 \Omega} = 0.006 \text{ cm}^{-6} \text{ pc}^{-1} \frac{N}{10^{-6} \text{ arcmin}^{-2}} \quad (2)$$

where $X_e = n_e/n_H = 1.21$ for the fully ionised gas with Solar metallicity, $d^2 \Omega$ is the area unit of the measured surface brightness (i.e. 1 arcmin if $N$ is measured per arcmin$^2$), and $L$ is the line-of-sight extent of the emitting region.

As the morphology and the radial profile of the X-ray emission suggest, the size of the emitting region is likely comparable to the size of the object, i.e. $L = a \times R$, with $a = 0.5 - 2$. As a result, from the measured values of the model normalisations $N_{inner} = 3.1^{+7.8}_{-1.8} \times 10^{-6}$, $N_{outer} = 1.8^{+3.8}_{-0.9} \times 10^{-6}$ we can estimate the number densities as

$$n_{e,inner,N} = 0.03^{+0.08}_{-0.02} \text{ cm}^{-3} \left(\frac{a_{inner} \times d}{3 \text{kpc}}\right)^{-0.5} \quad (3)$$

$$n_{e,outer,N} = 0.02^{+0.04}_{-0.01} \text{ cm}^{-3} \left(\frac{a_{outer} \times d}{3 \text{kpc}}\right)^{-0.5} \quad (4)$$

Thus, there is an inconsistency between the density estimates by factor of 7-10, which is hard to reconcile by adjusting the distance by a factor of 2 or so. This point is illustrated in Figure 14 where the inferred values for $n_{e,norm}$ and $n_{e,\tau}$ are plotted with corresponding uncertainties. In fact, the uncertainties in $n_{e,norm}$ and $n_{e,\tau}$ are not independent due to degeneracies between the fitting parameters of the non-equilibrium emission model. In Appendix C, we show degeneracies between the inferred values of $\tau$, final temperature $kT_2$, and normalisation $N$.

The degeneracy between $\tau$ and normalisation arises from the emissivity boost $\varepsilon(\tau)$ with respect to the equilibrium emissivity at the same temperature acquired due to enhanced efficiency of collisional excitation in the overheated plasma (Paper I). As a result, the observed X-ray intensity $I$ can be written as $I \approx \varepsilon(\tau) N$, where $N$ is the usual normalisation. Thus, $n_{e,norm} \propto \sqrt{N} \propto 1/\varepsilon^{1/2}(\tau)$ for the fixed $I$.

On the other hand, $n_{e,\tau} \propto \int_{\tau_{ge}}^{\infty} \tau \varepsilon(\tau) kT d\tau \propto \varepsilon(\tau) kT \propto \sqrt{N(\tau)}$, implying that we can also write down the ratio of the inferred values of densities (for the given distance) as

$$\frac{n_{e,norm}}{n_{e,\tau}}(\tau) \propto \frac{1}{\tau \varepsilon(\tau) kT} \propto \frac{\sqrt{N(\tau)}}{\tau kT(\tau)} \quad (5)$$

where we explicitly emphasised that $kT$ might be expressed as a function of $\tau$ by means of the observed degeneracy relations. An important observation is that this combination of the fitting parameters does not vary much over all area of the parameter space giving the best values of the fitting statistic (see the right panels in Figures C1 and C2).
imply relatively low density environment, with \( n_e,0 = 0.005 - 0.1 \) cm\(^{-3}\) consistent with the location of the object \( \sim 100 \) pc \((d/3kpc)\) away from the Galactic plane in the inter-arm region. The "hot" solution, with \( kT_1 \sim 0.3 \) keV and \( \tau = 10^9 \) cm\(^{-3}\) s, the ambient gas would have a factor few smaller density (as the compression ratio is probably not high in this case since relatively low Mach number).

The observed 0.4-2.3 keV flux corrected after interstellar absorption, 
\[
F_{X,0.4-2.3} = (26 \pm 2) \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ (see Table 1)},
\]
corresponds to the 0.4-2.3 keV luminosity \( L_X \approx 3 \times 10^{34}(d/3\text{kpc})^2 \text{ erg s}^{-1} \).

Finally, we can estimate the total mass of the ambient gas then as
\[
M = 4\pi R^3 \mu_e m_p n_0 \approx 10 M_\odot \left( \frac{d}{3 \text{kpc}} \right)^{3-\beta} \left( \frac{n_e,0}{0.025 \text{ cm}^{-3}} \right),
\]
where \( \beta = 1 \) for the \( \tau \)-based estimate, and \( \beta = 0.5 \) for the normalisation based estimate.

The lower limit on the total energy of the explosion can then be estimated as
\[
E_{\text{tot}} = \frac{M}{\mu_e m_p} kT \approx 2 \times 10^{49} \text{ erg} \left( \frac{d}{3 \text{kpc}} \right)^{3-\beta} \left( \frac{n_e,0}{0.025 \text{ cm}^{-3}} \right) \left( \frac{kT}{0.5 \text{ keV}} \right).
\]

For the fiducial distance of 3 kpc, the derived energy is quite small, although for the 2 times bigger distance it would be 4-6 times bigger, i.e. at the level of \( 10^{40} \) erg, and, for the distance of \( \sim 9 \) kpc, it reaches \((2 - 3) \times 10^{40} \) erg. For the "hot" solution, instead we would get \( M \sim 1M_\odot \) and \( E_{\text{tot}} \sim 10^{48} \) erg for the distance around 1 kpc or less. Since the temperature inferred from the X-ray fit is likely only a lower limit for the real 'mean' (i.e. averaged over ions and electrons) temperature, the estimates for the total explosion energy might also be considered as lower limits.

### 4.2 An explosion model and illustrative simulation

The current data do not allow us to unambiguously distinguish between the possible scenarios for the nature of such an object, so below we briefly discuss which of them appears to be more plausible.

First of all, all the observational properties point towards a scenario in which the newly found object is located in low density environment, suppressing efficiency of relativistic particles acceleration.

There are several possibilities that might be a reason for such an environment of a (massive) progenitor star. First, the object might be located out the plane of the Galactic disc and at large Galactocentric distance. Indeed, if we take \( d \sim 6 \) kpc, corresponding to the further edge of the Perseus arm in this direction, we obtain the estimated energy of the explosion \( E_{\text{tot}} \sim 1 \times 10^{50} \) erg, the age of 17 000 yrs and the size of 32 pc.

If the distance of 9 kpc would be assumed, one gets \( E_{\text{tot}} \sim (2 - 3) \times 10^{50} \) erg, the age of 25 000 yrs and the size \( \sim 50 \) pc.

The electron temperature inferred from the X-ray analysis most likely corresponds to the lower limit on the actual mean temperature of the gas, which would also include the temperature of ions. The
latter indeed, is expected to exceed the electron temperature for the collisionless shocks (e.g. Ghavamian et al. 2007), and, for the gas temperatures above 0.3 keV, the electron-ion temperature equilibration time scale might exceed $\tau_{ei} \sim 10^{11}$ cm$^{-3}$ s$^{-1}$ (e.g. Liedahl 1999). This would then imply, that the observed X-ray emission might either reflect the non-equilibrium ionisation state of temperature equilibrated plasma, or, instead, correspond to equilibrium ionisation of the gas with the evolving temperature.

The explosion energy from the Eq.8 needs then to be adjusted upward by a factor depending on the Mach number of the shock and its effective collisional "age". This should bring the explosion energy estimate even closer to the canonical value of $10^{51}$ erg.

In order to check the consistency of this picture, we have performed a set of 1D simulations of an SNR in the uniform medium with the gas density $\rho = 10^{-2} m_p$ cm$^{-3}$, temperature $kT = 10^8$ K, total energy $E_{tot} = 10^{51}$ erg and the ejecta mass $1.4 M_{\odot}$. Initially, the ejecta have an exponential density distribution suitable for type Ia supernovae (see, e.g. Dwarkadas & Chevalier 1998). The resulting radial profiles of the gas density and temperature at the moment 24400 yr after the explosion are shown in Figure 15, corresponding to the forward shock radius radius 48 pc. The Mach number of the shock is $M = 5.4$, the post-shock temperature $kT_2 \sim 0.8$ keV, and the ionisation parameter $\tau = 10^{10}$ cm$^{-3}$ s all broadly consistent with the inferred properties of G121.1-1.9. As a caveat, we note that these 1D simulations ignore radiative losses and other processes that can influence the gas effective equation of state or mixing near the contact discontinuity.

The small value of $\tau \sim 10^{10}$ cm$^{-3}$ s in our fiducial model implies that the gas downstream of the shock may be far from the equilibrium, both in terms of the electron and ion temperatures and the ionization temperatures. We illustrate potential departures from these equilibria in Fig. 16. It shows the evolution of the ionization balance as a function of $\tau$ (bottom panel) and the changes in the electron and ion temperatures (top panel). Here we assume that (i) the mean plasma temperature changes at the shock front in accordance with the Rankine-Hugoniot jump condition for $M = 5.4$, while the temperature of electrons changes adiabatically, i.e. $T_e = T_0 (\mu / \mu_0)^{5/3}$, where $C$ is the density compression factor ($C \approx 3.56$) and (ii) subsequent temperature equilibration is mediated by Coulomb collisions. In addition, the top panel (right vertical axis) shows the impact of the temperature and the ionization state on the emissivity of the major transitions. This was done by calculating the following quantity for a few transitions

$$\eta(\tau) = \delta_i \left( \frac{T_0}{T_e(\tau)} \right)^{1/2} e^{-E_i/kT_e(\tau)} + E_i/kT_0,$$

where $\delta_i$ is the fraction of a given ion and $E_i$ is the energy of the most important transition. The colour lines in the upper panel show $\eta(\tau)$ for O VII, Ne IX and Fe XVII. The yellow vertical line shows the characteristic value of the ionization age in the fiducial simulations. One can see that the Coulomb collision do not guarantee the temperature equilibration and in this case, the ionization balance does not change much in the shocked ISM for $\tau \sim 10^{10}$ cm$^{-3}$ s. The line emissivities for oxygen and, especially for neon, can be boosted by a large factor, potentially explaining the overabundance of neon in the outer layers of the SNR. This qualitative conclusion is broadly consistent with the results of fitting the outer shell spectrum with the vrnei model (see Table 1). In principle, changing the upstream gas temperature, the level of electron heating at the shock and the rate of temperatures equilibration (on top of Coulomb scatterings) provides enough flexibility in shifting the curves (mostly to the left) and offering a possibility of constraining these properties once deeper X-ray observations are available.

The spectrum of the inner region is likely contaminated by the contribution of outer layers (see Section 2.2) and might have a much more complicated time history (cf. the dedicated modelling for Ia supernovae by Badenes et al. 2003, 2005). We defer the modelliing of its spectrum and comparison with the data for future studies.

### 4.3 Possible progenitors and astrophysical context

G121.1-1.9 in some regards looks like a sibling of G116.6-26.1 (Paper I): both are (i) round-shaped, (ii) strongly decelerated, (iii) of extremely low radio surface brightness, and (iv) reside in the external Galactic sector $90^\circ < l < 270^\circ$.

It is not surprising, that such objects should be among the first ones found in a blind all-sky X-ray survey, since 1) the objects in more typical environments have already been found by means of the radio observations, 2) the unperturbed spherical shape makes it much easier to identify them against spatially inhomogeneous fore- and background emission, 3) the life-time of such objects is prolonged thanks to inefficient cooling, so that they stay observable in X-rays for longer periods of time; 4) finally, the objects located in the inner parts of the Galaxy and in the disc suffer from the confusion due to high density of the objects.

Unlike G116.6-26.1 that most likely belongs to the halo, G121.1-1.9 has low Galactic latitude and at first glance lies in the Galactic...
Figure 16. Evolution of the ionization balance and lines emissivities of the gas compressed by a plane shock with the Mach number $M = 5.4$. The initial gas temperature upstream of the shock is $T_0 = 10^4$ K; the gas is initially in a collisional equilibrium. The electron temperature just behind the shock is assumed to change adiabatically, according to the density compression factor, i.e. the initial electron downstream temperature is $T_e = T_0 C^{5/3}$, where $C$ is the density compression factor ($C = 3.56$ in the fiducial model). The initial temperature of ions is based on the assumption that ions and electrons combined obey the Rankine-Hugoniot jump condition for $M = 5.4$. The subsequent electron-ion temperature equilibration is mediated by Coulomb collisions (the electron and ions are shown in the top panel with a pale green and violet lines, respectively.) The bottom panel shows the evolution of the ion fractions for He-like ions: O VII (red), Ne IX (blue) and Ne-like Fe XVII (green). The dashed lines show the ion fractions for H-like O VIII (red) and Ne X (blue). The colored curves in the top panel show the order of magnitude estimates of the increased emissivity of the He-like ions compared to the pre-shock hot ISM. The boost factor values are indicated by the vertical axis on the right side of the plot. A more rapid electron-ion temperature equilibration would shift all the curves to the left.

disc. However, hydrodynamic simulations of the SNR expansion in the scenario of SN Ia in the hot rarefied medium combined with the X-ray data indicate the large distance, of $\sim 9$ kpc, in which case the Galactic height is of $\sim 300$ pc in line with SN Ia to be a likely progenitor.

A fact that we observe an excess of Ne and Fe emission might also be suggestive of the Type Ia scenario, since no oxygen-to-iron overabundance is produced in core collapse supernova, while the apparent overabundance of neon might be an indication of oxygen depletion or be a result of inaccuracies in the non-equilibrium emission modelling. Comprehensive models for the X-ray emission from SN Ia remnants have been constructed (Hamilton & Sarazin 1984; Badenes et al. 2003, 2005), but the current level of the X-ray data does not allow us to make direct comparisons. Somewhat similar morphology of the X-ray emission was discussed in the context of the supernova remnants RCW 86 (Williams et al. 2011). For this SNR in particular, the importance of non-equilibrium ionisation in the post-shock gas has been considered by (Shimoda et al. 2022), including a possible effect of the accelerated cosmic rays.

Another object that shares similar properties might be G272.2-3.2, first discovered in the ROSAT data (Greiner et al. 1994) and later suggested to be a remnant of a type Ia supernova (Sánchez-Ayaso et al. 2013). Both these objects, however appear to be sources of radio and even gamma-ray emission and feature the second, harder, component in the X-ray spectrum. Another difference might be connected to the fact in the distant and old SNR scenario, considered by us above, the reverse shock has already went through the entire ejecta (see Fig. 15), which might not be the case for more nearby and younger objects (embedded in the ISM with the same density), so that we observe shock heating of the ejecta at present time.

The newly discovered object might be a Galactic member of the class of iron rich supernova remnants discovered in Large Magellanic Cloud (Borkowski et al. 2006; Maggi et al. 2014, 2016; Kavanagh et al. 2016) and later found in Small Magellanic Cloud as well (Maggi et al. 2019). If confirmed, G121.1-1.9 might offer an opportunity to study the enrichment processes by SN Ia in the evolved phase in our own Galaxy.

It is important to notice, however, that direct physical interpretation of the spectral properties of the observed emission is challenging due to very limited count statistics hindering spatially resolved spectral analysis and application of the de-projection techniques. In particular, for the central part of the object several effects might be in play, e.g. strong overabundance of heavy elements (pure ejecta, or ejecta mixed with the shocked ISM), non-equilibrium ionization, inequality between ion and electron temperatures, thermal conduction and inhomogeneity of the emitting gas. Clearly, better X-ray data should allow clarifying some of these issues and we defer their discussion for future detailed studies.

It is natural to ask how probable it would be for a Ia supernova to explode in the hot and tenuous phase of the Galactic disc. Based of the double-exponential stellar density distribution in the thick disc with radial and vertical scales $h_r = 3$ kpc and $h_z = 0.9$ kpc, respectively, (Li et al. 2017) we expect to find in the external Galactic sector $90^\circ < l < 270^\circ \sim 5.5\%$ of all SNRs residing in the thick disc. Earlier (Paper I), the number of SNRs with the age $< 10^5 \text{ yr}$ related to SNe Ia in the thick disc was estimated to be of the order of $10^2$, which implies that the expected number of SNRs resembling G121.1-1.9 and G116.6-26.1 in the external Galactic sector is $\sim 5$. We therefore are surprisingly close to the detection of all similar SNRs in the external part of Milky Way.

4.4 Radio properties

The upper limit on the radio flux from G121.1-1.9 discussed above provides rather stringent constraints on a possible SNR model. Indeed the minimal radio emission flux is expected in the case of the adiabatic compression of the ambient magnetic field and radio emitting electrons by a forward shock suggested by van der Laan (1962). The model may successfully explain the radio emission of extended sources like the Cygnus Loop (see e.g. Raymond et al. 2020b) and G116.6-26.1 (Paper II). The adiabatic compression model allows to derive the synchrotron radio emissivity behind the SNR forward shock once the Galactic synchrotron emissivity distribution obtained from radio surveys (e.g. de Oliveira-Costa et al. 2008; Su et al. 2017, 2018; Irfan et al. 2022) is available. The diffuse Galactic synchrotron radio emissivity can be estimated from the measurements of the free–free absorption of the radiation by intervening HI regions along the line of sight. From the Murchison Wide-field Array observations at 88 MHz of the region $250 < l < 355$ degrees, and $|b| < 2$ degrees, Su et al. 2017 derived the synchrotron emissivities $\epsilon_r$ between 0.39 and 1.45 K pc$^{-1}$ depending on the distance from the Galactic centre (with a mean of 0.77 K pc$^{-1}$) and a variance of 0.14 K pc$^{-1}$). Then one can estimate the minimal excess of the synchrotron surface brightness from G121.1-1.9 as $\epsilon_r \times R \times f_r$ where $f_r$ is the adiabatic boost factor of the volume emissivity of van der Laan’s adiabatic compression model.

This study the enrichment processes by SN Ia in the evolved phase in our own Galaxy.
The dependence of the boost factor $f_r$ on the compression factor can be seen in Fig. 5 from Paper II. Using as a representative the data from fourth Galactic quadrant and extrapolating $e_r$ presented by Su et al. (2017) to 408 MHz with the spectral indexes given by Irfan et al. 2022 one can see that the excess is above $\sim 1$ K for the parameter space domain which includes the SNR radii above 10 pc and the forward shock compression factor larger then 2. For the fiducial model of SNR of the age $\sim 25000$ years with the radius $\sim 50$ pc, and the compression factor of 3.56 illustrated in Fig. 15 the estimated $f_r > 20$. This imply rather low values of $e_r$ to meet the derived upper limit of radio emission.

For SNR propagating in the wind produced of the progenitor star or in the larger scale collective wind cavern produced by a nearby star association the value $e_r$ can be substantially reduced due to the modulation effect of the wind on the low energy cosmic rays. Another possibility to understand the reduced local ambient synchrotron emissivity in the vicinity of G121.1-1.9 is to assume that it resides in the region filled with the hot interstellar gas where magnetic field could be low as it was suggested by Evirgen et al. 2017.

The core collapse supernovae at some stage are propagating in the fast supersonic progenitor wind. The supersonic winds may have a low magnetic field and density before the wind termination shock and they can prevent the background radio emitting cosmic ray electrons to reach the SN shock. However, the radius of the termination shock of the supersonic wind of a massive star is typically well below 10 pc (see e.g. Georgy et al. 2013). Therefore, in the scenario with the core-collapse SNR, the effect described above may help to reconcile the van der Laan’s model with the radio data on G121.1-1.9 only for a rather nearby SNR.

Bright radio emission observed from many young SNRs is associated with the acceleration of GeV range relativistic electrons by supernova blast waves (see e.g. Helder et al. 2012). Recently, radio detection of an unusual SNR candidate J0624–6948 which represents a ring of a very good circularity with a low-surface brightness and rather flat radio spectral index was reported by Filipović et al. (2022). The estimated radio surface brightness $\Sigma$ of $1.6 \times 10^{-22}$ W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$ at 1 GHz for the measured angular diameter of 196 arcsec would place the SNR candidate source J0624–6948 to the bottom area of the $\Sigma - D$ diagram either to left or right corner depending on the assumed distance to the source and it is likely that the ambient matter is very tenuous. The estimated radio spectral index is generally consistent with that observed in a number of young SNRs with efficient particle acceleration by the blast wave. The radio flux density decreases with time in young SNRs at the Sedov phase or later because of the adiabatic cooling of relativistic particles and magnetic field decreasing in the expanding SNR (see e.g. Dubner & Giacani 2015). For old and evolved SNRs, the "minimal" van der Laan’s adiabatic compression model, which we applied above to G121.1-1.9, is likely appropriate.

Once the association of G121.1-1.9 with an SNR is confirmed, then one can use it as a probe of the local variations of cosmic ray electron fluxes and Galactic magnetic fields in addition to the technique based on the free–free absorption of the radiation by intervening HII regions along the line of sight.

### 4.5 What is needed to remove ambiguities?

More sensitive X-ray observations will allow to clarify the picture by, first of all, better characterisation of the morphology of X-ray emission, namely, by checking whether strong clumpiness of the X-ray emitting gas is observed. Second, given the inferred geometry allows conducting de-projection analysis to be performed in a robust manner, spectral analysis of the de-projected spectra might be performed. This should allow testing the models for the observed spectral variations across the object, namely disentangling the contributions of iron lines is a result of time-dependent ionization effects or a result of chemical enrichment by the ejecta medium. Finally, improved statistics of the data and improvement in their description by physically-motivated models should allow constraining the interstellar absorption, and hence better constrain the distance of the object.

Clearly, detection of the counterparts at other wavelengths is crucial to pin down the nature of the object. Dedicated radio observations are needed to detect or further constrain intensity of radio emission, allowing to locate the object on the $\Sigma - D$ diagram and characterise properties of the object’s environment (as exemplified by the LOFAR detection of radio emission from G116.6-26.1 Churazov et al. 2022). Detection and characterisation of optical filaments coinciding with the object should also allow in depth comparison with other radio faint SNRs (e.g. Foster et al. 2013; Kothes et al. 2017; Raymond et al. 2020a; Reich et al. 2021; Palaiologou et al. 2022).

### 5 CONCLUSIONS

We report the discovery of diffuse X-ray source SRGe J003602.3+605421=G121.1-1.9 in the course of SRGe/ROSITA all-sky survey. The object is located at (l,b)=($121.1^\circ$,-1.9$^\circ$) in Galactic coordinates, it is $\sim 36$ arcmin in angular diameter, features nearly circular shape and has soft X-ray spectrum dominated by emission lines of oxygen, neon and iron characteristic to the temperatures of 0.2–0.6 keV. Contrary to the bulk majority of the known supernova remnants located in the Galactic disc, the object lack clear counterparts in radio, infrared and $H\alpha$ images, probably indicating high temperature and low density of the object’s environment, akin the recently discovered candidate SN Ia remnant G116.6-26.1 in the Galactic halo (Churazov et al. 2021a, 2022). The lack of radio is not surprising since otherwise this SNR would have already been found in sensitive radio surveys. Interestingly, the two newly discovered objects (G121.1-1.9 and G116.6-26.1) have a very similar appearance and could become founding members of apparently not very numerous SNR class.

Clear variations in spectral shape of the X-ray emission across the object are detected, with the inner ($r < 9$ arcmin) and outer part ($r > 9$ arcmin) being dominated by emission lines of iron and oxygen/neon respectively. The non-equilibrium plasma emission model with the initial temperature 0.1 keV, final temperature 0.5 keV, and the ionisation parameter $2 \times 10^{10}$ cm$^{-3}$ s$^{-1}$ is capable of describing emission from the outer part, while emission from the inner part appears to be more complex (partially due to contribution of the projected outer shell emission), but shows signatures of substantial relative overabundance of iron.

The X-ray absorbing column density derived from the spectral fitting, $N_H \approx (4 - 6) \times 10^{21}$ cm$^{-2}$, locates the object at the distance beyond 1.5 kpc, implying the age of the supernova $\sim (5 - 30) \times 1000$ yrs. An illustrative model of an SN Ia explosion with energy $10^{51}$ erg in the environment with the gas temperature $kT \sim 10^6$ K and number density $10^{-2}$ cm$^{-3}$ at the distance of 9 kpc is able to reproduce main observational properties of the object.

More sensitive X-ray, radio and optical observations are needed to clarify the nature of the object, which might be a rare example of an old SN Ia remnant in our Galaxy bearing signatures of the ejecta enrichment in the central part and non-equilibrium processes in the outer shell allowing us to probe the thermal and non-thermal properties of the hot phase of the ISM above the cold disc.
APPENDIX A: ATLAS OF THE X-RAY, Hα AND RADIO EMISSION FROM THE REGION OF G121.1-1.9

Here we present maps of Hα and radio emissions covering 1.4×1.4 region around G121.1-1.9 and the map of its X-ray surface brightness, indicating its position, size and morphology. All images are on the linear scale. No associated emission in other bands can be noticed.

APPENDIX B: CUTOUTS FROM THE PPV CUBE OF HI EMISSION

In this Section we demonstrate cutouts (in Galactic coordinates) from the position-position-velocity cubes of the HI 21 cm emission from the CGPS survey (Taylor et al. 2003). Namely, Figure B1 shows slices corresponding to the CGPS survey (Taylor et al. 2003). Figure B1 shows slices corresponding to \( V_{\text{los}} = 68.2 \) km/s (left), -25.4 km/s (center), and -7.2 km/s (right), where emission from the region of G121.1-1.9 (red central box) significantly differs from the average profile extracted from the surrounding background regions (green boxes).

APPENDIX C: DEGENERACY IN THE PARAMETERS OF THE NEI PLASMA EMISSION MODEL

In this section we show degeneracies between the parameters of the absorbed non-equilibrium plasma emission models, as constrained by the currently available X-ray data for the inner (0'-9') and outer (9'-18') regions of the object.

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DATA AVAILABILITY

X-ray data analysed in this article were used by permission of the Russian SRG/eROSITA consortium. The data will become publicly available as a part of the corresponding SRG/eROSITA data release along with the appropriate calibration information. All other used data are publicly available and were can be accessed at the corresponding public archive servers.

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SNR candidate G121.1-1.9

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Figure A1. An atlas of $1.4 \times 1.4 \text{ deg}^2$ images centred on the position of the newly discovered SNR candidate G121.1-1.9, starting from the background-subtracted vignetting corrected X-ray image obtained by SRG/eROSITA in the 0.4-2.3 keV band (the image was smoothed with $\sigma = 1$ arcmin gaussian kernel after masking of the point sources down to the flux limit of $3 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ in 0.5-2 keV band). Next two figures in the first row show H$\alpha$ images constructed from the IGAPS and VTSS data, while the images on the following panels show radio emission at 74 MHz (VLSS), 150 MHz (TGSSADR), 326 MHz (WENSS), 408 MHz (CGPS), 1.4 GHz (CGPS and NVSS), 2.7 GHz (Effelsberg), 5 GHz (Green Bank), and 16 GHz (AMIGPS). The small white circles indicate point sources detected at 14 GHz in the CGPS data, which are excluded for the radio flux estimation from the "source" (big white circle, R=18 arcmin) and "background" (white dashed boxes) regions. All images are on the linear scale and show no signatures of excess emission from the G121.1-1.9 region with the only exception of the X-ray image.
Figure B1. Cutouts from the HI emission cubes at $V_{los} = -68.2$ km/s (left), -25.4 km/s (center), -7.2 km/s (right). The white circle shows R=18” extend of G121.1-1.9, while the 30’x30’ boxes show regions used for the velocity profile extraction, with the red box being the source region, and the green boxes are background regions. The images and the box regions are aligned with Galactic coordinates, according to the orientation of the original data cubes.

Figure C1. Degeneracy between the fit parameters for the inner 9” region. The right panel shows dependence of the boost factor on $\tau$. The color of the symbol shows the excess in the $\chi^2$ statistic over the minimum value, while the size is proportional to the value absorbing column density value. The dashed lines show simple powerlaw approximations for the ridge of the distribution.

Figure C2. The same as Figure C1 but for the 9’-18’ annuli.

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