LOFAR detection of faint radio emission from the supernova remnant SRGeJ0023+3625=G116.6-26.1: probing the Milky Way synchrotron halo.

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ABSTRACT

A supernova remnant (SNR) candidate SRGe J0023+3625 = G116.6-26.1 was recently discovered in the SRG/eROSITA all-sky X-ray survey. This large (~ 4 deg in diameter) SNR candidate lacks prominent counterparts in other bands. Here we report detection of radio emission from G116.6-26.1 in the LOFAR Two-metre Sky Survey (LoTTS-DR2). Radio images show a shell-like structure coincident with the X-ray boundary of the SNR. The measured surface brightness of radio emission from this SNR is very low. Extrapolation of the observed surface brightness to 1 GHz places G116.6-26.1 well below other objects in the Σ ~ D diagram. We argue that the detected radio flux might be consistent with the minimal level expected in the van der Laan adiabatic compression model, provided that the volume emissivity of the halo gas in the LOFAR band is ~ 10^{-42} Wm^{-3}Hz^{-1}sr^{-1}. If true, this SNR can be considered as a prototypical example of an evolved SNR in the Milky Way halo. In the X-ray and radio bands, such SNRs can be used as probes of thermal and non-thermal components constituting the Milky Way halo.

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

A supernova remnant (SNR) candidate SRGe J0023+3625 = G116.6-26.1 was found (Churazov et al. 2021, hereafter, Paper I) in the SRG/eROSITA all-sky survey. The SRG X-ray observatory (Sunyaev et al. 2021) with the two wide-angle grazing-incidence X-ray telescopes, eROSITA (0.3-10 keV, Predehl et al. 2021) and Mikhail Pavlinsky ART-XC telescope (4-30 keV, Pavlinsky et al. 2021) started its all-sky X-ray survey on December 13, 2019. G116.6-26.1 features a large angular extent (~ 4° in diameter, see the left panel of Fig. 1), nearly circular shape, and X-ray spectrum dominated by emission lines of helium- and hydrogen-like oxygen. Given the relatively high Galactic latitude of the source, b ≈ −26°, this SNR is plausibly associated with a Type Ia supernova that exploded some 40,000 yr ago in the low density gas of the Milky Way halo. G116.6-26.1 lacks bright counterparts of similar extent at other wavelengths, in particular, we didn’t find clear evidence of radio features in the 408 MHz survey (Haslam et al. 1982). The hope was that higher sensitivity of the LOFAR survey at lower frequencies might be able to find the radio counterpart and confirm the SNR nature of this object.
Figure 1. Side by side comparison of the X-ray (0.5-0.7 keV; eROSITA) and radio (144 MHz; LOFAR) images of the SRGe J0023+3625 field (equatorial orientation). Bright compact sources in the LOFAR image have been masked; the image was convolved with $\sigma = 30''$ Gaussian. The bright object in the upper left corner is M31 (Andromeda galaxy).

According to the description of the LoTSS-DR2 data, the baselines shorter than 0.1 km are not used when making images (Shimwell et al. 2022) and, therefore, large-scale diffuse structures can be sig-

Figure 2. A composite image showing surface brightness of the radio emission at 144 MHz after masking of the point sources (in red) and diffuse X-ray emission in the 0.5-0.7 keV band smoothed with a $\sigma = 4'$ Gaussian filter (in green).

For comparison, the green curve shows the radial profile extracted from the LOFAR image (after masking bright point sources). Due to the limited $uv$ coverage of the LOFAR DR2 data, much of the extended emission (if any) might be filtered out. However, sharp features should be preserved in the data. In particular, the peak at 100' is clearly present in both X-ray and radio data.

Figure 3. Comparison of radial profiles of the SNR candidate SRGe J0023+3625 in the X-ray (eROSITA; red, blue) and radio (LOFAR; green) bands. The profile in the 0.5-0.7 keV band (same as in Paper I, see their fig.2) is in units of counts s$^{-1}$ arcmin$^2$ per one eROSITA telescope. The red points show the total sky surface brightness, while the blue points show the same data once the estimated sky background level is subtracted. For comparison, the green curve shows the radial profile extracted from the LOFAR image (after masking bright point sources). Due to the limited $uv$ coverage of the LOFAR DR2 data, much of the extended emission (if any) might be filtered out. However, sharp features should be preserved in the data. In particular, the peak at 100' is clearly present in both X-ray and radio data.
spectrum with spectral index $\alpha = 0.5$

$$\Sigma_{1 \text{GHz}} \approx I_{\text{peak}} \times \frac{1}{\eta} \left(\frac{1 \text{ GHz}}{\nu}\right)^{-\alpha} \approx 7 \times 10^{-24} \left(\frac{I_{\text{peak}}}{10 \mu \text{Jy/beam}}\right) \left(\frac{\eta}{0.5}\right)^{-1} \text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1},$$

(1)

where the beam size of 20'' was used for the low resolution version of the LoTSS-DR2 images. The corresponding values of $\Sigma_{1 \text{GHz}}$ are shown in Fig. 4 (blue points) together with the data from two SNR samples. For G116.6–26.1, the uncertainties (apart from the noisy data) come from the uncertainty in the adopted spectral index $\alpha$, the distance to the SNR and filtering attenuation factor $\eta$. But even allowing for uncertainties, it is clear that G116.6–26.1 is located at the very bottom of the $\Sigma - D$ diagram that is poorly covered by the existing surveys.

The standard assumption is that the radio emission from young SNRs is powered by the DSA mechanism (see e.g. Reynolds & Chevalier 1981; Helder et al. 2012). During the late stages of an SNR evolution, the surface brightness gradually goes down as the size of the SNR increases and the expansion velocity decreases (e.g. Berezhko & Völk 2004; Asvarov 2006). This qualitatively explains the $\Sigma - D$ diagram, albeit with large uncertainties. Broadly, the parameters of G116.6–26.1 are consistent with the extension of this diagram. However, given that the surface brightness of G116.6–26.1 in the LOFAR band is very low, it is interesting to consider yet another possibility, namely adiabatic compression of the existing population of relativistic electrons in the Milky Way halo. For instance, Webster (1975); Subrahmanyan & Cowsik (2013) postulate the existence of a very extended (10-15 kpc) halo around the Milky Way, which can explain some of the sky brightness in the radio band (see, however Singal et al. 2010, for counter arguments).

Since we are interested only in the adiabatic compression (other gains or losses are neglected), the problem is fully specified by the volume emissivity of the gas around the SNR in the radio band $\varepsilon_{r,0}$, the compression/rarefaction of the gas, and magnetic field in the shock downstream. The model was developed by van der Laan (1962) for the extended evolved SNRs like the Cygnus Loop and IC 443. The origin of the non-thermal emission from evolved SNRs with relatively weak shocks may differ from young objects like e.g. SN 1006. In strong forward shocks in young SNRs, the Diffusive Shock Acceleration (DSA) mechanism is considered to be efficient enough to accelerate electrons to TeV regime energies and provide super-adiabatic amplification of turbulent magnetic fields by cosmic ray driven instabilities (see e.g. Helder et al. 2012; Schure et al. 2012). In general, in the middle-aged and old SNRs, both mechanisms (DSA and adiabatic compression) can contribute to the observed radio emission depending on the shock characteristics and the ambient matter conditions. We consider here a ‘minimal scenario’ with the pure adiabatic boost of the synchrotron emissivity by van der Laan’s mechanism. For a power law distribution of relativistic particles with slope $p$, the boost of the volume emissivity in the radio band due to adiabatic compression with the density ratio $C = \rho_d/\rho_u$ (where $\rho_d$ and $\rho_u$ are the downstream and upstream densities, respectively) can be written as

$$f_r = C_b^{p-1} C^{-\frac{p+1}{2}},$$

(2)

where the $C_b$ reflects the change of magnetic field due to compression, the second term accounts for the change of the particles’ Lorentz factor $\gamma/\gamma_0 = C^{1/3}$, and the last term stands for the increase of particles density. We used $p = 2\alpha + 1 = 2.4$, motivated by the spectral index $\alpha = 0.7$ found by MeerKat (Irfan et al. 2022). For $C_b$
we consider two cases: \( C_h = C \) and \( C_b = C^{2/3} \). The former corresponds to the case when the magnetic field is along the shock front (can be relevant for selected patches of the shock surface), while the latter assumes that the field is random and behaves like the gas with adiabatic index 4/3. In all cases, an isotropic distribution function of relativistic electrons is assumed. Fig. 5 shows the radial profiles of the volume emissivity boost factors for these two cases (dashed lines). Here we use \( C \) from the simple hydrodynamic simulations of G116.6–26.1 (Paper I). For comparison, the boost in the X-ray volume emissivity \( f_x = C^2 \) is also shown\(^1\). From the observational point of view, a more important is the boost factor \( f_p \) integrated along the line of sight \( I(R) = \int f_p dl \) (within the spherical volume encompassed by the shock). This quantity, which characterizes the surface brightness increase, is also shown in Fig. 5 with colored solid lines. For comparison, the black solid line shows the same quantity for \( f_x = 1 \). In this case, the surface brightness profile \( I_1(R) \) simply reflects the length of the l.o.s. inside the shock volume. With these definitions the change in the surface brightness associated with the presence of the shock is

\[
\delta I(R) = e_{r,0} \times [I(R) - I_1(R)],
\]

where \( e_{r,0} \) is the volume emissivity of unperturbed gas. Combining Eq. 1 (for 144 GHz) and the peak values for two curves (for \( C_b = C \) and \( C_b = C^{2/3} \)) from Fig. 5, we estimate the required emissivity

\[
e_{r,0} \approx 0.6 - 1.2 \times 10^{-42} \left( \frac{B}{0.5} \right)^{-1} \text{Wm}^{-3} \text{Hz}^{-1} \text{sr}^{-1}
\]

Interestingly, \( e_{r,0} \) turns out to be close to values suggested in Webster (1975); Subrahmanyan & Cowsik (2013) in the frame of the extended halo model. While this exercise does not prove that the halo model is correct, it illustrates that using SNRs in the halo, one can get interesting constraints on the emissivity of the medium.

Therefore, even if DSA is not operating at the later stage of SNR evolution, the adiabatic compression is sufficiently powerful. This argument can of course be reversed and the observed surface brightness can be used as an upper limit on the DSA efficiency or \( e_{r,0} \). Note here that if SNR is expanding in a locally homogeneous regular magnetic field then the adiabatic compression mechanism discussed above would predict an anisotropic image of the radio emission. Indeed from the observations of the galactic foreground rotation-measure distribution Beck et al. (2016) derived a correlation length of the magnetic field to be about 220 pc (with 50 pc 5\( \sigma \) lower limit). Therefore one can expect a relatively homogeneous ambient magnetic field at the scale size of the SNR. The boosting factor of the synchrotron emissivity in the \( \text{van der Laan} \ (1962) \) adiabatic compression mechanism is maximal for the parts of the shock expanding transverse to the local field direction. On the other hand, the diffusive acceleration mechanism could also produce anisotropy. The model has a minimal number of parameters. Since the ambient synchrotron emissivity of the halo is likely rather homogeneous at a kpc scale height therefore SNR G116.6-26.1 can be considered as a radio test bed for a typical SNR in the Milky Way halo. Recently, Raymond et al. (2020) discovered in the optical band an evolved Type Ia SNR G70.0–21.5 of the estimated age \( \leq 90,000 \) yrs located in the halo at a distance of about 1 kpc. Radio and X-ray studies of the SNR may provide another test of the simple model. The sizes, properties, and origins of radio halos in spiral galaxies is a subject of active studies (see e.g. Beck 2015; Krause 2019) and new very sensitive instruments like MeerKat and SKA are needed to resolve the issue. On the other hand, an indirect approach based on a model interpretation of the galactic cosmic ray Be/B ratio measured by AMS-02 was used to constrain the cosmic ray halo size as \( 5^{+2} \) kpc at 68% confidence level (Weinrich et al. 2020). The size of the galactic cosmic ray halo is connected to the magnetic field scale height.

It is interesting that in the scenario when the adiabatic compression powers the synchrotron emission and the radiative losses of the shock heated gas can be neglected (the case of G116.6–26.1), the X-ray and radio bands are tightly related. Indeed, both the radio and X-ray volume emissivities can be expressed via upstream emissivities \( e_{0_x} \) and \( e_{0_x} \), respectively and the compression ratio \( C \). For the X-ray band, the boost factor is

\[
f_x = C^2 N(C),
\]

where \( N(C) \) describes the impact of non-equilibrium ionization (NEI) on the X-ray emissivity of the gas. To the first approximation, the NEI factor can be written as

\[
N(C) \sim e^{-E/kT+E/kT_0},
\]

where \( E \) is the observed energy range, \( T_0 \) and \( T \) are electron temperatures upstream and downstream, respectively. This expression assumes that the ionization state does not change much after the passage of the shock (due to an extremely low density of the gas), but electrons are now hotter and excite relevant transitions more efficiently. This is, of course, the maximal possible boost factor. In real systems, it is expected to be smaller. We adopt \( T_0 \approx 210^9 \text{K} \) as the characteristic temperature of the hot gas in the Milky Way halo, while \( T \) is the function of the compression factor \( C \). We consider two limiting scenarios for \( T \): pure adiabatic heating of electrons, i.e. \( T = T_0 = T_0C^{2/3} \) and higher value \( T = T_0 \) that follows from the Rankine-Hugoniot condition for the gas with the adiabatic index 5/3. The true electron temperature is somewhere in between \( T_0 \) and \( T_0 \). The boost factors \( f_p \) and \( f_x \) are shown in Fig. 6. While the scatter is large, it is plausible that both X-ray and radio volume emissivities are enhanced by a comparable factor \( \sim 10 \).

The number of SNRs in the Milky Way halo (presumably remnants of type Ia SN) is small. They are embedded into the hot low-density gas of the halo, and, therefore, are expected to be X-ray faint. Departures from ionization equilibrium boost their X-ray fluxes and improve the chances of being detected in the sensitive all-sky surveys, such as the SRG/eROSITA survey. Similarly, the presence of extended synchrotron halo implies that even in the absence of DSA mechanism, the adiabatic compression of the gas boosts the emissivity in the low-frequency band by the factor of \( \sim 10 \) and sets the minimum level of the radio surface brightness, within reach of the LOFAR or MeerKat surveys. If the DSA mechanism is efficient, the surface brightness might be be even higher. G116.6–26.1, which is now detected in both the X-ray and radio bands, might be an example of such an object. The measured fluxes provide a new probe on the properties of the thermal gas in the halo (at the location of the SNR), as well as the non-thermal component. In principle, radio polarization observations may help to distinguish between the adiabatic compression and DSA mechanisms.

Another extended (about 4.4 degrees in diameter) high latitude galactic SNR G249.5+24.5 (Hoinga) was recently discovered by SRG/eROSITA observatory Becker et al. (2021). The authors constrained the distance D to be within the range of \( 0.45 < D < 1.2 \) kpc. The estimated local number density \( 0.42–0.16 \text{cm}^{-3} \) and the radio flux obtained below 2 GHz are higher than that in the case of G116.6-26.1 discussed above. The Hoinga likely has the lower height than G116.6-26.1 in the disk-halo transition layer. The radio

\(^1\) Note that this factor accounts only for the density change. Another important factor for this SNR is the emissivity boost due to non-equilibrium ionization (Paper I), which we discuss below.
spectral index obtained for the Hoinga was 0.69±0.08 and linear polarization is detected from the brightest parts of the shell with high compression. Both these characteristics are consistent with the adiabatic compression scenario discussed above while the possible role of diffusive shock acceleration mechanism requires more studies. In this respect, it would be especially interesting to determine the radio emission indexes and polarization of yet another high-latitude SNR G70.0–21.5 (Raymond et al. 2020).

4 CONCLUSIONS

The high-latitude SNR candidate G116.6-26.1, originally found in the SRGeROSITA survey has been identified in the LOFAR-DR2 data with the shell-like morphology that traces the X-ray boundary of the SNR. The peak surface brightness extrapolated to 1 GHz is extremely low ~ 10^{-23} W m^{-2} Hz^{-1} sr^{-1}, placing G116.6-26.1 well below other objects in the $\Sigma - D$ diagram. We argue that such low surface brightness can be explained by the compression of relativistic electrons and magnetic fields (van der Laan model) in the Milky Way halo. In this model, the required volume emissivity in the LOFAR band of the halo gas upstream of the shock is ~ 10^{-12} Wm^{-3}Hz^{-1}sr^{-1}. This value is comparable to those envisaged by models postulating the existence of very extended (more than 10 kpc) synchrotron-emitting diffuse halo around the Milky Way, demonstrating that (admittedly rare) SNR in the halo can be used to probe not only the thermal gas but also the non-thermal components of the ISM.

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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. The LOFAR-DR2 data are publicly available.

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