

RESEARCH ARTICLE

TELEIOS (G305.4–2.2) – THE MYSTERY OF A PERFECTLY SHAPED NEW GALACTIC SUPERNOVA REMNANT

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Abstract

We present the serendipitous radio-continuum discovery of a likely Galactic supernova remnant (SNR) G305.4–2.2. This object displays a remarkable circular symmetry in shape, making it one of the most circular Galactic SNRs known. Nicknamed Teleios due to its symmetry, it was detected in the new Australian Square Kilometre Array Pathfinder (ASKAP) Evolutionary Map of the Universe (EMU) radio-continuum images with an angular size of $1320'' \times 1260''$ and $PA = 0^\circ$. While there is a hint of possible H α and gamma-ray emission, Teleios is exclusively seen at radio-continuum frequencies. Interestingly, Teleios is not only almost perfectly symmetric, but it also has one of the lowest surface brightnesses discovered among Galactic SNRs and a steep spectral index of $\alpha = -0.6 \pm 0.3$. Our best estimates from H I studies and the Σ –D relation place Teleios as a type Ia SNR at a distance of either ~ 2.2 kpc (near-side) or ~ 7.7 kpc (far-side). This indicates two possible scenarios, either a young (under 1000 yr) or a somewhat older SNR (over 10000 yr). With a corresponding diameter of 14/48 pc, our evolutionary studies place Teleios at the either early or late Sedov phase, depending on the distance/diameter estimate. However, our modelling also predicts X-ray emission, which we do not see in the present generation of eROSITA images. We also explored a type Iax explosion scenario that would point to a much closer distance of < 1 kpc and Teleios size of only ~ 3.3 pc, which would be similar to the only known type Iax remnant SN1181. Unfortunately, all examined scenarios have their challenges, and no definitive Supernova (SN) origin type can be established at this stage. Remarkably, Teleios has retained its symmetrical shape as it aged even to such a diameter, suggesting expansion into a rarefied and isotropic ambient medium. The low radio surface brightness and the lack of pronounced polarisation can be explained by a high level of ambient rotation measure (RM), with the largest RM being observed at Teleios's centre.

Keywords: radio continuum: general – ISM: supernova remnants – individual: Teleios (G305.4–2.2)

1. Introduction

There is no doubt that SNRs are essential objects in the evolution of every galaxy, as they enrich and impact the structure and physical properties of the surrounding Interstellar Medium (ISM) (Filipović & Tothill, 2021). The census of the Galactic SNR population is well-known to be incomplete (Foster *et al.*, 2013; Dokara *et al.*, 2021; Ball *et al.*, 2023), as only some 300+ such objects are currently established (Green, 2022; Ferrand & Safi-Harb, 2012; Green, 2024). As many as up to ~ 2000 additional Galactic SNRs are expected to remain undiscovered in the Milky Way (MW) (Ranasinghe & Leahy, 2022). Recently, Anderson *et al.* (2024), Ball *et al.* (2023) and Hurley-Walker *et al.* (2019b,a) demonstrated that a significant number of these missing Galactic SNRs may have a low surface brightness or be located in complex regions where clear distinctions from other source types (e.g. HII regions and Planetary Nebula (PN)) can prove challenging. Moreover, bright, small-sized (compact), and presumably young SNRs are not likely to be found in abundance due to their rapid expansion and small size (Ranasinghe *et al.*, 2021). However, we have recently found one such object – the young Galactic SNR Perun (G329.9–0.5; Smeaton *et al.*, 2024b).

In several recent studies with the new generation of radio telescopes such as ASKAP and MeerKAT, a number of new SNRs have been discovered, including the circumgalactic SNR J0624–6948 (Filipović *et al.*, 2022b), the Galactic SNRs G288.8–6.3 (Ancora; Filipović *et al.*, 2023; Burger-Scheidlin *et al.*, 2024), G181.1–9.5 (Kothes *et al.*, 2017), G278.94+1.35 (Diprotodon; Filipović *et al.*, 2024), and G121.1–1.9 (Khabibullin *et al.*, 2023), as well as the Galactic SNR candidates G308.73+1.38 (Raspberry; Lazarević *et al.*, 2024) and G312.65+2.87 (Unicycle; Smeaton *et al.*, 2024a). These examples demonstrate the ability of newer generation radio-telescopes to discover these Galactic SNRs in abundance. They are mainly located outside the Galactic Plane, where they can preserve their original circular shape for longer. Presumably, they are expanding in a low-density environment, thus resulting in a lower surface brightness than typical SNRs.

We present the ASKAP radio-continuum detection of a new Galactic SNR, G305.4–2.2, nicknamed Teleios (Greek $\tau\epsilon\lambda\epsilon\iota\omicron\varsigma$ – perfect), due to its almost perfectly circular shape.

2. DATA

2.1 Radio-continuum observations

2.1.1 ASKAP

The ASKAP observation of Teleios was conducted as part of the EMU (Norris *et al.*, 2011, 2021, Hopkins *et al.* submitted) and Polarisation Sky Survey of the Universe’s Magnetism (POSSUM) (Gaensler *et al.*, 2010) surveys, using 36 antennas at a frequency of 943.5 MHz with a bandwidth of 288 MHz. The observation was taken on 7th May 2024, and the data is available through the CSIRO ASKAP Science Data Archive (CASDA)^a, in scheduling block SB62225 (EMU_1309–64 tile). The data reduction used the standard ASKAPSoft pipeline as

described in Guzman *et al.* (2019), which produces both a multifrequency synthesis (MFS) band-averaged Stokes I image for the EMU survey, and full Stokes I, Q, U and V frequency cubes with 1 MHz channels for POSSUM. Primary beam correction in all Stokes parameters is performed using beam models derived from standard observatory holography observations. This correction mitigates leakage from Stokes I into Stokes Q and U at around the 1 per cent level or less over most of the field. The resulting images (Figure 1) have a restoring beam of 15×15 arcsec² and achieve a Root Mean Squared (RMS) noise sensitivity of $\sigma \sim 15$ μ Jy beam^{−1} for Stokes I and ~ 15 μ Jy beam^{−1} for polarised intensity. ASKAP short baselines recover spatial scales up to ~ 20 arcmin at ~ 1 GHz (Hopkins *et al.* in prep.).

We find no detectable emission in the corresponding Stokes V image. To obtain the polarised intensity image shown in Figure 2 we used the RM synthesis technique. We did not use the Fourier transform method from the POSSUM pipeline but the de-rotation technique as described in Ball *et al.* (2023).

2.1.2 GLEAM-X

The GaLactic and Extragalactic All-sky Murchison Wide-field Array (MWA) (GLEAM; Wayth *et al.*, 2015; Hurley-Walker *et al.*, 2017) survey and GLEAM-eXtended (GLEAM-X; Hurley-Walker *et al.*, 2022; Ross *et al.*, 2024) surveys have been conducted by the Murchison Widefield Array (MWA, Tingay *et al.*, 2013; Wayth *et al.*, 2018) over a frequency range of 72–231 MHz. A joint deconvolution of these surveys over the Southern Galactic Plane will be presented by Mantovanini *et al.* (2025), which will be sensitive to angular scales from $45'' - 15^\circ$. A preliminary image from this effort shows a faint shell at the location of Teleios. The data achieved RMS noise levels from 5–30 mJy beam^{−1} over the five 30-MHz bandwidth mosaics, which enabled flux density measurements (see Figures 3 and 4 right). To enhance the S/N ratio, we used the Aegean software (Hancock *et al.*, 2018) to find the point sources and removed them with the Aegean Residual (AeRes) package within Aegean. We then convolved the three images to achieve a uniform resolution before co-addition. The resulting image is centred at a frequency of 151.5 MHz and features a beam size of 144.9×71.2 arcsec² with a P.A. of 145° .

2.2 H I observations

We use H I data from the HI4PI survey (HI4PI Collaboration *et al.*, 2016), which consists of data from the Effelsberg–Bonn H I Survey (EBHIS) the Parkes Galactic All-Sky Survey (GASS) surveys, as discussed in Section 3.3. The HI4PI survey resolution is $16''.2$, and the average RMS noise for the final data is 43 mK.

2.3 Optical observations

Some possible corresponding detection is that of H α emission from SuperCOSMOS H α Survey (SHS)^b as examined in Section 3. This H α image (Figure 1, bottom right inset) was

^a<https://research.csiro.au/casda>

^b<http://www-wfau.roe.ac.uk/sss/halpha/>

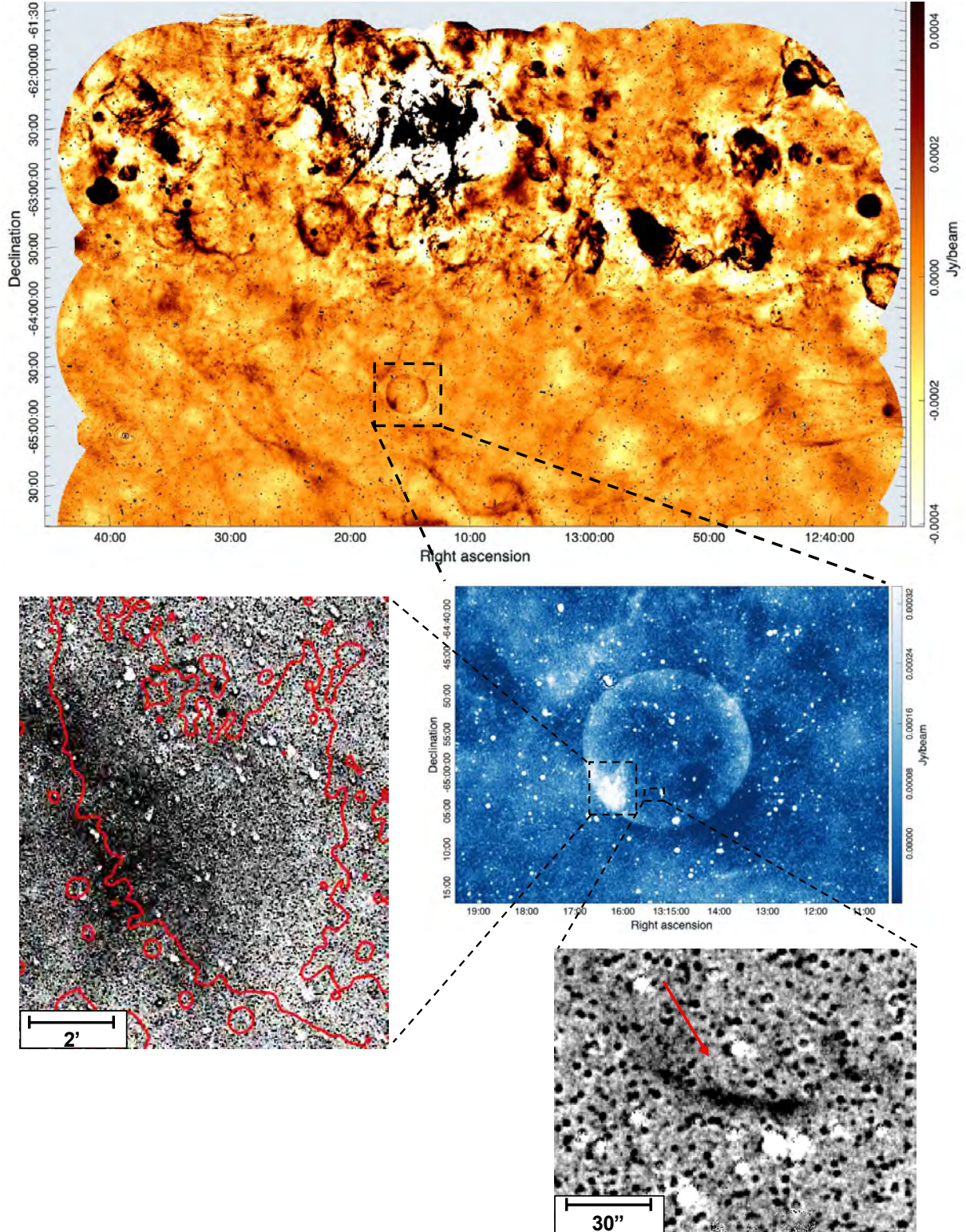


Figure 1. ASKAP 943.5 MHz radio-continuum image of Teleios and the surrounding environment showing the Galactic plane (top) with a zoomed-in inset of the same image (middle right). The H α optical images are shown in the left and bottom insets. The bottom right inset shows a thin line of optical emission (marked with a red arrow) as a possible sign of Teleios's reverse shock. The left inset shows the H α emission corresponding with the south-eastern patch of radio emission. The contour is from the ASKAP image at $100 \mu\text{Jy beam}^{-1}$. Both radio images have a convolved restoring beam of $15 \times 15 \text{ arcsec}^2$ and an rms noise level of $\sim 15\text{--}20 \mu\text{Jy beam}^{-1}$. All images have linearly scaled colour bars. The H α images were created as described in Section 2 and have scale bars in the bottom left corner.

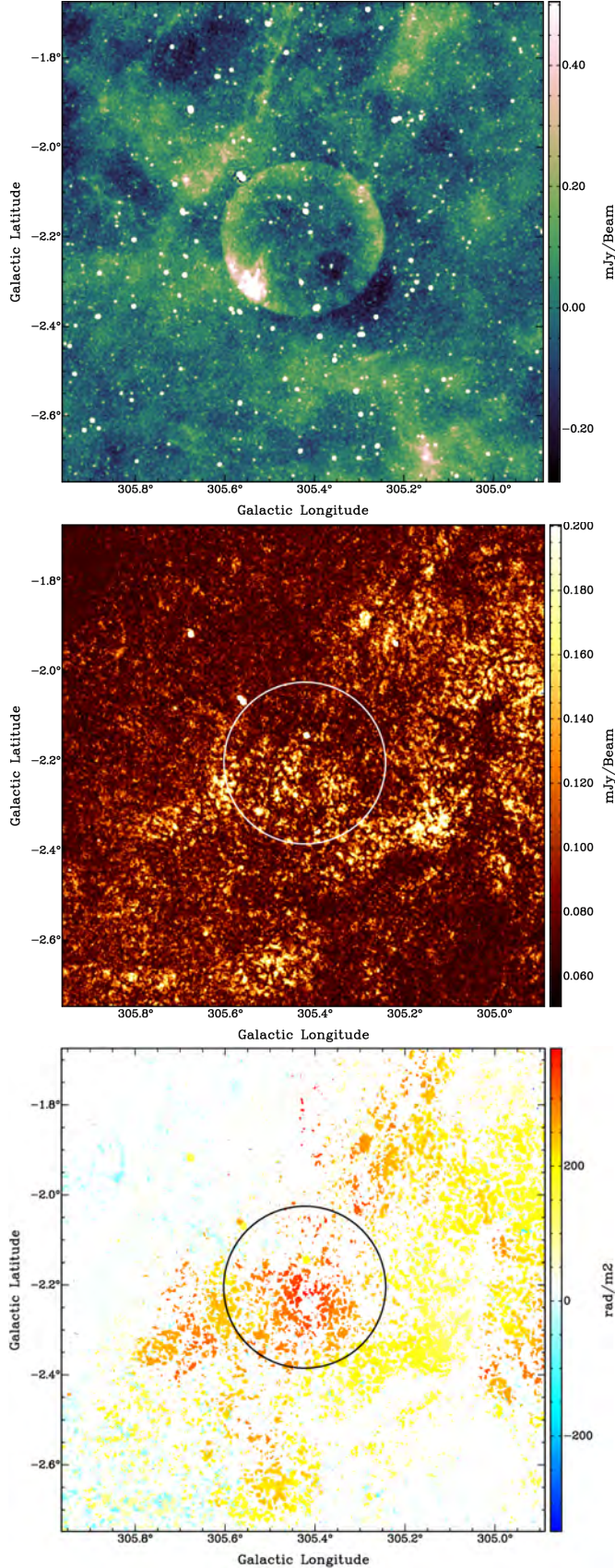


Figure 2. ASKAP radio images of Teleios as Stokes I (top), polarised intensity (PI) (middle) and RM (bottom).

created by scaling by a factor of 0.65 to more closely match the typical star intensities in the corresponding short-R image. This short-R image was blurred slightly so that the PSFs more closely matched the H α image, and the H α image was then divided by this blurred short-R image.

2.4 γ -ray observations

2.4.1 *Fermi*-LAT

We first analysed almost 16 years of Pass 8 *Fermi*-LAT (Atwood et al., 2009) SOURCE class data (from 2008 August to 2024 July) with the software *fermitools* (version 2.2.0) through the *fermipy* package (version 1.2.0) using the response functions P8R3_SOURCE_V3 and recommended cuts^c. We used front and back-converted events and, following Abdollahi et al. (2020), we used an energy-dependent maximum zenith angle cut such that a maximum of 90° was used in the energy range 0.4–500 GeV, 100° in the 1–500 GeV range and 105° for analyses above 5 GeV. We included all sources in the 4FGL-DR4 catalogue (Abdollahi et al., 2022) and used 20° -wide and 15° -wide regions of interest for analyses, for events below and above 1 GeV, respectively, around the location of Teleios in the centre of the region. We performed maximum likelihood fits to the spectral normalizations and calculated the test-statistic (TS, Mattox et al., 1996) of the sources located within 5° of the centre, including those of the Galactic diffuse emission (given by *gll_iem_v07.fits*) and the isotropic and residual cosmic-ray background (given by *iso_P8R3_SOURCE_V3_v1.txt*). The spectral index was also fit for sources catalogued within 3° of the centre. We searched for new point sources with a TS > 16 to improve the model. There are no catalogued sources within $\sim 1^\circ$ of the location of Teleios. In all these analyses, we saw a hint of point-like excess emission in the southwestern shell of Teleios.

We repeated the analyses using different event classes with different degrees of cosmic-ray background contamination using their corresponding response functions and isotropic diffuse models. We found that the (pre-trials) significance of the emission is maximized using events in the 10–500 GeV energy range and the ULTRACLEAN class, which contains events having the highest probability of being photons (filtered with the parameter *evclass* = 512). The source search algorithm in *fermipy* found a point source candidate at RA(J2000) = $13^{\text{h}}14^{\text{m}}22^{\text{s}}.9$, Dec(J2000) = $-65^\circ02'06''.0$ (with a 95%-confidence level positional uncertainty of 0.07° , position is shown by the green cross in Figure 4, left). Using a power law spectrum with a fixed index of 2 the resulting TS of the source is 19.6, corresponding to a detection (pre-trials) significance of 3.7σ for three degrees of freedom. Assuming the source candidate is Galactic in origin, we derived a 95%-confidence level upper limit on its 10–500 GeV luminosity of $2.6 \times 10^{32} d^2 \text{ erg s}^{-1}$. Here, d is the distance in units of kpc.

^cSee https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data_Exploration/Data_preparation.html

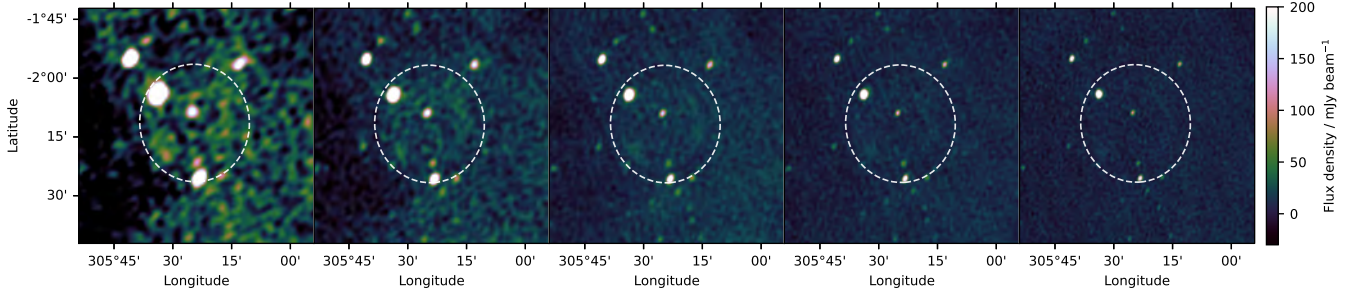


Figure 3. Region surrounding Teleios as observed by the MWA respectively at 88, 118, 154, 185 and 216 MHz. All the images are linearly scaled.

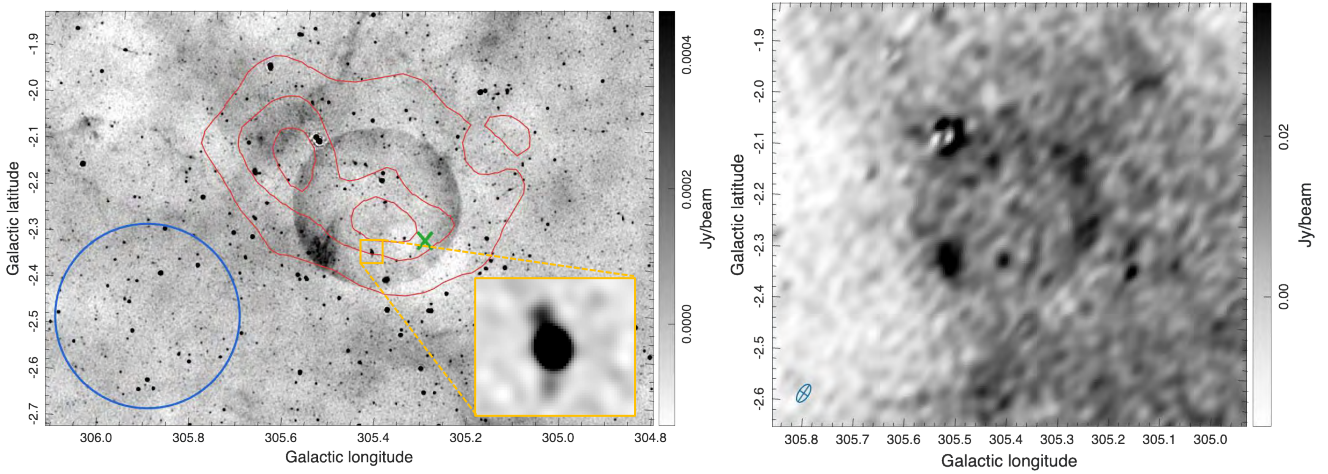


Figure 4. **Left:** ASKAP radio image at 943.5 MHz overlaid with H.E.S.S. γ -ray contours. The green cross marks the location of the Fermi point source candidate described in Section 2.4.1. Orange-bordered inset shows the radio counterpart to the X-ray point source discussed in Section 4.2.2. ASKAP image has a convolved restoring beam of 15×15 arcsec² and a local RMS noise of $15 \mu\text{Jy beam}^{-1}$. H.E.S.S. has a mean point spread function (PSF) of $0''.2$, shown by the blue circle in the bottom left. Contours are at significance levels of 2, 3 and 3.5σ . **Right:** MWA broad-band radio image centred at 151.5 MHz. MWA image has a convolved restoring beam size of 144.9×71.2 arcsec² with a P.A. = $-35^\circ 0$, shown in the bottom left corner. The image has a local RMS value of 14 mJy beam^{-1} . Both images are linearly scaled, the right one has undergone point source subtraction as described in Section 3.2.

2.4.2 H.E.S.S.

We inspected the publicly released data of very high-energy γ -ray emission from the H.E.S.S. Galactic plane survey (HGPS; H.E.S.S. Collaboration et al. (2018)). Data presented in the HGPS consisted of nearly 2700-h of data taken between 2004 and 2013, although the exposure at the position around Teleios is very much unclear. Its proximity to the known H.E.S.S. source PSR B1259-63/LS 2883 suggests that it could have been observed serendipitously, and additional data could be available due to more recent observations of the region since the release of the HGPS (H.E.S.S. Collaboration et al., 2020, 2024). The HGPS contains data within an energy range of 0.2–100 TeV and the size of the point-spread-function (PSF) for the observations is given to be around $5'$. Significance maps from the survey published with a $0''.2$ oversampling radius show hints of excess spatially coincident with the SNR shell. Contours indicating levels of 2, 3 and 3.5σ significance are shown in Figure 4 (left).

2.5 Other data

We searched for Teleios's signature in various multi-frequency surveys. These include optical (DSS2 and DECaPS DR2), IR (Wide-Field Infrared Survey Explorer (WISE) and Spitzer) and X-ray (eROSITA). There are no *Chandra* or *XMM-Newton* observations which cover this area. We also searched available Galactic SNR, PN, HII region and Luminous Blue Variable (LBV) catalogues. However, we found no sources or emissions matching Teleios.

3. RESULTS

3.1 Teleios's morphology and classification

We clearly see Teleios's faint circular shell in our ASKAP EMU image (Figure 1), and we see a possible hint of H α and γ -ray emission, which draws immediate attention to the true nature of this object.

Given Teleios's proximity to the Galactic Plane, circular morphology, and the fact that it is visible almost exclusively in radio-continuum (Section 2), we can exclude its classification as a PN, LBV, Nova Super Remnant (NSR), Wolf-Rayet (WR)

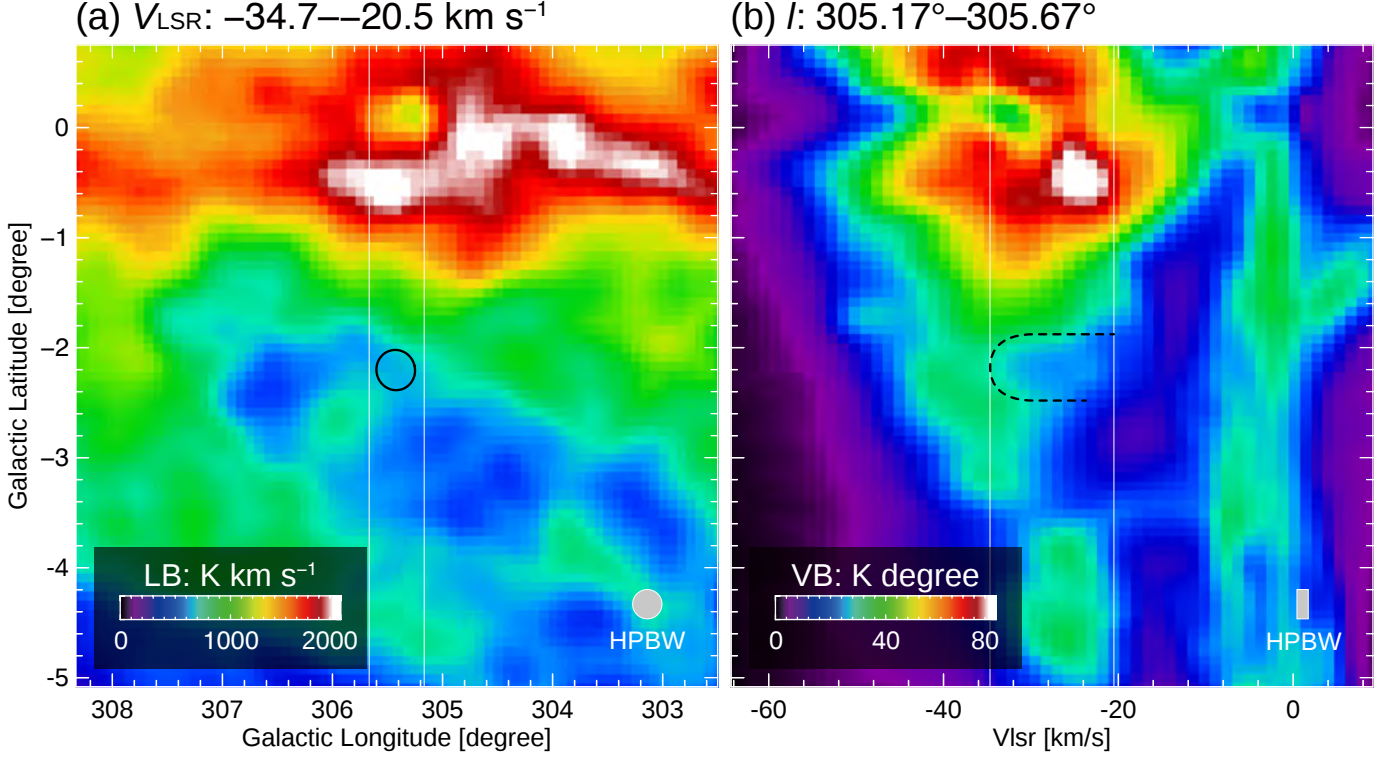


Figure 5. (a) Integrated intensity map of H I obtained from HI4PI (HI4PI Collaboration et al., 2016) at integrated velocity range -34.7 km s $^{-1}$ to -20.5 km s $^{-1}$. The black circle represents Teleios's position and the beam size is shown in the bottom right. (b) Position-velocity ($p-v$) diagram of H I integrated over the same velocity range and Galactic longitude range $305^{\circ}17'$ to $305^{\circ}67'$. The black dashed curve indicates a possible expanding H I cavity centred at Teleios's Galactic latitude. The beam size is shown in the bottom right for both images.

or (super)bubble. These source types should have a very prominent infrared (IR) or optical (narrow-band) appearance, which is lacking in the case of Teleios (Filipović & Tothill, 2021). Also, apart from (super)bubbles, which would have a physical size in excess of 100 pc (Kavanagh et al., 2015; Sano et al., 2017; Kavanagh et al., 2019; Yamane et al., 2021), all these Galactic source types would have angular sizes of less than a few arcminutes or would be located at distance <200 pc.

We also exclude classification as an Odd Radio Circle (ORC) (Norris et al., 2021,?; Koribalski et al., 2021; Gupta et al., 2022; Shabala et al., 2024; Bordiu et al., 2024), since this object is very unlikely to be connected with anything extragalactic at larger distances of several hundred Mpc. We checked the Australia Telescope National Facility (ATNF) Pulsar Catalogue (<https://www.atnf.csiro.au/research/pulsar/psrcat/>), and the closest pulsar (J1309–6526) is ~ 1.8 away from Teleios's centre at a distance of 11.257 kpc (Yao et al., 2017) and old age of 3.43×10^8 years. We consider this pulsar as unrelated to Teleios.

Given the apparent circularity, we also considered that Teleios could be a Dyson Sphere (Vukotić et al., 2021; Wright, 2020). However, given that no IR (Spitzer, WISE) emission can be detected anywhere within Teleios's boundaries, we also conclude this to be an unlikely scenario.

The circular appearance of Teleios and the prominence of its radio emission compared with other wavelengths are consistent with the SNR hypothesis, and from now on, we

will treat Teleios as a most likely Galactic SNR (G305.4–2.2) especially given the evidence presented in Sections 3.2 and 3.4.

Tantalising hints of excess emission up to 3.75σ in the H.E.S.S. γ -ray image (see Figure 4 left) might be in some smaller part related to nearby strong background sources. While we recognise that the H.E.S.S. γ -ray excess may be attributed to background fluctuations, together with hints of emission seen with *Fermi*-LAT at HE γ -rays from the region, we believe that there may be a physical connection with Teleios that could be revealed by further high-sensitivity and high-resolution VHE γ -ray observations.

Based on the publicly available flux maps, the >1 TeV integral photon flux for this region is estimated as $\sim 2.8 \times 10^{-13}$ ph cm $^{-2}$ s $^{-1}$. Converting this to a luminosity gives values of 2.2×10^{32} erg s $^{-1}$ for a distance of 2.2 kpc and 2.7×10^{33} erg s $^{-1}$ for a distance of 7.7 kpc. This possible overlapping gamma-ray emission at GeV to TeV energies may come from protons and/or electrons which are accelerated and potentially still trapped within the SNR. Similar to the work of (Filipović et al., 2024), who examined a similarly mature SNR Diprotodon, this gamma-ray emission may be a combination of hadronic and leptonic emission mechanisms. If Teleios is located in a low-density ISM, this may suggest that the leptonic component is dominant at this phase. If the emission is caused by a hadronic-dominant case, we can estimate the required proton energy W . Assuming an ISM density $n = 0.1$ cm $^{-3}$, we calculate a proton energy of 3.7×10^{48} erg (for 2.2 kpc distance) and 4.5×10^{49} erg (for

7.7 kpc distance).

We note some extended radio emission inside the south-eastern edge of Teleios’s shell, which is at odds with the almost perfect circular symmetry of the rest of the shell shape. We suggest that at least some parts of this region might be affected by an interaction of Teleios with local ISM structures, as somewhat weak H α emission in this region is evident in Figure 1 (bottom left) even beyond the Teleios boundaries. This H α emission could be an unrelated HII region or even a related HII region, ionised by X-rays from the SN shock where the radio emission is of thermal (free-free) nature. In the absence of a reliable spectral index for the exterior and interior emission in this location, we cannot 100% rule out a priori that this enhanced patch of Teleios radio emission is free-free. However, if the weak and small size (compared to the entire SNR) H α filament emission from Figure 1 (bottom right) is associated with Teleios, it might represent the reverse shock from the SNR. McKee & Truelove (1995) find a ratio between the blastwave and the reverse shock radii of 1.33 for an SNR at the beginning of the Sedov phase. For Teleios, we find a ratio of 1.44, indicating a very young SNR, in the Sedov phase. However, we caution this as this filament is tiny compared to the size of Teleios, and thus, if it is the reverse shock, then we would see an area at a slightly different evolutionary phase than the rest of Teleios, or an area with a slightly different environment.

On the other hand, if Teleios comes from the type Ia SN event, one should not expect to find hydrogen at the reverse shock. Also, the reflected reverse shock could act as a secondary internal blast wave that will go through the whole ejecta and swept-up ISM. An alternative scenario could be as in the case of the Large Magellanic Cloud (LMC) SNR DEM L71 where Ghavamian et al. (2003) suggested that H α emission inside the rim of the Balmer-dominated collisionless shock is lumps of exterior neutral material ionised by He II $\lambda 304 \text{ \AA}$ (Ghavamian et al., 2000). The fact that it is seen inside the radio shell could be a projection effect. A reflected reverse shock occurs for relatively evolved objects such as the LMC SNR DEM L71 with the age of 4360 ± 90 years, which now suggests that if this H α emission is associated after all, then Teleios is not a youngish SNR, which is in contradiction with the above speculation of a very young SNR.

3.2 Teleios’s radio-continuum properties

In the same manner as described in Filipović et al. (2023), we measured Teleios’s radio-continuum properties, including its extension and flux density. As seen in Figure 1, Teleios is a circular object centred at RA(J2000) = $13^{\text{h}}15^{\text{m}}1^{\text{s}}.2$, Dec(J2000) = $-64^{\circ}57'40''.7$, some $2^{\circ}2'$ below the Galactic plane (Galactic G305.4–2.2). The ellipse axes are estimated to be $1320''$ by $1260''$ at PA=0° which gives it a circularity $c = 95.4\%$.

We note that Teleios’s exceptional circularity is unusual for an SNR as we can find only a handful of similar SNRs. Some such examples are the newly discovered circumgalactic SNR J0624–6948 (Filipović et al., 2022b, $e = 3.9\%$) and several young (under 2000 yr old) Magellanic Cloud (MC) SNRs

such as SN1987A (Cendes et al., 2018), MC SNR J0509–6731 (Bozzetto et al., 2014; Roper et al., 2018), N 103B (Alsaberi et al., 2019), and 1E0102 (Alsaberi et al., 2024). Despite their young age, all the young (under 2000 years) Galactic SNRs such as, for example, the youngest G1.9+0.3 (Luken et al., 2020; Enokiya et al., 2023) lack pronounced circular symmetry as shown by Ranasinghe & Leahy (2019).

One of the most perfectly circular ring-like sources seen in the sky is MAXI J1348–630 (Lamer et al., 2021) – a giant dust-scattering X-ray ring around the black hole transient.

3.2.1 Radio spectral index

The average spectrum for the bright ring of Teleios was estimated as follows using the ASKAP 943.5 MHz map in combination with the GLEAM-X 151.5 MHz map. First we used the DiffuseFilter script^d, based on the minimum/maximum filtering of Rudnick (2002) to remove the point sources in the field. We then perform background subtraction and then regridded the maps to make them the same, convolved the 943.5 MHz image to match the $91'' \times 64''$ resolution at 151.5 MHz, and blanked compact regions that were brighter than the ring at 151 MHz. We measured the fluxes in three annuli, covering the radii $500''$ – $650''$ (covering Teleios’s bright ring), $650''$ – $800''$, and $800''$ – $950''$, (which we designate as A, B, and C, respectively). Because of large-scale background variations, we divided each annulus into eight sectors of 45° . For each sector, the flux density from the bright Teleios ring, in practice, its excess over the background, was calculated by subtracting the flux in B from the flux in A, and then summing over all sectors. This yields an excess flux density for the ring of $0.17 \pm 0.03 \text{ Jy}$ at 943.5 MHz and $0.50 \pm 0.17 \text{ Jy}$ at 151.5 MHz, for a spectral index of $\alpha = -0.6 \pm 0.3$. The total flux densities of the ring would be higher if we did not remove the background. However, this was necessary due to the missing short spacings from ASKAP (it begins losing flux at $20'$ scale, and Teleios has an average diameter of $1290'' = 21.5'$). It is not clear what the total spectral index would be if the entire structure were sampled at both frequencies.

The errors were estimated using the scatter in the sector-by-sector differences between annulus B and annulus C. The errors are dominated by large-scale galactic background structures, and future observations and more detailed spectral modelling may allow these to be reduced. The most discrepant value was observed for the bright sector in the southeast, and dropping it led to an overall spectrum of -0.6 . This does not affect the above overall spectral index, and confirmation of a possible flatter spectrum in the SE can be made with upcoming MeerKAT observations.

We also attempted to measure the total flux and spectral index of Teleios within $\approx 650''$ at both frequencies instead of just its bright ring. While an enhancement in brightness inside the ring is clearly visible at 151 MHz, it is completely absent at 943.5 MHz, due to insufficient sampling at short baselines, and so this calculation was dropped. In addition, we

^d<https://gitlab.com/Sunmish/diffusefilter>

attempted to measure the spectral index within the ASKAP 288 MHz band, but found extremely steep apparent spectra ($\alpha \sim -2.5$), a problem for large angular size sources that is still under investigation within the EMU collaboration.

Overall, after attempting several different methods to determine the spectral index across Teleios, the only reliable method we find is that for the excess in the bright ring, yielding $\alpha = -0.6 \pm 0.3$, as described above. This estimate has a high intrinsic uncertainty due to Teleios's low surface brightness. It was not possible to generate a detailed spectral index map due to the low signal-to-noise, missing short spacings, and the presence of fluctuations on comparable brightness and size scales from the Galactic background. The smaller-scale radio-continuum variations in the spectra can not be determined at this time, without more sensitive observations such as the upcoming MeerKAT observations.

Teleios's spectral index of -0.6 ± 0.3 is only slightly steeper compared to the observed value of -0.5 ± 0.3 for shell-type SNRs, both within the MW and in several nearby galaxies (Reynolds *et al.*, 2012; Galvin & Filipovic, 2014; Bozzetto *et al.*, 2017; Maggi *et al.*, 2019; Filipović & Tothill, 2021; Bozzetto *et al.*, 2023; Ranasinghe & Leahy, 2023; Cotton *et al.*, 2024). Such a steep spectral index is expected for somewhat young (<2000 years) or very old SNRs (Bozzetto *et al.*, 2017; Brose *et al.*, 2020; Kavanagh *et al.*, 2022; Das *et al.*, 2022; Sushch *et al.*, 2022; Das *et al.*, 2024).

This spectral index, combined with the measured angular size, gives us a surface brightness ($\Sigma_{1\text{GHz}}$) of $\sim 5.1 \times 10^{-23} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ arcmin}^{-2}$ making it one of the lowest surface-brightnesses of any known SNRs, similar to the Galactic SNR Diprotodon (Filipović *et al.*, 2024).

3.3 Teleios's H I appearance

We analyse archival H I data from the HI4PI (HI4PI Collaboration *et al.*, 2016) to reveal any physical association with Teleios and the surrounding environment. HI4PI achieves an angular resolution of $16'$, which is a modest size with respect to Teleios's shell size. This makes it difficult to resolve any small-scale H I differences over Teleios's area, however, we find a possible H I association in the form of an H I cavity (Figure 5).

This possible cavity is at a velocity range of $V_{\text{LSR}} = -34.7$ to -20.5 km s^{-1} . Adopting the systemic velocity of $V_{\text{LSR}} = -27 \pm 3 \text{ km s}^{-1}$, this corresponds to kinematic distances of $\sim 2.2 \pm 0.3 \text{ kpc}$ (near side) and far-side at $\sim 7.7 \pm 0.3 \text{ kpc}$ ^e.

The H I integrated intensity map (Figure 5a) shows a low-density H I bubble ($<0.01 \text{ cm}^{-3}$ as per Weaver *et al.* (1977)) at Teleios's location (indicated by the black circle), which corresponds with a possible expanding gas motion in the $p-v$ diagram (Figure 5b). This cavity seen in the $p-v$ diagram correlates with Teleios's Galactic latitude and is indicated by the curved black dashed line. For an SNR this can indicate an expanding H I shell caused by initial SN shockwaves or stellar winds from the progenitor carving out a bubble of rarefied

space, as has been observed in other SNRs (e.g. Kes 75 (Su *et al.*, 2009), RCW 86 (Sano *et al.*, 2017), N103B (Sano *et al.*, 2018), CTB87 (Liu *et al.*, 2018)).

It is, therefore, possible that this cavity represents such a H I wind bubble. If Teleios's progenitor were able to carve out such a bubble prior to Teleios's expansion, then expansion into this rarefied but highly homogeneous environment could help explain Teleios's remarkable circularity.

3.4 Teleios's polarisation and rotation measure

In Figure 2, we show Stokes I (top), polarised intensity (PI) (middle), and RM (bottom) images of Teleios and the area around it, created using the available ASKAP POSSUM data. The values for PI and RM were taken from the peak of the Faraday Depth (FD) function in each pixel. Instead of a Fourier transform, we used the de-rotation method to produce the FD function for each pixel. To that end, we derotated the Stokes Q and U data in each frequency channel for each rotation measure. We probed an RM range from -2000 to $+2000 \text{ rad m}^{-2}$.

We did not find any polarised emission coincident with the SNR's total power emission, likely due to its low radio surface brightness and perhaps high internal Faraday rotation effects. Curiously, the overall RM amplitude is highest at the SNR's centre and getting radially lower. There also seems to be a large foreground screen with very high RM related to relatively high surface brightness polarisation signal almost all around the SNR.

It seems like this Faraday screen is actually in the background of Teleios, and the SNR is Faraday rotating its polarised emission. Since this additional RM is highest in the centre of the remnant, we should find a magnetic field mainly along the line of sight there. This would be the case for either a young SNR with a radial magnetic field or if the SNR is expanding inside a Galactic magnetic environment with the field lines going mainly along the line of sight. However, the former should not add any Faraday rotation to the background polarisation if the SNR is symmetric along the line of sight. And for the latter case, the RM should again increase towards the edge of the source. Clearly, further studies are required.

To get an estimate of the maximum fractional polarization of Teleios, we produced radial profiles for total power and the polarised emission, shown in Figure 6. We only calculated those profiles over the western half of the SNR to avoid any contribution from the diffuse patch in the lower left corner of Teleios and the emission outside the top left area. Bright point-like sources were removed from the maps through Gaussian fitting.

The shell of the SNR is clearly visible in the total power profile, but there is no obvious polarized emission. An estimate of the standard deviation of the PI values in the radio shell area results in about $3.5 \text{ mJy beam}^{-1}$. If we now assume that the polarized emission must be lower than $3\sigma = 10.5 \text{ mJy beam}^{-1}$, we derive a maximum fractional polarization of 6 % for Teleios' radio shell. This is a very low value but certainly not unusual at this low frequency. It could also indicate that Teleios is in the transition phase between free and Sedov expansion like

^eThe kinematic distance was calculated using the values $R_{\odot} = 8.5 \text{ kpc}$ and $V = 220 \text{ km s}^{-1}$, as recommended by the International Astronomical Union (IAU) (Kerr & Lynden-Bell, 1986).

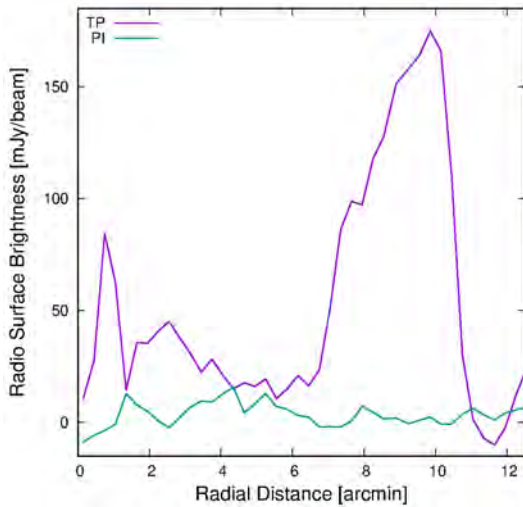


Figure 6. Radial profiles averaged over the western half of Teleios calculated for total power (TP) and polarized intensity (PI).

G11.2–0.3, which has only 2 % integrated fractional polarization at a frequency of 32 GHz and clearly shows characteristics of both a free expanding and a Sedov type SNR (Kotthes & Reich, 2001). This would favour the near-side distance of 2.2 kpc (see distance discussion in Section 4.1).

4. DISCUSSION

The most obvious characteristic of Teleios is its remarkable circular symmetry, coupled with a low surface brightness and a slightly steeper radio spectral index. Most SNRs exhibit some form of asymmetries, and there can be several different physical processes behind these.

For a very young SNR in the free-expansion phase, the ejecta freely expands into the surrounding medium, and this ejected mass is much greater than the swept-up ISM mass. Thus, any initial asymmetries in the explosion and circumstellar material (CSM) are present in this initial expansion.

Once the ejecta has all been heated by the reverse shock, the remnant enters into the Sedov phase, where the shock begins being driven by this internal thermal pressure. The expansion is now subsonic with respect to the SNR interior, and so the Sedov solution is effectively independent of the explosion geometry. This means that the pressure-driven expansion dominates over any inherent explosion asymmetries, and the expansion will relax into a roughly spherical shape. This expansion is expected to remain inherently symmetrical throughout the Sedov phase, and the remnant should only become asymmetric in the Sedov phase if there is very asymmetric ISM or CSM on length scales of ~ 5 – 10 pc. For example, in the case of the $\sim 10^3 M_{\odot}$ bow shocks swept up by the stellar winds in Meyer et al. (2015).

The following phase after Sedov is the radiative phase, where the shell becomes thinner, and fragmentation of the shell can occur. The thinner shell also becomes more susceptible to instabilities, and so local density variations become more important. However, as the outer shock becomes radiative, we

also expect strong optical line emission, which is not present in Teleios.

Therefore, Teleios’s symmetrical shape and lack of pronounced optical emission indicate that it is likely in the Sedov evolutionary stage, and the shell results from the pressure-driven expansion. The fact that there are no large and obvious asymmetries in shape indicates that there is insufficient asymmetry in the swept-up material to distort the shape. This could be due to Teleios being a younger Sedov phase SNR, as these possible asymmetries will become more apparent as Teleios expands further into the medium, or it could also be due to expansion into an isotropic but rarefied environment. Given the apparent size of Teleios (~ 21.5) and position of $2^{\circ}2$ below the Galactic Plane, we argue that the ISM would have to be rarefied to a level of $< 0.1 \text{ cm}^{-3}$ (Urošević, 2020) unless the SNR is inside a wind-driven bubble where much lower densities of $\approx 0.02 \text{ cm}^{-3}$ are possible.

While the Sedov phase is expected to be the most symmetric, most Sedov phase SNRs still display some form of bilateral asymmetry due to the ambient magnetic field. As the remnant expands, it compresses the ambient magnetic field, resulting in some compression being parallel and some being perpendicular to this ambient field. The compression that occurs perpendicular causes brighter radio synchrotron emission, resulting in a typical bilateral radio morphology with opposite shells of brighter emission. Maintaining a perfectly symmetrical shape for a size greater than ~ 10 pc would require an unreasonably low magnetic field strength. The observed symmetry can, therefore, be explained as an orientation effect if we are viewing Teleios end-on, that is, viewing Teleios while the magnetic fields are in our line of sight. This would mean that the brighter emission where the expansion is perpendicular to the magnetic field would occur along the entire outer ring. This orientation would explain the apparent symmetry, as well as the lower surface brightness, as the radio synchrotron emission would be predominantly oriented perpendicular to our line of sight, thus making it appear fainter.

An example of the effect of a rarefied environment on SNR morphology is the circumgalactic SNR J0624–6948, which has a diameter of ~ 72 pc and a possible age of ~ 2350 years. While it also has a prominent radio and X-ray emission (Sasaki et al., 2025), due to its position in the rarefied circumgalactic medium, this SNR demonstrates how SNRs can preserve their circular shape in such rarefied environments of constant and uniform ambient density.

4.1 Teleios’s distance and position in MW

4.1.1 Σ – D method

Teleios’s surface brightness estimate is compared to other Galactic and Magellanic Cloud (MC) shell-type SNRs (Figure 7). To estimate the most likely intrinsic diameter, we use the Σ – D method as described in Pavlović et al. (2018, their Figure 3). We obtain a wide diameter range ($D=30$ – 150 pc). This diameter range would also correspond to a wide distance range of approximately $d = 4.8$ – 24.0 kpc.

We compare Teleios’s estimated surface brightness value

with empirical calibration from Vukotić *et al.* (2019). For a fixed surface brightness of $5.1 \times 10^{-23} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ this empirical calibration gives a diameter probability distribution with the median value of 33 pc and a 95% confidence interval range of 11 – 134 pc. This translates to a distance probability with a median value at 5 kpc and a 2–21 kpc as a 95% confidence interval.

The orthogonal $\Sigma - D$ fit on the same calibration gives higher values, 48 pc diameter and a corresponding distance of 8 kpc.

Given Teleios’s somewhat unusual morphology as larger, rounder, and fainter than any other known SNR, it means that the expectations to fit into the $\Sigma - D$ method would be challenging. Especially given that the $\Sigma - D$ method was not designed for or built off of extremely low surface brightness SNRs. Still, the above $\Sigma - D$ method results, despite the wide range, show a definite tendency when combined with other (see below) methods.

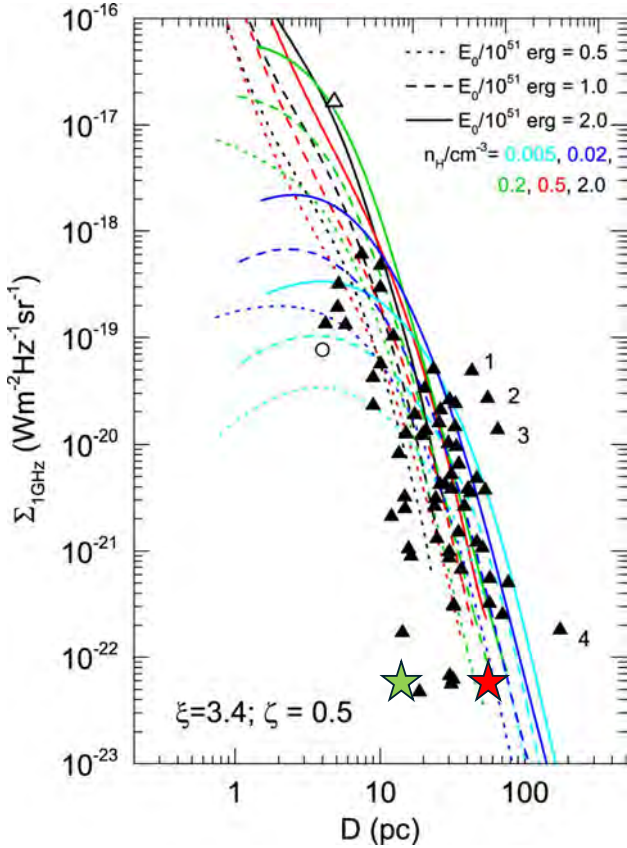


Figure 7. Radio surface brightness to diameter diagram for SNRs at frequency $\nu = 1$ GHz, obtained from Pavlović *et al.* (2018, Figure 3), shown as black triangles. Different line colours represent different ambient densities, while different line types represent different explosion energies. The open circle is young Galactic SNR G1.9+0.3 (Lukic *et al.*, 2020), and the open triangle represents Cassiopeia A. The numbers represent SNRs (1): CTB 37A, (2): Kes 97, (3): CTB 37B, and (4): G65.1+0.6. The stars represent Teleios at estimated surface brightness of $5.89 \times 10^{-23} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$. The red star corresponds to Teleios diameter of 48 pc, and the green star with a diameter of 14 pc. The image shows evolutionary tracks for representative cases with injection parameter $\xi = 3.4$ and nonlinear magnetic field damping parameter $\zeta = 0.5$.

4.1.2 Churchwell MW model map

To further constrain possible distances, and thus size, one could compare the Churchwell MW model map (Churchwell *et al.*, 2009; Filipović *et al.*, 2013; Efremov, 2011; Hou & Han, 2014; Vallée, 2017) with Teleios’s Galactic longitude to estimate the most likely distances. As Core Collapse (CC) SN only occur for massive, short-lived stars, one can argue that they would typically occur in areas of massive star formation (Bartunov *et al.*, 1994; Anderson *et al.*, 2017; Verberne & Vink, 2021) such as the Galactic spiral arms. Namely, Teleios’s Galactic longitude of $l \sim 305^\circ$ passes tangentially through the inner Sagittarius arm at ~ 2 kpc and Scutum-Centaurus arm at approximately 4–8 kpc, and then through the outer Sagittarius arm at about 11–14 kpc. Using the same reasoning as in Smeaton *et al.* (2024b), this gives distances ~ 2 kpc, ~ 6 kpc or ~ 12 kpc, corresponding to ~ 13 pc, ~ 38 pc and ~ 75 pc diameters, respectively. It is also worth noting that if we assume that the MW extends out to about 20 kpc in that direction (Churchwell *et al.*, 2009), this would give a somewhat unrealistic maximum diameter of 125 pc if it is a Galactic object. Therefore, this can be taken as the upper limit of our distance estimations.

4.1.3 H I method

Finally, from our H I study (Section 2), we infer a possible cavity in which Teleios could be expanding at the systemic velocity of $V_{\text{LSR}} \sim -27 \pm 3 \text{ km s}^{-1}$, which suggests the kinematic distance of $\sim 2.2 \pm 0.3$ kpc (near-side) or $\sim 7.7 \pm 0.3$ kpc (far-side). For these distances, we calculate physical sizes of 14 pc (for 2.2 kpc distance) and 48 pc (for 7.7 kpc distance). We deem that both of these sizes are realistic for a wind-blown cavity, and thus, for the remainder of the paper, we use both distances (2.2/7.7 kpc) and corresponding diameters of 14/48 pc as the most likely values. We note that the H I diameter estimate of 48 pc is in excellent agreement with the orthogonal fit distance estimate from empirical $\Sigma - D$ calibration (Vukotić *et al.*, 2019). The derived distance probability from the same calibration gives $\approx 30\%$ chance that Teleios’s distance is > 8 kpc and a $\approx 70\%$ for < 8 kpc values.

Using the calculated radii of the wind-blown cavities, we can estimate a progenitor mass using the method of Chen *et al.* (2013). Comparing with their Table 1, we find corresponding progenitor masses of $28 M_\odot$ (for 14 pc size) and $54\text{--}72 M_\odot$. Assuming the distance of ~ 2.2 kpc with a corresponding diameter of ~ 14 pc and an optimistic upper limit of a constant expansion speed of $\sim 7,000 \text{ km s}^{-1}$ we estimate Teleios’s minimum age of ~ 980 years (~ 1045 A.D.). This is a similar age to a well-known historical SNR SN1054 (Filipović *et al.*, 2021a,b, 2022a). We note that Teleios is at $\text{Dec}(J2000) \sim -65^\circ$, placing it in the Southern hemisphere where a very limited amount of firm astronomical events have been recorded in the past.

For a far distance of 7.7 kpc, our estimated upper limit on the source γ -ray luminosity above 10 GeV is $\sim 2 \times 10^{33} \text{ erg s}^{-1}$, which is compatible with the luminosities of some GeV-emitting SNRs. For a closer distance of 2.2 kpc our γ -ray luminosity upper limit is $0.6 \times 10^{33} \text{ erg s}^{-1}$, which is relatively low but still comparable to those of GeV SNRs likely evolving in low-

density environments (e.g., [Acero et al., 2016](#)).

4.2 Teleios’s SN explosion type

At the distances of the inner Sagittarius arms, Scutum–Centaurus and outer Sagittarius arms, Teleios’s Galactic latitude (-2.2°) would place the object at ~ 70 – 540 pc (assuming distances of 2, 6 and 12 kpc) below the Galactic plane. The most likely distances of ~ 2.2 kpc and ~ 7.7 kpc (from Section 3.3) places Teleios at ~ 70 pc or ~ 300 pc below the plane. Therefore, assuming that the MW’s thin disk has a scale height of ~ 220 – 450 pc ([Bland-Hawthorn & Gerhard, 2016](#)), this would indicate that Teleios is located out of the densest Galactic plane regions if at a distance of 7.7 kpc.

Since the Galactic spiral arms represent the areas of the greatest star formation within the MW, it is still possible that Teleios’s progenitor, whether CC or type Ia SN, originated from these areas ([Drimmel, 2000](#)). [Poggio et al. \(2018, Figure 3\)](#) argue that the spatial distribution of upper main sequence stars shows enhancement corresponding to Galactic spiral arms. However, the distribution of red giants is smooth and can be described as an exponential disk (radial decrease in density) plus a decrease of stellar numbers as a function of heliocentric distance (due to it being a magnitude-limited sample). Therefore, a potential spatial correlation with the Galactic spiral arms would depend on Teleios’s progenitor star type.

4.2.1 Teleios as a CC SN

At a distance of ~ 70 – 540 pc below the Galactic plane, one still can expect to find a significant number of massive stars above $8M_\odot$. It is natural to expect that some of these massive stars may explode as CC SN and form SNRs that will expand in this more rarefied and uniform environment outside of the Galactic plane.

However, Teleios could also come from an isolated runaway massive star CC SN ([Blaauw, 1993](#); [Oh et al., 2015](#); [Weßmayer et al., 2024](#)). This would explain its location far from star-forming regions and 2.2° below the Galactic Plane. [Smith & Tombleson \(2015\)](#) were able to explain the isolation of some LBV stars using a similar scenario.

In the case of Teleios, a massive star in a binary system could have been kicked from its birth cluster by the explosion of a (more massive) companion. The star then “escapes” in a random direction (in this case, perpendicular to the Galactic Plane), ending up in a rather rarefied medium, where it eventually explodes. Still, close to a perfectly symmetric explosion is challenging to achieve for a runaway scenario ([Zhang et al., 2018](#)), not only because the ejecta will be faster on one side but also because a runaway massive star will create a bow shock, which will then disrupt the symmetry of the expanding ejecta ([Meyer et al., 2015](#); [Smeaton et al., 2024b](#)).

From Figure 1, we can see that Teleios is actually located just ($\sim 1^\circ$) below a massive HII region complex. A similar case might be seen in Galactic SNR DA530 ([Booth et al., 2022](#)) located some 500 pc above a major HII region complex. DA530 is an SNR that came from a CC explosion and has a central neutron star with an X-ray pulsar-wind nebula (PWN). Teleios

differs in morphology from DA530, as DA530 is an example of a symmetrically bilateral SNR, potentially indicating an environmental difference.

4.2.2 Teleios as a type Ia SN

Teleios, at 2.2° below the Galactic Plane, is away from any obvious and nearby star formation activity. Given its circular shape ([Ranasinghe & Leahy, 2019](#); [Lopez et al., 2011](#)), which is similar to circumgalactic SNR J0624–6948 ([Filipović et al., 2022b](#)), and its location outside the Galactic Plane ([Hakobyan et al., 2017](#)), Teleios could be a type Ia SN explosion from a star that was formed (and lived) below the Galactic Plane. While it is possible for a more massive star to travel outside of the Galactic Plane and explode as a CC SNRs, this scenario is more likely for a smaller Type Ia progenitor. It is also suggested that Type Ia SNRs are more symmetrical than their CC counterparts ([Lopez et al., 2011](#)), however there is some debate about this relationship, particularly concerning radio morphology [Leahy et al. \(2019, Leahy et al. in prep.\)](#). However, if Teleios is located inside the cavity as suggested in Section 4.1, then the type Ia scenario is no longer viable. While the type Ia scenario does not preclude Teleios’s location within a cavity, it is difficult to explain how such a large cavity would have formed. A white dwarf progenitor is not likely to be able to form an ~ 50 pc sized cavity, and this scenario would favour a more massive progenitor.

There have been previous attempts to use an SNR’s circularity as an indicator of its SN type, however we note that this can be a difficult correlation to draw, and circularity is typically a poor indicator of SN type. For example, as shown in [Ranasinghe & Leahy \(2019\)](#), we see many SNRs with identical morphological features but coming from various explosion types. [Soker \(2019, 2024b\)](#) argues that all CC SNRs are non-spherical because of the effect of jets, which will imprint “ears” onto the spherical bubble. As we do not see any sign of “ears” in Teleios, one could conclude that the thermonuclear (type Iax) SN is a more likely scenario. However, we note that the present generation of 3D SN simulations doesn’t easily produce (show) the SN jets. Another caveat is that the jet-driven SN explosion is more likely to be relevant for the morphology of younger SNRs. Further on, the most prominent SNR with “ears” can be seen in Kepler’s SNR (G4.5+6.8), and that was definitely a type Ia. Also, [Soker \(2019, 2024b\)](#) suggests that some (but not all) of the many possible explosion mechanisms of type Iax do produce perfectly spherically symmetric remnants (Table 1 and Section 4.2, [Soker, 2024b](#)). As the best example of a circular remnant, [Soker \(2024b\)](#) takes SNR Pa 30, the likely remnant of SN 1181. Certainly, Teleios is even more circular (the circularity of $c = 95.4\%$) than Pa 30 ($c = 90.8\%$).

We also discuss the possibilities of Teleios being a type Ia as single-degenerate (SD), double degenerate (DD) or Iax. Type Iax has only recently been distinguished from type Ia as they have lower explosion energy (0.01 – 0.1×10^{51} erg), lower optical luminosity (-14 to -19 mag) and lower or absent X-ray emission. If Teleios indeed comes from a type Iax SN, this lower energy could be the reason why there is no X-ray

detection (Foley et al., 2013). We note that there is one prominent eROSITA point source within Teleios’s area (1eRASS J131507.1–650312). This source is also seen in the radio and appears to resemble a typical background active galactic nuclei (AGN) with jet structure (see Figure 4, left panel inset). Therefore, it is unlikely to be associated with Teleios, and we observe no corresponding diffuse X-ray emission in the eROSITA data. As pointed out in Srivastav et al. (2022), there should be dozens of so-far unidentified type Iax remnants in the MW. No definitive type Iax identification has been proposed for MW remnants, except probably for SN 1181 (as discussed above).

We also note that Teleios’s circular shape is consistent with the theoretical “lonely white dwarf (WD)” scenarios presented in Soker (2024a,b). These scenarios include the core degenerate (CD) and the DD with a long Merger to Explosion Delay (MED) time. The CD scenario is when a WD merges with a more massive companion, forming a massive WD, which then explodes after the MED time. The DD with a long MED time involves the merging of two WDs, and then the merger remnant explodes. If the MED time is long enough, then the remnant has relaxed, and Soker (2024b) predicts a spherical, near Chandrasekhar mass explosion. Soker (2024b) also predicts that these mergers can form PN shells that can clear the surrounding ISM. For massive and energetic PN ejecta, as could be formed by a merger of a WD with a relatively massive companion star (about 4–5 $M_{\odot}$ in the CD scenario), if it were expanding at $\sim 50 \text{ km s}^{-1}$, the expansion time to clean 24 pc (radius) would be $\sim 500\,000$ years (MED time). For this to happen, one needs to account for a very rarefied CSM/ISM. These scenarios could account for a spherical explosion and a rarefied CSM/ISM. These properties would impact Teleios’s circularity, however if Teleios is in the Sedov phase, then it is more likely that the uniformity of the surrounding medium and Teleios’s age contributes more to the observed symmetry rather than the initial explosion geometry.

4.3 Teleios’s possible SN progenitor

To better constrain Teleios’s SN explosion type (as type Ia or Iax), we search the available GAIA DR3 (Gaia Collaboration et al., 2016, 2023) data for a possible progenitor near Teleios’s geometric centre. We investigate stars off of the main sequence; that is, a WD (a.k.a. zombie) star could indicate a type Iax scenario, and a red giant could indicate a SD type Ia scenario.

We applied a set of parameters based on the GAIA magnitude and colour data to identify any potential post-SN explosion WD or giant branch (GB) star candidates (remnant star). Our criteria are based on López-Sanjuan et al. (2019, their Figure 2). We used the restrictions $G_{\text{abs}} > 7$ and $(G_{\text{BP}} - G_{\text{RP}}) < 0.4$ to search for potential WDs and $G_{\text{abs}} < 4$ and $(G_{\text{BP}} - G_{\text{RP}}) > 0.4$ to search for potential GB stars.

Restricting this to Teleios’s geometric centre and Galactic distances (assuming a maximum distance of 20 kpc), we found 1 WD candidate within $1'$ of Teleios’s centre and 9 GB star candidates within $30''$.

Analysing the GAIA proper motion data, we find that the

WD candidate (Gaia DR3 5858854017669128192) does not originate from the direction of Teleios’s centre, and thus, we deem it somewhat unlikely to be a progenitor. Also, the measured parallax of $1.8981 \pm 1.7116 \text{ mas}$ gives a distance $527 \pm 475 \text{ pc}$ implying $D = 3.3 \text{ pc}$, which is at odds with the distance estimates from Section 3.3. However, the well-studied type Iax remnant SN1181 has a similar diameter of about 1.82 pc at the age of 843 years and expansion velocity of $\sim 1100 \text{ km s}^{-1}$ (Fesen et al., 2023). Assuming the same expansion velocity of $\sim 1100 \text{ km s}^{-1}$ of Teleios’s ring, we arrive at the SNR age of ~ 1467 year. This young age would argue that such events could be recorded in historical records. However, as mentioned above, Teleios can be seen only from the Southern Hemisphere, where a limited number of historical astronomical events have been recorded.

Conducting a similar proper motion analysis on the nine potential GB star candidates, we find no stars that could have originated from Teleios’s centre. We conclude that we could not find any suitable white dwarf or red giant candidates as a remnant star from the Teleios original explosion as SN.

4.4 Teleios’s evolutionary state

To evaluate Teleios’s possible evolutionary phase as type Ia or type Iax, we investigated two SNR evolutionary models.

4.4.1 Radio Σ – D modeling

Since Teleios’s surface brightness is one of the lowest measured, it is expected to evolve in a very rarefied medium. This is certainly in contradiction with the relative proximity of Teleios to the Galactic plane, where densities lower than 0.01 cm^{-3} can hardly be expected. To estimate its possible ambient densities, we calculate several radio Σ – D evolutionary paths for Teleios. Three cases for the SNR diameter are considered: a) $D = 48 \text{ pc}$, b) $D = 14 \text{ pc}$ (these two correspond to kinematic distances obtained from HI data), and c) $D = 3.3 \text{ pc}$ (the case of WD progenitor from Section 4.3). We combined different explosion energies and ejecta masses (all parameters are listed in Table 1), in order to model different SN scenarios: type Ia ($E_0 = 10^{51} \text{ erg}$, $M_e = 1.4 M_{\odot}$), type Iax ($E_0 = 3 \times 10^{48} \text{ erg}$, $M_e = 0.1 M_{\odot}$), and four cases between these two, as well as CC SN of a massive star ($E_0 = 10^{51} \text{ erg}$, $M_e = 20 M_{\odot}$). Not all of these models are applied to every diameter. The synchrotron emission is modelled with test-particle approximation (non-modified shock) of diffusive shock acceleration (DSA) mechanism (Axford et al., 1977; Bell, 1978; Blandford & Ostriker, 1978), from Kostić et al. (2024), for a circularly symmetric shell-type SNR. The lower limit for the shock thickness of 5% of the radius (estimated from the radio image on Figure 1) is used in the model. The evolution of SNR shock velocity is calculated using the simple equation from Finke & Dermer (2012):

$$\frac{v_s^2}{2} = \frac{kE_0}{kM_e + 4\pi R^3 \rho_0/3}, \quad (1)$$

which approximately covers the free expansion and Sedov phase (the constant k is determined so the equation tends to Sedov solution for $R \rightarrow \infty$). Based on the results of the models, we propose the evolutionary phase of Teleios, as shown in

Table 1. The evolutionary paths of these models are shown on panels (a), (b), and (c) of Figure 8.

In the case a) ($D = 48$ pc), an SNR with the lowest explosion energy ($E_{0.01}$) cannot reach the given diameter with the measured surface brightness for any density (the closest approach is at $n_H = 0.3 \text{ cm}^{-3}$), so it is ruled out. The highest density (0.082 cm^{-3}) is obtained in $E_{0.03}$ case, with SNR being in a pressure-driven shell (PDS) phase. All other models give densities below 0.005 cm^{-3} , with the lowest value of 0.0006 cm^{-3} for the SN type Ia model. In the case b) ($D = 14$ pc), the highest density (0.021 cm^{-3}) is obtained for the lowest energy model ($E_{0.003}$), with the remnant still in Sedov phase. The SN Type Ia model results in the lowest ambient density (0.0009 cm^{-3}), being in the ejecta-dominated phase. In case c) ($D = 3.3$ pc), we did not model the CC SN type as all model results require an asymmetric remnant with significant X-ray emission. As this is at odds with what is observed, this scenario is deemed very unrealistic. The highest density (0.015 cm^{-3}) is obtained with the lowest explosion energy ($E_{0.003}$). Here, all models are in an ejecta-dominated phase, where the surface brightness of the SNR increases with diameter. However, a very young SNR would be a bright X-ray source (see the next chapter), making it an unlikely scenario.

As we can see, all the obtained densities are much lower than the value expected close to the Galactic plane. Since the test-particle DSA mechanism gives lower emission than modified DSA, and we use a lower limit for the shock thickness, as well as the equation (Equation 1), which gives lower initial shock velocities, we conclude that these models give strict upper limits for the ambient densities.

As an alternative possibility, the young SNRs with fast oblique shocks, where the ambient field inclination of the amplified magnetic field structures creates a superluminal configuration for magnetized electrons (see Zeković et al., 2024), may have a steeper electron momentum spectra than in the DSA mechanism. This mechanism, known as quasi-periodic shock acceleration (QSA), can result in the spectral index in the range of $\alpha = -0.55$ to -1.35 and up to GeV. Such a steep spectrum could, in the case of a young SNR (e.g. at $D = 3.3$ pc for Teleios), result in much lower synchrotron emission than through DSA mechanism, which would possibly give rise to higher ambient densities than in our models.

4.4.2 Evolutionary model for SNR including X-ray emission

We can apply the Leahy et al. (2019) evolutionary models for circularly symmetric SNR to estimate its evolutionary state. Important input parameters are SNR radius, explosion energy, ejected mass and ISM density. The reference distance is 7.7 kpc (radius 24 pc) for Teleios, but we test distances half and twice as large as well as the nearest distance of 2.2 kpc. For energy, we test values of 3×10^{48} , 10^{49} , 10^{50} and 10^{51} erg, thus allowing the possibility of a low-energy SN. For ejected mass, we use $1.4 M_\odot$ for a type Ia but also test lower ($0.2 M_\odot$) and higher ($20 M_\odot$) values. The environment is likely low density, so we test ISM densities of 0.001, 0.01, 0.1 and 0.3 cm^{-3} . For the ejecta power law index, we use $n = 7$ for most cases, and $n = 10$

for a subset.

The SNR models yield several properties, including shock temperatures and emission measures for forward and reverse shocks and transition times that yield the evolutionary phase. The transition time from ejecta-dominated to Sedov-Taylor phase is labelled EDtoST, and from Sedov-Taylor to pressure-driven shell as STtoPDS. For all $n = 7$ cases, the forward shock produces much more flux than the reverse shock, so we give the forward shock properties (emission measure, EM_{FS} , and temperature, kT_{FS}). We calculate the 0.2–10 keV flux from the shocked gas from EM_{FS} and kT_{FS} using the WebSpec tool at HEASARC^f for an APEC hot plasma spectrum with interstellar absorption. The total column of interstellar absorption in the direction of Teleios is $7.5 \times 10^{21} \text{ cm}^{-2}$, and likely column densities for distances of 3.85, 7.7 and 15.4 kpc are $2 \times 10^{21} \text{ cm}^{-2}$, $4 \times 10^{21} \text{ cm}^{-2}$ and $7 \times 10^{21} \text{ cm}^{-2}$ so we calculate unabsorbed flux and absorbed (observed) fluxes (labeled flux_0 , $\text{flux}_{2 \times 10^{21}}$, $\text{flux}_{4 \times 10^{21}}$ and $\text{flux}_{7 \times 10^{21}}$).

The results of the models are given in Table 2, with case a) for the reference distance, b) for half that distance, c) for twice that distance and d) for the near distance case. We also give the results for $n=10$ for the reference distance, e) in Table 2. The properties of the above set of models can be summarised as follows. For the fiducial case (10^{50} erg, $1.4 M_\odot$, 0.01 cm^{-3}), the age to reach a radius of 24 pc is 17700 yr and it is in the Sedov phase. It has forward shock temperature of 5.8×10^6 K and emission measure of $1.3 \times 10^{61} \text{ cm}^{-3}$. However, it would be a bright X-ray source in the 0.2–10 keV band.

Changing the explosion energy to 10^{49} or 10^{51} erg changes the age (to 56000 or 5600 yr, resp.) and shock temperature (to 9.9×10^5 K or 1.4×10^7 K) but does not change the emission measure. Changing the ejecta mass to 0.2 or $20 M_\odot$ changes the age (to 16000 or 30000 yr, resp.) and changes emission measure by a factor < 1.5 , shock temperature by a factor < 1.2 and the X-ray flux by a factor < 2 . Decreasing the energy to 3×10^{48} erg, however, decreases the shock temperature enough that the SNR is no longer detectable in X-rays.

Changing the ISM density to 0.001 cm^{-3} similarly changes shock temperature and emission measure by small factors and the flux by a factor < 2 . However, increasing the density to 0.1 cm^{-3} puts the SNR age at 53000 yr well in the PDS phase which starts at 30000 yr and reduces the shock temperature to 7×10^5 K, which yields a much smaller absorbed X-ray flux, but still detectable by eROSITA. Increasing the density to 0.3 cm^{-3} however, decreases the shock temperature enough to make the SNR undetectable in X-rays. The $n=10$ case with energy 10^{49} erg, is the only case where the reverse shock flux is higher than the forward shock flux, but it is only brighter by a factor of ~ 1 to 20, and does not change the conclusion that the SNR would be a bright X-ray source.

Decreasing the distance to either 3.85 or 2.2 kpc results in a bright X-ray source for all cases. Increasing the distance decreases the shock temperature and makes the SNR considerably fainter, mainly because of decreased shock temperature and partly because of increased ISM absorption. Increasing the

^fheasarc.gsfc.nasa.gov

Table 1. The results of the radio Σ - D evolutionary models. Note: Density values below 0.001 H cm^{-3} are included in the modelling; however, are likely too low to exist within the Galaxy.

a) $D = 48 \text{ pc}$							
Energy (10^{51} erg)	Ejecta ($M_{\odot}$)	Density (H cm^{-3})	Swept mass ($M_{\odot}$)	Shock velocity (km s^{-1})	Age (yr)	Spectral Index	Phase
0.03	0.2	0.08	470	130	72000	0.55	PDS
0.1	0.4	0.005	30	970	11200	0.52	Sedov
0.3	0.8	0.001	8	2800	5200	0.51	Sedov
1	1.4	0.0006	3.5	6100	3100	0.50	Ejecta/Sedov
1	20	0.002	12	2000	10800	0.51	Ejecta

b) $D = 14 \text{ pc}$							
Energy (10^{51} erg)	Ejecta ($M_{\odot}$)	Density (H cm^{-3})	Swept mass ($M_{\odot}$)	Shock velocity (km s^{-1})	Age (yr)	Spectral Index	Phase
0.003	0.1	0.02	3	490	7100	0.51	Sedov
0.01	0.1	0.006	0.8	1550	2800	0.5	Sedov
0.1	0.4	0.002	0.3	4550	1400	0.5	Ejecta
1	1.4	0.0009	0.1	8300	800	0.5	Ejecta

b) $D = 3.3 \text{ pc}$							
Energy (10^{51} erg)	Ejecta ($M_{\odot}$)	Density (H cm^{-3})	Swept mass ($M_{\odot}$)	Shock velocity (km s^{-1})	Age (yr)	Spectral Index	Phase
0.003	0.1	0.01	0.03	1650	940	0.5	Ejecta
0.01	0.1	0.008	0.01	3100	510	0.5	Ejecta
0.1	0.4	0.004	0.008	5000	320	0.5	Ejecta
1	1.4	0.002	0.004	8400	190	0.5	Ejecta

Table 2. The results of the SNR evolutionary models.

a) distance=7.7 kpc radius=24 pc											
Density (cm ⁻³)	Energy (10 ⁵¹ erg)	Ejecta (M _⊙)	age (yr)	EDtoST (yr)	STtoPDS (yr)	EM _{FS} (10 ⁵⁸ cm ⁻³)	kT _{FS} (K)	flux ₀ (erg/s/cm ²)	flux _{2 × 10²¹} (erg/s/cm ²)	flux _{4 × 10²¹} (erg/s/cm ²)	flux _{7 × 10²¹} (erg/s/cm ²)
0.01	0.003	1.4	115000	35000	53000	1.60E+03	1.50E+05	7.11E-14	2.36E-18	8.77E-21	2.81E-23
0.01	0.01	1.4	56000	19000	69000	1.30E+03	9.90E+05	1.51E-08	4.14E-10	6.65E-11	7.96E-12
0.01	0.1	1.4	17700	6100	113000	1.30E+03	5.80E+06	5.51E-08	2.24E-08	1.15E-08	5.27E-09
0.01	1	1.4	5600	1900	185000	1.30E+03	1.40E+07	4.48E-08	2.49E-08	1.71E-08	1.14E-08
0.01	0.1	0.2	16200	1200	113000	1.30E+03	5.50E+06	5.46E-08	2.18E-08	1.11E-08	4.97E-09
0.01	0.1	20	29600	56000	113000	1.90E+03	4.90E+06	7.81E-08	3.01E-08	1.49E-08	6.46E-09
0.001	0.1	1.4	8600	13000	420000	1.90E+03	7.10E+06	8.43E-08	3.70E-08	2.00E-08	9.94E-09
0.1	0.1	1.4	53500	2800	30000	1.30E+03	6.70E+05	4.21E-09	4.22E-11	5.28E-12	4.76E-13
0.3	0.1	1.4	122000	2000	16000	2.10E+03	1.00E+05	2.72E-16	8.85E-22	5.31E-25	2.24E-28
b) distance=3.85 kpc radius=12 pc											
Density (cm ⁻³)	Energy (10 ⁵¹ erg)	Ejecta (M _⊙)	age (yr)	EDtoST (yr)	STtoPDS (yr)	EM _{FS} (10 ⁵⁸ cm ⁻³)	kT _{FS} (K)	flux ₀ (erg/s/cm ²)	flux _{2 × 10²¹} (erg/s/cm ²)	flux _{4 × 10²¹} (erg/s/cm ²)	flux _{7 × 10²¹} (erg/s/cm ²)
0.01	0.01	1.4	14400	19000	69000	2.50E+02	4.50E+06	4.03E-08	1.47E-08	7.10E-09	2.96E-09
0.01	0.1	1.4	4500	6100	113000	2.50E+02	1.10E+07	4.25E-08	2.20E-08	1.37E-08	8.28E-09
0.01	1	1.4	1430	1900	185000	2.50E+02	3.45E+07	8.51E-09	7.34E-09	9.94E-09	1.29E-08
b) distance=15.4 kpc radius=48 pc											
Density (cm ⁻³)	Energy (10 ⁵¹ erg)	Ejecta (M _⊙)	age (yr)	EDtoST (yr)	STtoPDS (yr)	EM _{FS} (10 ⁵⁸ cm ⁻³)	kT _{FS} (K)	flux ₀ (erg/s/cm ²)	flux _{2 × 10²¹} (erg/s/cm ²)	flux _{4 × 10²¹} (erg/s/cm ²)	flux _{7 × 10²¹} (erg/s/cm ²)
0.01	0.01	1.4	380000	19000	69000	1.10E+04	4.40E+04	8.50E-19	2.63E-25	2.25E-29	1.01E-33
0.01	0.1	1.4	91500	6100	113000	1.10E+04	1.25E+06	5.40E-08	2.74E-09	5.23E-10	7.50E-11
0.01	1	1.4	29000	1900	185000	1.10E+04	7.30E+06	1.23E-07	5.46E-08	2.97E-08	1.49E-08
d) distance=2.2 kpc radius=6.85 pc											
Density (cm ⁻³)	Energy (10 ⁵¹ erg)	Ejecta (M _⊙)	age (yr)	EDtoST (yr)	STtoPDS (yr)	EM _{FS} (10 ⁵⁸ cm ⁻³)	kT _{FS} (K)	flux ₀ (erg/s/cm ²)	flux _{2 × 10²¹} (erg/s/cm ²)	flux _{4 × 10²¹} (erg/s/cm ²)	flux _{7 × 10²¹} (erg/s/cm ²)
0.01	0.01	1.4	9580	8900	18500	4.02E+01	4.28E+06	1.92E-08	6.98E-09	3.39E-09	1.41E-09
0.01	0.1	1.4	3030	2800	30300	4.05E+01	1.70E+07	1.32E-08	8.09E-09	6.20E-09	4.65E-09
0.01	1	1.4	958	890	49600	4.10E+01	4.21E+07	1.38E-08	9.81E-09	8.63E-09	7.66E-09
e) distance=7.7 kpc radius=24 pc n=10											
Density (cm ⁻³)	Energy (10 ⁵¹ erg)	Ejecta (M _⊙)	age (yr)	EDtoST (yr)	STtoPDS (yr)	EM _{FS} (10 ⁵⁸ cm ⁻³)	kT _{FS} (K)	flux ₀ (erg/s/cm ²)	flux _{2 × 10²¹} (erg/s/cm ²)	flux _{4 × 10²¹} (erg/s/cm ²)	flux _{7 × 10²¹} (erg/s/cm ²)
0.01	0.01	1.4	55500	12600	68900	1.31E+03	9.98E+05	1.94E-08	5.94E-10	9.96E-11	1.12E-11
0.01	0.1	1.4	17600	3990	11300	1.40E+03	5.81E+06	6.41E-08	2.70E-08	1.42E-08	6.60E-09
0.01	1	1.4	5550	1260	185000	1.49E+03	1.39E+07	4.87E-08	2.86E-08	2.05E-08	1.40E-08

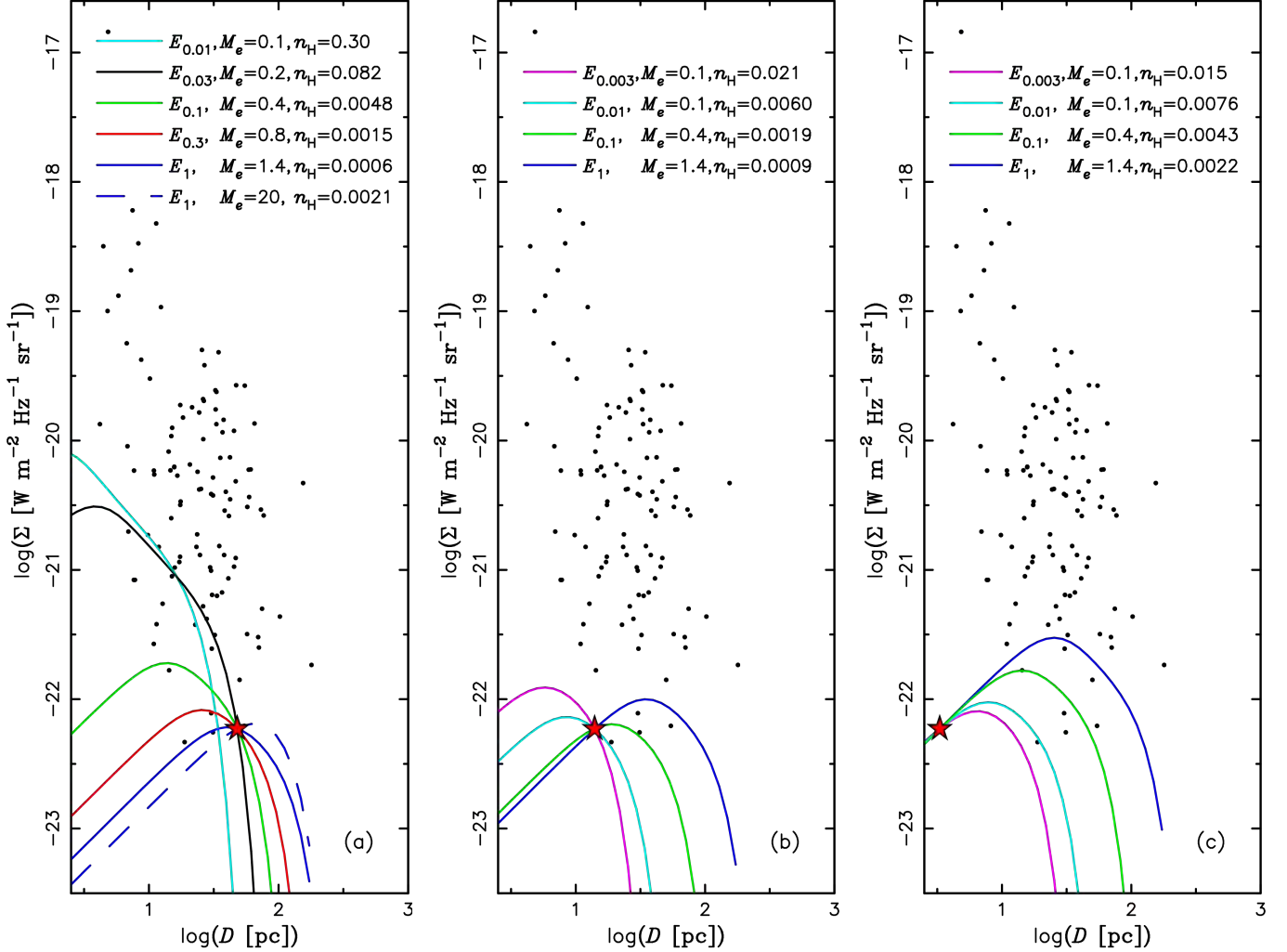


Figure 8. The evolutionary paths for Teleios, obtained using the emission model from Kostić et al. (2024). The panels (a), (b), and (c) stand for the diameters $D = 48 \text{ pc}$, $D = 7 \text{ pc}$, and $D = 3.3 \text{ pc}$, respectively. The explosion energy (in ergs), ejecta mass (in solar masses, $M_\odot$) and ambient density (in cm^{-3}) for different models are displayed in the legend. The black points represent the Galactic SNR sample from Vukotić et al. (2019). The red star marks the Teleios's position on Σ - D plot. Note: Density values below 0.001 H cm^{-3} are included in the modelling; however, are likely too low to exist within the Galaxy.

ejecta power-law index to $n=10$ (case e) yields slightly brighter X-ray emission in all cases in comparison to $n=7$ models, so it cannot give an SNR with low enough X-ray flux.

In summary, to have a low X-ray flux (below $3 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$), the shock temperature needs to be below $\sim 3 \times 10^5 \text{ K}$. The models can satisfy this if the energy is low ($\lesssim 10^{49} \text{ erg}$) and either the distance is large ($\gtrsim 15 \text{ kpc}$) or the ISM density is high ($\gtrsim 0.2 \text{ cm}^{-3}$), so that the SNR is in an evolved state. In this case, the SNR has transitioned from the Sedov-Taylor phase into the pressure-driven shell phase. This is certainly in contradiction with our initial suggestion that Teleios should be a youngish SNR.

4.5 What is Teleios?

Teleios's unusually close-to-perfect circular shape, steep radio spectral index ($\alpha = -0.6 \pm 0.3$), weak polarisation signature and low surface brightness are rather challenging to reconcile with typical SNR characteristics. However, despite only confirmed radio-continuum emission, there is little doubt that Teleios is

a Galactic SNR as no other known source type could better fit its radio properties.

We observe that Teleios is located in an environment with a high level of ambient RM, with the largest RM being observed at Teleios's centre (Section 3.4). This unusual RM environment, combined with Teleios's remarkably low surface brightness, raises the possibility that this may be caused by Teleios's orientation. That is, if Teleios is being viewed end on, and if the ambient magnetic field is oriented along our line of sight, either towards or away from us, then the compression would be perpendicular to our line of sight. Thus, the typical synchrotron emission observed from most SNRs would be predominantly oriented perpendicular to our line of sight, resulting in Teleios's observed low surface brightness. This scenario would also explain the lack of polarisation from the shells, as this magnetic field orientation would result in increased Faraday rotation rather than synchrotron emission in our direction. It would also explain the observed circular symmetry, as the compression occurs perpendicular to our line

of sight.

This scenario is also supported by Teleios’s possible Galactic location when compared with the magnetic field models of West et al. (2016). Namely, the West et al. (2016) model of SNR G302.3+00.7 is the best comparison, as it is the example located closest to Teleios and so is the best representation of the local Galactic magnetic field in this area. Comparing Teleios with West et al. (2016, their Figure D.1), we see that the models for ~ 6 kpc show a round morphology similar to Teleios. This model demonstrates that these circular morphologies typically occur in regions where the Galactic magnetic field lines are orientated along our line of sight, i.e. we are viewing the Galactic magnetic field end on.

We investigated Teleios’s possible evolutionary state as SN CC, type Ia or Iax explosions by applying two different theoretical models. We have a challenge reconciling the observational evidence, such as Teleios’s low surface-brightness and circular shape, steep spectral index (-0.6) and a possible size of $D = 14/48$ pc with any of the presented scenarios. As in the case of only known type Iax SNR from SN1181 with $D = 1.8$ pc, Teleios’s size of $D = 48$ pc at the distance of 7.7 kpc is very much out of any acceptable range. If Teleios comes from type Iax SN explosion, it should be located at much closer distances than even our lower distance estimate of 2.2 kpc and corresponding $D = 14$ pc. This immediately places WD Gaia DR3 5858854017669128192 in the spotlight as a possible remnant star at only 527 pc distance, thus giving Teleios a diameter $D = 3.3$ pc (see Section 4.3). However, none of the other independent measurements place Teleios at this distance. At the same time, neither of the two evolutionary methods (see Section 4.4) could explain Teleios as a type Ia SNR without detectable X-ray emission.

Certainly, future high-resolution multi-frequency observations could determine a possible expansion velocity, which could more accurately indicate Teleios’s properties.

5. CONCLUSION

We suggest that the low surface-brightness circular object G305.4–2.2, Teleios, detected in our new ASKAP EMU images, is most likely a new Galactic SNR with spectral index of $\alpha = -0.6 \pm 0.3$, a diameter of either 14 pc or 48 pc and at a distance of ~ 2.2 or 7.7 kpc.

We consider several different scenarios to explain Teleios’s unusual properties, all of which have their challenges. We consider a CC progenitor scenario, but this is deemed unlikely due to Teleios’s distance from the Galactic Plane (70–540 pc) and spherical symmetry. We also explored a type Iax explosion scenario that would argue for a much closer distance (< 1 kpc) and sizes of only ~ 3.3 pc, which would be comparable to the only known type Iax remnant SN1181. We also consider a Type Ia scenario, which we argue to be the most likely. Although we note that the lack of detectable X-ray emission is puzzling, and the hint of $H\alpha$ emission projected within the remnant would be surprising for an SN Ia.

We have made an exhaustive exploration of the possible evolutionary state of the SN based on its surface brightness,

apparent size and possible distances. All possible scenarios have their challenges, especially considering the lack of X-ray emission that is expected to be detectable given our evolutionary modelling. While we deem the Type Ia scenario the most likely, we note that no direct evidence is available to definitively confirm any scenario and new sensitive and high-resolution observations of this object are needed.

Acknowledgement

This scientific work uses data obtained from Inyarrimanha Ilgari Bundara, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Murchison Radio-astronomy Observatory. We acknowledge the Wajarri Yamaji People as the Traditional Owners and native title holders of the Observatory site. CSIRO’s ASKAP radio telescope is part of the Australia Telescope National Facility (<https://ror.org/05qajvd42>). Operation of ASKAP is funded by the Australian Government with support from the National Collaborative Research Infrastructure Strategy. ASKAP uses the resources of the Pawsey Supercomputing Research Centre. Establishment of ASKAP, Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory and the Pawsey Supercomputing Research Centre are initiatives of the Australian Government, with support from the Government of Western Australia and the Science and Industry Endowment Fund. We thank I. Sushch for scientific discussions which improved the paper. We thank an anonymous referee for comments and suggestions that greatly improved our paper.

Funding Statement MDF, GR and SL acknowledge Australian Research Council (ARC) funding through grant DP200100784. N.H.-W. is the recipient of an ARC Future Fellowship (project number FT190100231). HS acknowledges funding from JSPS KAKENHI Grant Number 21H01136. DU and BA acknowledge the financial support provided by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia through the contract 451–03–66/2024–03/200104 and for support through the joint project of the Serbian Academy of Sciences and Arts and Bulgarian Academy of Sciences “Optical search for Galactic and extragalactic supernova remnants”. BA additionally acknowledges the funding provided by the Science Fund of the Republic of Serbia through project #7337 “Modeling Binary Systems That End in Stellar Mergers and Give Rise to Gravitational Waves” (MOBY). RB acknowledges funding from the Irish Research Council under the Government of Ireland Postdoctoral Fellowship program. JM acknowledges support from a Royal Society–Science Foundation Ireland University Research Fellowship (20/RS-URF-R/3712). CBS acknowledges support from a Royal Society Research Fellows Enhancement Award 2021 (22/RS-EA/3810). JM and CBS acknowledge that this publication results from research conducted with the financial support of Taighde Éireann – Research Ireland under Grant numbers 20/RS-URF-R/3712, 22/RS-EA/3810. SL, PK, AM and BV were supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (MSTDIRS) through contract no.

451–03–66/2024–03/200002 made with Astronomical Observatory (Belgrade). RS is supported by INAF grant 1.05.23.04.04.

Data Availability Statement The data that support the plots/images within this paper and other findings of this study are available from the corresponding author upon reasonable request. The ASKAP data used in this article are available through the CASDA[§].

References

- Abdollahi, S., Acero, F., Ackermann, M., et al. 2020, *ApJs*, 247, 33
- Abdollahi, S., Acero, F., Baldini, L., et al. 2022, *ApJs*, 260, 53
- Acero, F., Ackermann, M., Ajello, M., et al. 2016, *ApJs*, 224, 8
- Alsaberi, R. Z. E., Barnes, L. A., Filipović, M. D., et al. 2019, *Ap&SS*, 364, 204
- Alsaberi, R. Z. E., Filipović, M. D., Dai, S., et al. 2024, *MNRAS*, 527, 1444
- Anderson, L. D., Wang, Y., Bihl, S., et al. 2017, *A&A*, 605, A58
- Anderson, L. D., Camilo, F., Faerber, T., et al. 2024, *arXiv e-prints*, arXiv:2409.16607
- Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, *ApJ*, 697, 1071
- Axford, W. I., Leer, E., & Skadron, G. 1977, in *International Cosmic Ray Conference*, Vol. 11, *International Cosmic Ray Conference*, 132
- Ball, B. D., Kothes, R., Rosolowsky, E., et al. 2023, *MNRAS*, 524, 1396
- Bartunov, O. S., Tsvetkov, D. Y., & Filimonova, I. V. 1994, *Publications of the Astronomical Society of the Pacific*, 106, 1276
- Bell, A. R. 1978, *MNRAS*, 182, 147
- Blaauw, A. 1993, in *Astronomical Society of the Pacific Conference Series*, Vol. 35, *Massive Stars: Their Lives in the Interstellar Medium*, ed. J. P. Cassinelli & E. B. Churchwell, 207
- Bland-Hawthorn, J., & Gerhard, O. 2016, *ARA&A*, 54, 529
- Blandford, R. D., & Ostriker, J. P. 1978, *ApJL*, 221, L29
- Booth, R. A., Kothes, R., Landecker, T., et al. 2022, *ApJ*, 941, 17
- Bordiu, C., Filipovic, M. D., Umana, G., et al. 2024, *arXiv e-prints*, arXiv:2408.07727
- Bozzetto, L. M., Filipović, M. D., Urošević, D., Kothes, R., & Crawford, E. J. 2014, *MNRAS*, 440, 3220
- Bozzetto, L. M., Filipović, M. D., Vukotić, B., et al. 2017, *Astrophys. J. Suppl.*, 230, 2
- Bozzetto, L. M., Filipović, M. D., Sano, H., et al. 2023, *MNRAS*, 518, 2574
- Brose, R., Pohl, M., Sushch, I., Petruk, O., & Kuzyo, T. 2020, *A&A*, 634, A59
- Burger-Scheidlin, C., Brose, R., Mackey, J., et al. 2024, *A&A*, 684, A150
- Cendes, Y., Gaensler, B. M., Ng, C. Y., et al. 2018, *ApJ*, 867, 65
- Chen, Y., Zhou, P., & Chu, Y.-H. 2013, *ApJ*, 769, L16
- Churchwell, E., Babler, B. L., Meade, M. R., et al. 2009, *Publications of the Astronomical Society of the Pacific*, 121, 213
- Cotton, W. D., Filipović, M. D., Camilo, F., et al. 2024, *MNRAS*, 529, 2443
- Das, S., Brose, R., Meyer, D. M. A., et al. 2022, *A&A*, 661, A128
- Das, S., Brose, R., Pohl, M., Meyer, D. M. A., & Sushch, I. 2024, *A&A*, 689, A9
- Dokara, R., Brunthaler, A., Menten, K. M., et al. 2021, *A&A*, 651, A86
- Drimmel, R. 2000, *A&A*, 358, L13
- Efremov, Y. N. 2011, *Astronomy reports*, 55, 108
- Enokiya, R., Sano, H., Filipović, M. D., et al. 2023, *PASJ*, 75, 970
- Ferrand, G., & Safi-Harb, S. 2012, *Advances in Space Research*, 49, 1313
- Fesen, R. A., Schaefer, B. E., & Patchick, D. 2023, *The Astrophysical Journal Letters*, 945, L4
- Filipovic, M. D., Horner, J., Crawford, E. J., Tothill, N. F. H., & White, G. L. 2013, *Serbian Astronomical Journal*, 187, 43
- Filipović, M. D., & Tothill, N. F. H., eds. 2021, *Multimessenger Astronomy in Practice*, 2514–3433 (IOP Publishing), doi:10.1088/2514–3433/ac2256
- Filipović, M. D., Ilić, M., Jarrett, T., et al. 2021a, *European Journal of Science and Theology*, 17, 11
- Filipović, M. D., Payne, J. L., Jarrett, T., et al. 2021b, *European Journal of Science and Theology*, 17, 147
- Filipović, M. D., Payne, J. L., Jarret, T., et al. 2022a, *European Journal of Science and Theology*, 18, 51
- Filipović, M. D., Payne, J. L., Alsaberi, R. Z. E., et al. 2022b, *MNRAS*, 512, 265
- Filipović, M. D., Dai, S., Arbutina, B., et al. 2023, *AJ*, 166, 149
- Filipović, M. D., Lazarević, S., Araya, M., et al. 2024, *PASA*, 41, e112
- Finke, J. D., & Dermer, C. D. 2012, *ApJ*, 751, 65
- Foley, R. J., Challis, P. J., Chornock, R., et al. 2013, *ApJ*, 767, 57
- Foster, T. J., Cooper, B., Reich, W., Kothes, R., & West, J. 2013, *A&A*, 549, A107
- Gaensler, B. M., Landecker, T. L., Taylor, A. R., & POSSUM Collaboration. 2010, in *American Astronomical Society Meeting Abstracts*, Vol. 215, *American Astronomical Society Meeting Abstracts #215*, 470.13
- Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, *A&A*, 595, A1
- Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al. 2023, *A&A*, 674, A1
- Galvin, T. J., & Filipovic, M. D. 2014, *Serbian Astronomical Journal*, 189, 15
- Ghavamian, P., Rakowski, C. E., Hughes, J. P., & Williams, T. B. 2003, *ApJ*, 590, 833
- Ghavamian, P., Raymond, J., Hartigan, P., & Blair, W. P. 2000, *ApJ*, 535, 266
- Green, D. A. 2022, *A Catalogue of Galactic Supernova Remnants (2022 December version)*
- Green, D. A. 2024, *An updated catalogue of 310 Galactic supernova remnants and their statistical properties*, arXiv:2411.03367
- Gupta, N., Huynh, M., Norris, R. P., et al. 2022, *Publications of the Astronomical Society of Australia*, 39, e051
- Guzman, J., Whiting, M., Voronkov, M., et al. 2019, *ASKAPsoft: ASKAP science data processor software*, *Astrophysics Source Code Library*, record ascl:1912.003
- Hakobyan, A. A., Barkhudaryan, L. V., Karapetyan, A. G., et al. 2017, *Mon. Not. R. Astron. Soc.*, 471, 1390
- Hancock, P. J., Trott, C. M., & Hurley-Walker, N. 2018, *PASA*, 35, e011
- H.E.S.S. Collaboration, Abdalla, H., Abramowski, A., et al. 2018, *A&A*, 612, A1
- H.E.S.S. Collaboration, Abdalla, H., Adam, R., et al. 2020, *A&A*, 633, A102
- H.E.S.S. Collaboration, Aharonian, F., Ait Benkhali, F., et al. 2024, *A&A*, 687, A219
- HI4PI Collaboration, Ben Bekhti, N., Flöer, L., et al. 2016, *A&A*, 594, A116
- Hou, L. G., & Han, J. L. 2014, *A&A*, 569, A125
- Hurley-Walker, N., Callingham, J. R., Hancock, P. J., et al. 2017, *MNRAS*, 464, 1146
- Hurley-Walker, N., Gaensler, B. M., Leahy, D. A., et al. 2019a, *PASA*, 36, e048
- Hurley-Walker, N., Filipović, M. D., Gaensler, B. M., et al. 2019b, *PASA*, 36, e045
- Hurley-Walker, N., Galvin, T. J., Duchesne, S. W., et al. 2022, *PASA*, 39, e035
- Kavanagh, P. J., Sasaki, M., Bozzetto, L. M., et al. 2015, *A&A*, 573, A73
- Kavanagh, P. J., Sasaki, M., Filipović, M. D., et al. 2022, *MNRAS*, 515, 4099
- Kavanagh, P. J., Vink, J., Sasaki, M., et al. 2019, *A&A*, 621, A138
- Kerr, F. J., & Lynden-Bell, D. 1986, *MNRAS*, 221, 1023
- Khabibullin, I. I., Churazov, E. M., Bykov, A. M., Chugai, N. N., & Sunyaev, R. A. 2023, *MNRAS*, 521, 5536
- Koribalski, B. S., Norris, R. P., Andernach, H., et al. 2021, *MNRAS*, 505, L11
- Kostić, P., Arbutina, B., Vukotić, B., & Urošević, D. 2024, *ApJ*, 974, 236
- Kothes, R., Reich, P., Foster, T. J., & Reich, W. 2017, *A&A*, 597, A116
- Kothes, R., & Reich, W. 2001, *A&A*, 372, 627
- Lamer, G., Schwöpe, A. D., Predehl, P., et al. 2021, *A&A*, 647, A7
- Lazarević, S., Filipović, M. D., Koribalski, B. S., et al. 2024, *Research Notes of the American Astronomical Society*, 8, 107

[§]<https://research.csiro.au/casda>

- Leahy, D., Wang, Y., Lawton, B., Ranasinghe, S., & Filipović, M. 2019, *AJ*, 158, 149
- Liu, Q.-C., Chen, Y., Chen, B.-Q., et al. 2018, *The Astrophysical Journal*, 859, 173
- Lopez, L. A., Ramirez-Ruiz, E., Huppenkothen, D., Badenes, C., & Pooley, D. A. 2011, *ApJ*, 732, 114
- López-Sanjuan, C., Varela, J., Cristóbal-Hornillos, D., et al. 2019, *A&A*, 631, A119
- Luken, K. J., Filipović, M. D., Maxted, N. I., et al. 2020, *MNRAS*, 492, 2606
- Maggi, P., Filipović, M. D., Vukotić, B., et al. 2019, *Astron. & Astrophys.*, 631, A127
- Mantovanini, S., Hurley-Walker, N., & Anderson, G. 2025, *PASA*, 42, e021
- Mattox, J. R., Bertsch, D. L., Chiang, J., et al. 1996, *ApJ*, 461, 396
- McKee, C. F., & Truelove, J. K. 1995, *Phys. Rep.*, 256, 157
- Meyer, D. M. A., Langer, N., Mackey, J., Velázquez, P. F., & Gusdorf, A. 2015, *MNRAS*, 450, 3080
- Norris, R. P., Crawford, E., & Macgregor, P. 2021, *Galaxies*, 9, doi:10.3390/galaxies9040083
- Norris, R. P., Hopkins, A. M., Afonso, J., et al. 2011, *PASA*, 28, 215
- Norris, R. P., Marvil, J., Collier, J. D., et al. 2021, *PASA*, 38, e046
- Norris, R. P., Intema, H. T., Kapińska, A. D., et al. 2021, *PASA*, 38, e003
- Oh, S., Kroupa, P., & Pflamm-Altenburg, J. 2015, *ApJ*, 805, 92
- Pavlović, M. Z., Urošević, D., Arbutina, B., et al. 2018, *Astrophys. J.*, 852, 84
- Poggio, E., Drimmel, R., Lattanzi, M. G., et al. 2018, *MNRAS*, 481, L21
- Ranasinghe, S., & Leahy, D. 2019, *JHEP Grav. Cosmol.*, 5, 907
- Ranasinghe, S., & Leahy, D. 2022, *ApJ*, 940, 63
- . 2023, *ApJs*, 265, 53
- Ranasinghe, S., Leahy, D., & Stil, J. 2021, *Universe*, 7, 338
- Reynolds, S. P., Gaensler, B. M., & Bocchino, F. 2012, *Space Science Reviews*, 166, 231
- Roper, Q., Filipovic, M., Allen, G. E., et al. 2018, *MNRAS*, 479, 1800
- Ross, K., Hurley-Walker, N., Galvin, T. J., et al. 2024, *arXiv e-prints*, arXiv:2406.06921
- Rudnick, L. 2002, *New A Rev.*, 46, 101
- Sano, H., Yamane, Y., Voisin, F., et al. 2017, *ApJ*, 843, 61
- Sano, H., Reynoso, E., Mitsuishi, I., et al. 2017, *Journal of High Energy Astrophysics*, 15, 1
- Sano, H., Yamane, Y., Tokuda, K., et al. 2018, *The Astrophysical Journal*, 867, 7
- Sasaki, M., Zangrandi, F., Filipović, M., et al. 2025, *A&A*, 693, L15
- Shabala, S. S., Yates-Jones, P. M., Jerrim, L. A., et al. 2024, *PASA*, 41, e024
- Smeaton, Z. J., Filipović, M. D., Koribalski, B. S., et al. 2024a, *Research Notes of the American Astronomical Society*, 8, 158
- Smeaton, Z. J., Filipović, M. D., Lazarević, S., et al. 2024b, *MNRAS*, 534, 2918
- Smith, N., & Tombleson, R. 2015, *MNRAS*, 447, 598
- Soker, N. 2019, *New A Rev.*, 87, 101535
- . 2024a, *Research in Astronomy and Astrophysics*, 24, 015012
- . 2024b, *The Open Journal of Astrophysics*, 7, 31
- Srivastav, S., Smartt, S. J., Huber, M. E., et al. 2022, *MNRAS*, 511, 2708
- Su, Y., Chen, Y., Yang, J., et al. 2009, *The Astrophysical Journal*, 694, 376
- Sushch, I., Brose, R., Pohl, M., Plotko, P., & Das, S. 2022, *ApJ*, 926, 140
- Tingay, S. J., Goeke, R., Bowman, J. D., et al. 2013, *PASA*, 30, e007
- Urošević, D. 2020, *Nature Astronomy*, 4, 910
- Vallée, J. P. 2017, *Astronomical Review*, 13, 113
- Verberne, S., & Vink, J. 2021, *Monthly Notices of the Royal Astronomical Society*, 504, 1536
- Vukotić, B., Čiprijanović, A., Vučetić, M. M., Onić, D., & Urošević, D. 2019, *Serbian Astronomical Journal*, 199, 23
- Vukotić, B., Čirković, M. M., & Filipović, M. D. 2021, in *Multimessenger Astronomy in Practice: Celestial Sources in Action*, ed. M. D. Filipović & N. F. H. Tothill (IOP Publishing), 11–1
- Wayth, R. B., Lenc, E., Bell, M. E., et al. 2015, *PASA*, 32, e025
- Wayth, R. B., Tingay, S. J., Trott, C. M., et al. 2018, *PASA*, 35, e033
- Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, *ApJ*, 218, 377
- Weßmayer, D., Urbaneja, M. A., Butler, K., & Przybilla, N. 2024, *A&A*, 687, L7
- West, J. L., Safi-Harb, S., Jaffe, T., et al. 2016, *A&A*, 587, A148
- Wright, J. T. 2020, *Serbian Astronomical Journal*, 200, 1
- Yamane, Y., Sano, H., Filipović, M. D., et al. 2021, *ApJ*, 918, 36
- Yao, J. M., Manchester, R. N., & Wang, N. 2017, *ApJ*, 835, 29
- Zeković, V., Spitkovsky, A., & Hemler, Z. 2024, *arXiv e-prints*, arXiv:2408.02084
- Zhang, M. F., Tian, W. W., & Wu, D. 2018, *ApJ*, 867, 61