Supernova-remnant origin of the Galactic-Centre filaments

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ABSTRACT

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The mechanism to produce the numerous Galactic-Centre filaments (GCFs) that vertically penetrate the Galactic plane without clear evidence of connection to the disc remains a mystery. Here, we show that the GCFs are explained by relics of supernova remnants (rSNRs) driven by hundreds of supernovae (SNe) that exploded in the star-forming ring of the central molecular zone at an SN rate of $\sim 2 \times 10^{-4}$ yr⁻¹ in the past ~ 0.5 Myr. The evolution of rSNRs is simulated by the propagation of fast-mode magnetohydrodynamic waves, which are shown to converge around the Galactic rotation axis by the focusing effect. Tangential projection of the cylindrical wavefronts on the sky constitutes the vertical filaments. The SNR model explains not only the morphology, but also the non-thermal radio spectrum, smoothed brightness over the distribution area consistent with the Σ -*D* relation of SNR, and the heating mechanism of hot plasma. We discuss the implication of the SNR model on the study of the interstellar physics in the Galactic Centre and star-formation activity.

Key words: MHD-ISM: magnetic fields-ISM: supernova remnants-Galaxy: centre-stars: supernovae.

1 INTRODUCTION

The high-resolution radio continuum observations with the Very Large Array in the decades (Yusef-Zadeh, Morris & Chance 1984; Morris et al. 1985; Anantharamaiah et al. 1991; Lang et al. 1999a; LaRosa et al. 2004; Paré et al. 2019) and more recently by MeerKAT (Heywood et al. 2019, 2022; Yusef-Zadeh et al. 2022a, b) have revealed the numerous Galactic-Centre filaments (GCFs) that vertically penetrate the Galactic plane without clear evidence of interaction with the disc. The forest of GCFs runs predominantly inside the GC lobe (GCL; Sofue & Handa 1984; Heywood et al. 2019), drawing a large 'harp' shape from $l \sim -1^{\circ}$ to $+0.3^{\circ}$ and $b \sim -1^{\circ}$ to $+1^{\circ}$. The major filaments are often bifurcated into thinner strings (Yusef-Zadeh et al. 2022b), composing a number of 'mini-harps'. Individual filaments exhibit more complicated morphology, curving, crossing, horizontal (Lang et al. 1999a; Yusef-Zadeh et al. 2022a), and partial loops. There are also many filaments running outside the GCL, covering a wide area from $l \sim -1.5^{\circ}$ to $+1^{\circ}$ (~ -200 to $\sim +150$ pc). The GCF is also called non-thermal filament, non-thermal radio filament, thread, or string (the literature as above).

There have been several models to explain the origin of the GCF as due to outflow and ejection from the magnetized central disc (Dahlburg et al. 2002; Barkov & Lyutikov 2019; Yusef-Zadeh & Wardle 2019; Zhang et al. 2021; Yusef-Zadeh et al. 2022c) or by interaction with high-energy objects such as pulsar winds (Boldyrev & Yusef-Zadeh 2006). They attribute the driving momentum and energy to outflow activities in the disc or to direct energy injection from the sources. These mechanisms require that the roots of GCF are connected to the galactic disc or to high-energy driving sources. However, the majority of the filaments appear to have no clear evidence of association with such driving objects, although some

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possible correlations of filaments with compact radio sources are suggested (Yusef-Zadeh et al. 2022c). Therefore, the mechanism that produces the apparent free penetration through the disc and the unique 'harp string'-like morphology seems to be still shrouded in mystery.

In order to solve this problem, we have proposed a model that attributed the GCF to magnetohydrodynamic (MHD) disturbances excited by the central activity near Sgr A in a vertical magnetic cylinder (Sofue 2020a), which was partially successful to explain the GCF morphology. In this paper, we extend this idea, and propose that a more plausible mechanism to produce the GCF by supernovae (SNe) occurred in the star-forming (SF) ring of the central molecular zone (CMZ). The GCFs are here interpreted as 'relic' of supernova remnants (rSNRs) and are approximated by MHD disturbances of small amplitude propagating at the Alfvén velocity.

2 PROPAGATION OF MHD WAVES

2.1 Fast-mode MHD waves

MHD disturbances excited by explosive events as SNe in the interstellar space propagate as spherical shock waves in the initial expansion phase. In the fully expanded phase, they propagate as the fast-mode MHD compression wave (hereafter, MHD wave), Alfvén wave, and the sound wave. Among the three modes, the fast MHD wave is most efficient to convey the energy released by the rSNR into the interstellar medium (ISM) in the present circumstances (Sofue 2020a), which propagates at the group velocity equal to the Alfvén velocity, $v_g \simeq V$ (Porter, Klimchuk & Sturrock 1994; Kumar, Kumar & Singh 2006). Predominance of MHD wave is confirmed by the low value of plasma $\beta = (c_s/V)^2 \sim 0.01$, as $V \sim 10^3$ km s⁻¹ and $c_s \sim 10^2$ km s⁻¹ in the present circumstance.

Here, we assume that an rSNR after sufficient expansion of an SNR, which should actually be a shock wave, is represented



Figure 1. Schematic illustration of rSNR as a fast-mode MHD wavefront. An SN produces an SNR expanding as a Sedov sphere. As it fully evolves, the shell is strongly deformed and merged into the ISM as an MHD wave (disturbance) propagating at Alfvén velocity (sub-Alfvénic). The tangential projection of the front on the sky is observed as a GCF.

by an MHD wave propagating at the Alfvén velocity. So, rSNR is no more a shocked shell, but is a sub-Alfvénic wave. Fig. 1 schematically illustrates the assumed situation in this paper. The wavelength is assumed to be comparable to the shock thickness, which is of the order of $\lambda \sim 0.1-0.3r_{\text{shock}}$ for a usual SNR or adiabatic shock-wave shell of radius r_{shock} . We assume that the amplitude of the wave is infinitesimal, so that the waves are treated by the WKB (Wentzel–Kramers–Brillouin) approximation (Uchida 1974). By this approximation, however, we cannot compute the nonlinear compression of the gas and magnetic field and therefore radio emission. So, the present work is mainly aimed at morphological studies of the shape of GCFs.

The propagation of MHD waves is traced by solving the Eikonal equations developed for the Solar coronal Moreton waves (Uchida 1970, 1974). The method has been applied to the GC and SNRs (Sofue 1977, 1978, 1980, 2020a, b). In the interstellar space, a gas cloud with higher density and lower Alfvén velocity acts as a convex lens (low-V lens) gathering the waves, while a gaseous hole with higher magnetic strength acts as a concave lens (high-V lens) reflecting the waves (Sofue 1978). As discussed later, the hot plasma in the GC filling the vertical magnetic cylinder (low-V pillar) acts as a convex toric lens gathering the waves towards the cylinder axis.

The Eikonal equations describing the propagation of an MHD wave packet are given as follows (Uchida 1970, 1974):

$$\frac{\mathrm{d}r}{\mathrm{d}t} = V \frac{p_r}{p},\tag{1}$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = V \frac{p_{\theta}}{rp},\tag{2}$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = V \frac{p_{\phi}}{rp\sin\theta} + \Omega,\tag{3}$$

$$\frac{\mathrm{d}p_r}{\mathrm{d}t} = -p\frac{\partial V}{\partial r} + \frac{V}{rp}(p_\theta^2 + p_\phi^2),\tag{4}$$

$$\frac{\mathrm{d}p_{\theta}}{\mathrm{d}t} = -\frac{p}{r}\frac{\partial V}{\partial\theta} - \frac{V}{rp}(p_{\theta}p_{r} - p_{\phi}^{2}\cot\theta), \tag{5}$$

$$\frac{\mathrm{d}p_{\phi}}{\mathrm{d}t} = -\frac{p}{\sin\theta}\frac{\partial V}{\partial\phi} - \frac{V}{rp}(p_{\phi}p_r + p_{\phi}p_{\theta}\cot\theta),\tag{6}$$

where $V = V(r, \theta, \phi) = V(x, y, z)$ is the Alfvén velocity, the vector $\boldsymbol{p} = (p_r, p_{\theta}, p_{\phi}) = \text{grad } \Phi$ is defined by the gradient of the Eikonal $\Phi, p = (p_r^2 + p_{\phi}^2 + p_{\theta}^2)^{1/2}, (r, \theta, \phi)$ and (x, y, z) are the polar and Cartesian coordinates, respectively, and Ω is the angular velocity of the ambient material around the Galactic rotation axis (*z*-axis).

2.2 Magnetic view of the GC and Alfvén velocity

We assume an oblique dipole-like magnetic cylinder (Sofue, Machida & Kudoh 2010; Sofue 2020a) filled with a hot plasma (Nakashima et al. 2019; Ponti et al. 2019, 2021), which are coexisting with the CMZ and SF ring in the GC (Henshaw et al. 2022; Sofue 2022). Fig. 2 schematically illustrates the assumed magnetic configuration and gas density distribution based on the primordial magnetic field scenario (Sofue et al. 2010).

The Alfvén velocity is calculated from the magnetic field B and gas density ρ by

$$V = \sqrt{B^2/4\pi\rho}.\tag{7}$$

The gas density is expressed by superposition of a molecular ring (Sofue 1995; Henshaw et al. 2022), hot plasma filling the magnetic cylinder (Nakashima et al. 2019; Ponti et al. 2019), and an extended halo with constant density as follows:

$$\rho = \rho_{\rm ring} + \rho_{\rm hot} + \rho_{\rm halo},\tag{8}$$

where

$$\rho_{\rm ring} = \rho_1 \exp[-((\varpi - r_{\rm ring})/w_{\rm ring})^2 + (z/w_{\rm ring})^2], \tag{9}$$

$$\rho_{\rm hot} = \rho_2 \exp(-\xi^4),\tag{10}$$

and

$$\rho_{\text{halo}} = \rho_3. \tag{11}$$

Here, (x, y, z) are Cartesian coordinates with the origin at the GC and *x* denotes distance projected on the sky towards the east (positive longitude), *y* towards the anticentre direction, and *z* is the polar axis (rotation axis) towards the northern Galactic pole. The radius

$$\overline{\omega} = \sqrt{(x - qz)^2 + y^2} \tag{12}$$

represents distance from the tilted cylinder axis inclined by $q = \tan \chi \sim 0.2$ from the z-axis with $\chi \sim 10^{\circ}$, and ξ represents the shape of the elliptical cavity,

$$\xi = \sqrt{(\varpi/r_{\rm cav})^2 + (z/z_{\rm cav}))^2}.$$
(13)

We assume that $\rho_1 = 10\rho_{\text{unit}}$ for the molecular ring, $\rho_2 = 0.1\rho_{\text{unit}}$ for hot plasma in the magnetic cavity, $\rho_3 = 0.01\rho_{\text{unit}}$ for uniform halo, and $r_{\text{cav}} = 1L_{\text{unit}}$ and $z_{\text{cav}} = 3L_{\text{unit}}$ for the hot cavity's radial



Figure 2. Magnetic view of the Galactic Centre (Sofue et al. 2010). (a) Formation of the ring, spiral, and vertical magnetic fields in a primordial galaxy moving through the intergalactic magnetic field. (b) Magnetic view of the GC with the cavity, hot plasma, CMZ, SF ring, and SN explosions.

and vertical radii with the density and length units described below, respectively.

The magnetic strength is assumed to have an oblique dipole-like distribution with a cavity filled by the hot plasma elongated in the polar direction, which is expressed as

$$B = B_0 D(\varpi, z) C(\varpi, z), \tag{14}$$

where

 $D(\varpi, z) = 1/(1 + \zeta^4)$ (15)

represents the dipole-like magnetic strength and

$$C(\varpi, z) = 1 - \eta \exp(-\zeta^4)$$
(16)

represents the central cavity with η being the depth and

$$\zeta = \sqrt{(\varpi/r_{\rm mag})^2 + (z/z_{\rm mag}))^2}.$$
 (17)

Fig. 3 shows the longitudinal variations of the assumed gas density, magnetic strength, and Alfvén velocity in the Galactic plane.

We assume $r_{\rm ring} \sim 1L_{\rm unit}$ and $w_{\rm ring} \sim 0.05-0.1L_{\rm unit}$ for the ring, and $r_{\rm cav} = r_{\rm mag} \sim 1L_{\rm unit}$ and $z_{\rm cav} = z_{\rm mag} \sim 3L_{\rm unit}$ for the magnetic cylinder with cavity and the filling hot plasma. The Alfvén speed has the maximum near the molecular ring and a broad minimum in the centre (Fig. 3). Due to the high density in the molecular ring, V has also a deep minimum in the ring.



Figure 3. (a) Model profiles of the gas density log ρ (in $\rho_{unit} = 1$ H cm⁻³: dashed line), magnetic field strength log *B* (in $B_{unit} = 1$ mG: thin line), and Alfvén velocity log *V* (in $V_{unit} = 2183$ km s⁻¹: thick line), and *x* is in $L_{unit} = 100$ pc. (b) Model distribution of the Alfvén velocity in B_{unit} in the (*x*, *z*) plane.

2.3 Units

The real quantities are obtained using the units of length L_{unit} , time t_{unit} , and velocity $V_{\text{unit}} = B_{\text{unit}}/\sqrt{4\pi\rho_{\text{unit}}}$. Here, the following units are assumed: $\rho_{\text{unit}} = 1 \text{ H cm}^{-3}$, $B_{\text{unit}} = 1 \text{ mG}$, $L_{\text{unit}} = 100 \text{ pc}$, leading to $V_{\text{unit}} = 2183 \text{ km s}^{-1}$ and $t_{\text{unit}} = 1L_{\text{unit}}/V_{\text{unit}} = 4.482 \times 10^4 \text{ yr}$.

For a typical magnetic strength in the GC of ~0.1 mG (Yusef-Zadeh et al. 2022a), the Alfvén velocity is $V \sim 72 \text{ km s}^{-1}$ in the disc (CMZ) with $\rho \sim 10\rho_{\text{unit}}$, and $V \sim 690 \text{ km s}^{-1}$ in the hot plasma with $\sim 0.1\rho_{\text{unit}} = 0.1 \text{ H cm}^{-3}$. The time-scale for a wave travel from the SF ring to the GC through hot plasma is $t_{\text{scale}} \sim 100 \text{ pc}/690 \text{ km s}^{-3} \sim 1.4 \times 10^5 \text{ yr.}$

The Alfvén velocity may be compared with the sound velocity in the CMZ with $c_s \sim 10 \text{ km s}^{-1}$ for $T \sim 10^4 \text{ K}$, and in the hot plasma with $c_s \sim 10^2 \text{ km s}^{-1}$ for $T \sim 10^6 \text{ K}$. Hence, the plasma β value is as low as $\beta \sim 0.02$ in both the CMZ and hot plasma, which confirms that the fast-mode MHD wave approximation is reasonable.

2.4 Dissipation of the wave

The fast-mode MHD wave of compression mode propagates across the magnetic field lines at the group velocity approximately equal to



Figure 4. Damping length $L_{damp} = 2V/v_{vis}$ following Porter et al. (1994) as a function of the wavelengths for $\theta = 90^{\circ}$. The lower line shows that in the GC for $T = 5.3 \times 10^{6}$ K, $\rho = 0.16$ H cm⁻³, and B = 0.1 mG (V = 545 km s⁻¹). The middle and upper dashed lines show those for the ISM with T = 10^{4} K, $\rho = 1$ H cm⁻³, and B = 3 µG, and for the solar corona with 2×10^{6} K, 10^{9} H cm⁻³, and 10 G (V = 1000 km s⁻¹; Porter et al. 1994), respectively. The grey thick lines represent possible ranges for the rSNR in the GC, ISM, and solar corona.

the Alfvén velocity. The wave suffers from the viscous and Ohmic energy losses, while the latter is much smaller and negligible, so that the wave is dissipated at the rate v_{vis} (Porter et al. 1994; Kumar et al. 2006) approximately given by

$$\frac{\nu_{\rm vis}}{\rm s^{-1}} \simeq 10^{7.3} \left(\frac{T}{K}\right)^{5/2} \left(\frac{\rho}{\rm H\,cm^{-3}}\right)^{-1} \left(\frac{k}{\rm cm^{-1}}\right)^2 \sin^2\theta.$$
(18)

Here, $k = 2\pi/\lambda$ is the wavenumber, and λ is the wavelength. The damping length (distance) is defined through the group velocity v_g and v_{vis} by $L_{damp} = 2v_g/v_{vis} \simeq 2V/v_{vis}$ (Porter et al. 1994). We here rewrite it in terms of *B*, ρ , and *T* as a function of λ .

$$\frac{L_{\text{damp}}}{\text{pc}} \sim 1.71 \times 10^3 \left(\frac{T}{10^6 \text{ K}}\right)^{-5/2} \left(\frac{B}{\text{mG}}\right) \left(\frac{\rho}{\text{H cm}^{-3}}\right)^{1/2} \\ \times \left(\frac{\lambda}{\text{pc}}\right)^2 \sin^{-2}\theta.$$
(19)

In Fig. 4, we plot the calculated damping length against wavelength for $\theta = 90^{\circ}$, where we adopted the plasma density and temperature from the Suzaku X-ray observations (Nakashima et al. 2019), $\rho =$ 0.16 H cm⁻³ and T = 0.46 keV = 5.3×10^6 K, and assume B = 0.1mG ($V = 545 \text{ km s}^{-1}$). The plot may be compared with that for the solar corona assuming $T = 2 \times 10^6$ K, $\rho = 10^9$ H cm⁻³, and B =10 G ($V = 1000 \text{ km s}^{-1}$) (Porter et al. 1994). We also show the case for the ISM with 10^4 K, 1 H cm⁻³, and 3 μ G. The grey thick lines represent possible ranges of the wavelength representing the scale length of the disturbances, and the corresponding damping distances. The wavelength is here taken as the representative size of the actual shock thickness of the rSNRs after they have fully expanded in the central ~ 100 pc region, where it is of the order of $\lambda \sim 0.1-0.3r_{\text{shock}}$ \sim 3–30 pc. The plot indicates that the damping length is $L_{\rm damp} \sim$ 100 pc for $\lambda \sim 10$ pc and greater for longer λ . The length will be even longer when the propagation is oblique ($\theta \gtrsim 90^\circ$) due to the term $\sin^{-2}\theta$.

3 SNR MODEL FOR THE GCF

3.1 Vertical filament as tangential projection of wavefront

Fig. 5 shows the result of computation for a spherical MHD wave produced at a point near the molecular ring in a non-rotating medium. The top panel illustrates the relation of the propagation of the front represented by the strings of dots and the background V distribution in the (x, z) plane, where an SN exploded at (x, y, z) = (-0.9, 0, 0) $0L_{unit}$. In the second and third panels, the wavefront is expressed by 1×10^4 wave packets (later, occasionally 1 to 4×10^4 packets per one rSNR), where the SN exploded at $(x, y, z) \sim (-0.8, 0, 0)$ $+0.1)L_{unit}$. Each of the wave packets is given random radial direction at the explosion centre and propagates radially making an expanding spherical front, representing a point (SN) explosion. Soon after the size becomes comparable to the ring and wall sizes, it is rapidly stretched in the z-direction along the vertical magnetic wall. Then, the front is refracted and converged towards the rotation axis (zaxis) by the focusing effect due to the decreasing Alfvén speed. The curved front projected on the sky composes a vertical sharp edge, mimicking the radio filaments. After passing the cylinder, the front is reflected by the magnetic wall on the opposite side, returns to its coming direction, and finally dilutes and loses the shape. Besides the expanding and deforming wave, some fraction of the front is trapped by the molecular ring, and makes a belt of filaments that are stretched, tangled, and spiralling along the SF and molecular gas ring.

The figure simulates the propagation of a single MHD front from the explosion origin. However, it also represents a case when multiple explosions take place periodically at the same place, or a case that a cluster of SNe happens in a small region. The tangential projection of the fronts appears as multiple parallel filaments, whose separation is proportional to the time interval of SN explosions. As discussed later, a cluster of SNe in a small area around an SF region at short time interval and limited duration, or a mini-starburst as taken place in Sgr B2 (Hasegawa et al. 1994), produces a bunch of short separation filaments, or a 'mini-harp'.

3.2 Fronts by multiple SNe

We then simulate a more realistic case on the assumption that SF activity in the molecular (SF) ring resulted in several SN explosions. Fig. 6 shows an example of the simulation for 10 SN explosions several t_{unit} ago at random near the SF ring of radius $r = 1L_{unit}$, where the ISM is not rotating. The initial positions of the explosions are marked by the thick shells whose sizes indicate the density of the surrounding medium with larger shells denoting faster Alfvén velocity. The bottom panel shows two images seen from 5 deg different azimuth directions for a stereo-graphic view of the wavefronts.

Fig. 7 shows a close-up of the simulated MHD fronts, where the SF ring's width is taken wider of $0.2L_{unit}$. Some fraction of the waves are trapped by the molecular ring due to the low Alfvén velocity, and propagate inside the ring, composing complicated front shapes. They may further affect the SF activity and cloud formation.

In Fig. 8, we show a cross-section of the radio brightness at 1.3 GHz for an isolated filament at G-2.5+2.0, and compare with the cross-section of one of the simulated filaments. The simulation well reproduces the sharp rise from the left side (convex side) followed by a gradual decrease towards the right. Such a shape is typical for sky projection of a curved thin surface. The surface is either expanding from the right (west) to left (east) or converging (focusing) from





Figure 5. [Top] Illustration of evolution of an rSNR near the CMZ and magnetic cavity filled by hot plasma. [Middle] MHD wavefronts from one SN exploded at the centre of the sphere around $x = 0.9L_{unit}$, which represents the front at $t = 0.1t_{unit}$. The density of dots projected on the sky simulates the brightness of an rSNR. Each dot represents one wave packet, and the wavefront is represented by 10^4 packets. The front is shown at t = 0.1, 1, 2, 3,... $10t_{unit}$, and projected on a plane 30 deg tilted from the *z*-axis. [Bottom] Same, but projection on the (*x*, *y*) plane (top view). The focusing effect is evident towards the rotation axis with the concave fronts converging to the focal point in the opposite side of the axis.

the left to right. We also compare radio brightness profiles along the brightest (black), second (red) and third (blue) filaments of the Radio Arc, and the long filament running through G0.10+0.10 with a simulated model filament. The coincidence of the observed and simulated cross-sections and profiles is in favor of the model.



Figure 7. [Top] Close-up of the MHD waves near the ring edge, [middle] central region, and [bottom] face-on view of the centre. The area size is $1L_{unit} \times 1L_{unit}$.



Figure 8. (a) Cross-section of the GCF G-0.25+0.20 from MeerKAT image (black line) compared with that of a simulated MHD front (red). Scale is relative in pixels. Simulation's intensity is proportional to the projected number density of the wave packets and is adjusted to fit the radio profile. (b) Radio profile along the brightest (black), second (red) and third (blue) filaments of the Radio Arc. (c) Profile along the long filament through G0.10+0.10. (d) Model profile along a simulated filament, which well reproduces the observed profiles (b) and (c). The wavy fluctuation is due to fore- and background fainter filaments.

So far, we have neglected the Galactic rotation. If the disc and halo are rotating, it causes differential rotation of the order of ~ 1500 km s^{-1} kpc⁻¹ in the CMZ, which will twist the wavefronts. Panel (a) of Fig. 9 shows a simulated result, where the surrounding medium is rotating at $V_{\rm rot} = V_{\rm rot0} (\varpi/\varpi_0)^2 / (1 + (\varpi/\varpi_0)^2)$ with $V_{\rm rot0} =$ $0.07V_{\text{unit}} \sim 150 \text{ km s}^{-1}$ and $\varpi_0 \sim 0.25L_{\text{unit}}$ (~25) pc, approximately mimicking the observed Galactic rotation in the GC (Sofue 2013). The observed curved GCFs are well reproduced in this simulation. The differential rotation causes twist of the fronts, and the filaments appear bent and spiralling with overlapped filaments crossing each other. Such crossing and twisted filaments are indeed observed for many MeerKAT filaments (Yusef-Zadeh et al. 2022a). Rapider rotation causes stronger twist and more complicated filaments as shown in panel (c) where a flat rotation as high as ~ 200 km s⁻¹ is assumed. These simulations result in more twisted and chaotic filaments than observed, so the real rotation in the GC would be milder than that assumed here.

3.4 Asymmetry and turbulence

Asymmetry and turbulence in the ISM distribution cause local variations of the Alfvén velocity, and the waves are refracted and reflected in a more complicated way, yielding more tangled and chaotic front shapes. The lower panels of Fig. 9 show such cases with asymmetric Alfvén velocity distribution. Panel (c) shows a case without rotation, where a sinusoidal variation is given to the Alfvén velocity distribution in the form of $V_A = V_{A,0}(1 - A \prod_i \sin 2\pi x_i/\Lambda)$ with the amplitude A = 0.5 and wavelength $\Lambda = 1.2L_{unit}$, where $V_{A,0}$ is the unperturbed Alfvén velocity given in the previous section. Panel (d) shows the same, but the disc is rotating and the perturbation amplitude is A = 0.2 and $\Lambda = 1L_{unit}$. The wavefronts suffer from more chaotic deformation and result in complicated filaments, mimicking some strongly bent and kinked GCFs.

3.5 Ring site versus central site of SNe

In order to confirm that the vertical GC filaments are produced by SNe exploded in and near the SF ring, we simulate different cases when the SNe occurred at various radii. Fig. 10 shows the results where the SNe exploded in rings of radii R = 0, 0.2, 0.6,..., 1.6 L_{unit} with equal width and vertical extent of $\delta R = 0.1$ and $\delta z = 0.1$. Explosions of 20 SNe occurred at random time interval in the past 20 t_{unit} (~1 Myr). From the simulation, we find the following properties about the efficiency of filament formation:

(i) It is shown that SNe that exploded in the central region at $R \leq 0.5L_{\text{unit}}$, which also simulate active galactic nucleus (AGN)origin waves from Sgr A and A*, produce round-shaped waves accumulating along the axis of the magnetic cavity filled with the hot plasma, resulting in loops and complicated filaments. However, these central SNe do not produce the vertical filaments. The fact that shells or loop filaments are very seldom in the radio maps as in Fig. 11 implies that SN is not a frequent phenomenon in the central ~50 pc in so far as the presently assumed magnetic structure is correct. However, it has been also shown that vertical filaments can be produced, if the magnetic cylinder is significantly offset from the rotation axis (Sofue 2020a). So, the SN rate in the nuclear region remains open as a question.

(ii) SNe that exploded in the rings at $R \gtrsim 0.6L_{\rm unit}$ produce vertically elongated filaments. Even waves from far outside the SF ring at $R \gtrsim 1.6L_{\rm unit}$ are focused around the axis of magnetic cylinder,

producing coherent and vertically stretched filaments. Obviously, the efficiency of focusing decreases at $R \gtrsim 1.6L_{unit}$ because of the wave dilution according to the increasing distance from the GC. From these simulations, we may conclude that the GCFs are a mixture of old rSNRs originating in a wide ringed area at $R \sim 0.6L_{unit}$ (~80 pc) to ~1.6 L_{unit} (~200 pc), predominantly associated with the SF ring in the CMZ.

(iii) It is pointed out that the waves from SNe exploded near the ring centre at $R \simeq 1L_{unit}$ (sixth panel of Fig. 10) are trapped by the molecular ring due to the low Alfvén velocity (Fig. 3), and propagate along the ring without forming vertical filaments. Therefore, SNe occurred in the ring centre, or the 'buried SNe' in the dense molecular clouds in the CMZ little or less contribute to the GCF formation.

(iv) The present simulation on the radius dependence may put more strict correlation between the SN rate and SF rate inferred from the rSNR counting in the sense that the currently estimated SN rate in the previous subsections would have been underestimated. They will also put another constraint on the SN rate in the nuclear region in and around Sgr A as well as the nuclear activity. These will be discussed in a separate paper on SNRs in the CMZ.

3.6 The SN orchestra plays the grand harp

Fig. 11 shows the 1.28 GHz radio continuum map made from the MeerKAT data (Heywood et al. 2022), where extended components with scale sizes greater than 10 pixels have been subtracted by the background-filtering (BGF) technique (Sofue & Reich 1979). The lower panels of Fig. 11 show the result of MHD simulation of the SNR model, where 100 SNe exploded at random over the past 0.45 Myr near the SF ring of radius 100 pc and inclination 85°. This result simulates a case of continuous SN explosions at an SN rate of 2×10^{-4} yr⁻¹ in the CMZ, assuming that relics of SNRs survive for ~0.45 Myr and then dissipate.

The middle panel shows the (x,z) projection of the wavefronts to be compared with the MeerKAT image in the top panel. The coordinates are scaled to the GC distance of 8.2 kpc. The bottom panel shows the same, but extended features are subtracted in order for a better comparison with the interferometric observations that are less sensitive to more extended emissions than those corresponding to the shortest baseline (~10 arcmin to 23 pc). Each filament or a shell represents each front of the rSNR at the present time, and hence, the entire filaments represent the 'present' shapes of the 100 rSNRs that exploded in the past 0.45 Myr at random. White dots represent the initial positions of all the SNe with their radius being equal to the local Alfvén velocity times $0.05t_{unit}$.

We then simulate a more realistic case, where SF activity occurred intermittently in the past ~1 Myr, and each SF region was associated with a cluster of SNe exploding at random on a shorter time-scale. The star formation occurs intermittently in localized molecular clouds randomly distributed in the molecular ring with radius ~100 pc of the CMZ, which composes the SF ring of the same radius (Henshaw et al. 2022; Sofue 2022). Here, 10 SF regions are born at random interval in the past 10–20t_{unit}. Each SF region continues to form stars for a duration of 0.05–0.1t_{unit}. Several to 15 SNe explode at random time interval within this duration in each SF region.

Fig. 12 shows the simulated results as projected on the (x, z) (top) and (x, y) (bottom) planes. Fig. 13 shows the same at higher resolution and compares with the 1.3 GHz MeerKAT image, where extended structures larger than 2 arcsec are subtracted in order to enhance finer GCFs. The bottom panel of Fig. 13 shows a case of a similar intermittent SN and SF activities, but for a different initial condition that the distribution of the SF regions is broader and the

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(c) $-1.5L_{unit}$ 0 $+1.5L_{unit}$ $-1.5L_{unit}$ 0 $+1.5L_{unit}$ Figure 9. (a) MHD fronts after five SNe exploded at random in Galactic rotation. (b) Same, but the rotation is flat till the centre, so that the differential rotation is stronger. (c) No rotation, but 3D sinusoidal asymmetry with amplitude × 0.5 and wavelength of $\Lambda = 1.2L_{unit}$ is given to the Alfvén velocity distribution. (d) Both the mild rotation and weaker amplitude sinusoidal asymmetry (× 0.2, $\Lambda = 1L_{unit}$) are given. Note: (a)–(d) The area sizes are all $3L_{unit} \times 3L_{unit}$.

duration is about twice up to $20t_{unit}$ in the past. White circles show the SN positions with the radius being $0.05t_{unit}$. Due to the longer duration of SF and hence due to older and more expanded fronts (SNRs) than those in the middle panel, the simulated GCFs are more widely distributed.

Thus, we have shown that the SNR model can well reproduce the morphological structures of the GCFs, not only the broadly distributed filaments composing the big harp, but also the bunched thin filaments, or the mini-harps that make up the entire big harp.

3.7 SN ensembles play mini-harps: the radio arc by a mini starburst

So far, we discussed the general morphology of the GCF over the GC region as in Fig. 11. However, closer inspection of the radio

images reveals that most of the brightest filaments are composed of bundles of multiple threads (Yusef-Zadeh et al. 2022b), shaped like 'mini-harps', as shown in Fig. 14. The well-known radio arcs can be categorized in the 'most prominent mini-harp'. It is stressed that the separation between the filaments is regulated around ~5–20 arcsec (Yusef-Zadeh et al. 2022b). The cross-section of the typical harp G+0.30–0.26, as inserted in Fig. 14, shows seven filaments spanning for 70 arcsec with the mean separation of $\Delta L \sim 0.4$ pc.

Since the propagation speed of MHD waves is $v \sim 200 \text{ km s}^{-1}$ (Fig. 3), the separation corresponds to the time interval of $\Delta t = \Delta L/v \sim 2000 \text{ yr}$. So, the harp is mimicked by the remnants of clustered seven SNe exploded within 1.4×10^4 yr in the SF ring ~0.5 Myr ago. The lower panels of Fig. 14 show a result of MHD simulation, where a cluster of 10 rSNRs exploded 8–9 t_{unit} ago at random in a region of radius $0.2L_{\text{unit}}$ on the SF ring. The fronts



Figure 10. MHD wavefronts produced by 20 SNe that exploded at random time intervals in the past $20t_{unit}$ (~1 Myr) in different rings of radius R = 0 (top left) to $R \sim 1.6 L_{unit}$ (bottom right) with a width of $\delta R = 0.1$, as seen from 30° above the Galactic plane. The area sizes are all $3L_{unit} \times 3L_{unit}$. The GCFs are produced by SNe that exploded at radii $R \gtrsim 0.6-0.8L_{unit}$. Note that even waves from SNe at such large radii as $R \gtrsim 1.6L_{unit}$ are focused towards the rotation axis, making vertical filaments, though the efficiency decreases. On the other hand, SNe occurred in the central region at $R \lesssim 0.5$ result in more complicated filaments and loops. Note also that a significant portion of the waves from SNe that exploded inside the SF ring at $R = 1.0L_{unit}$ (sixth panel) is trapped by the molecular ring and stays there for longer time, less contributing to the GCF formation.

reasonably reproduce the observed property of the harps. In the same context, the radio arc may be a relic of a cluster of about 15 SNe that took place in the CMZ some ~ 0.5 Myr ago. The variety of lengths and strength of the harps may be due to the different epochs of explosion and the paths in the ISM with various conditions of wave divergence. The particularly bright filaments and their high density in the radio arc indicate that the responsible SN cluster was more powerful than the other clusters driving the

other mini-harps and filaments. This suggests that the radio arc may be a relic of recent (within ~ 1 Myr) starburst activity in the CMZ.

The lower panels of Fig. 15 show a result when a mini-starburst took place in an SF region on the SF ring, where 10 SNe exploded within a duration of $1t_{unit}$ (0.045 Myr) about $10t_{unit}$ (0.45 Myr) ago. White dots represent the cluster of the SNe with the front shells at $t = 0.05t_{unit}$. The waves are stretched in the *z*-direction, are focused



Figure 11. [Top] 1.28 GHz MeerKAT image from archival data (Heywood et al. 2022) with structures greater than 10 pixels subtracted by BGF (Sofue & Reich 1979). Intensity scale is mJy per 4 -arcsec beam. [Middle] Side view of the MHD wavefronts, where 100 rSNRs exploded at random over the past 0.45 Myr near the SF ring with inclination 85°. Coordinates are scaled to GC distance of 8.2 kpc. [Bottom] Same, but extended features are subtracted for comparison with the BGF image.



 $-1.5L_{\text{unit}}$



x

and converged towards the axis, and form a bunch of vertical and twisted filaments on the sky, mimicking the radio arc's filaments.

3.8 Loop filaments: still a shell

One of the types of GCFs that are not noticed so far is the 'loop filament'. A typical loop is found centred on G+0.0+0.30 as shown in Fig. 16, which draws an Omega of longitude and latitude extents of $\Delta l \times \Delta b = 0.25^{\circ} \times 0.6^{\circ} = 36 \text{ pc} \times 85 \text{ pc}$ with two vertical filaments running through \sim G+0.10+0.2 and G-0.05+0.15. The northern top is capped by a horizontal curved filament at G0.0+0.61. The root of Ω extends towards the negative latitudes. A similar morphology has been recognized as the 'chimneys' that are composed of the northern and southern GCLs (Heywood et al. 2019), drawing a pair of dumbbell-shaped loops.

The loop filament can be understood by a projection of a closed front of the MHD wave due to an SN, or a compact cluster of SNe, exploded inside the SF ring assumed here. In the bottom panel of the figure, we show a calculated filament as a result of MHD front $\sim 8t_{\text{unit}}$ after an SN explosion at $R = 0.5L_{\text{unit}}$ in the Galactic plane. It is stressed that a closed front is obtained only when the SN explosion takes place at $R \sim 0.4 \sim 0.6 L_{unit}$, while SNe exploded inside or outside these radii cannot produce such an Ω shape.

3.9 Right-angle and crossing filaments

Among the many filaments crossing each other, some filaments intersect the other at large angles. The most typical case is seen at G-0.56-0.08, where a bright vertical filament near Sgr C is intersected by a horizontal filament, as shown in Fig. 17. The crossing features can be understood as projections of two filaments at different depths overlapped on the line of sight. The bottom panel of Fig. 17 shows an example of MHD simulation of such overlapping twisted filaments on the line of sight, where three SNe exploded $10t_{unit}$ ago at $R = 0.5L_{\text{unit}}$. Some filaments are crossing each other at right angles.

3.10 'Spaghetti': trapped rSNRs in CMZ

The simulation shows that MHD waves captured by the molecular ring propagate along the ring, and exhibit tangled noodle-like features near the tangential directions as shown in Figs 11 and 13. Such features have been noticed as the 'spaghetti-like' filaments in the MeerKAT 1.3 GHz high-pass images (Yusef-Zadeh et al. 2022a). In Fig. 18, we enlarge the tangential region around $l \sim 359^{\circ}$ from the MeerKAT BGF10 image and the MHD simulation. The simulation well reproduces the tangled filaments as the wavefronts that are trapped in the low-V molecular ring, exhibiting complicated helical structures.

However, the observed filaments near the galactic plane may be a mixture with thermal features like H II regions associated with the SF activity. So, the model here explains only a part of the phenomenon, and a more sophisticated modelling would be necessary for the origin of the spaghetti filaments. A more general study of tangled filaments in the CMZ as well as in the Galactic disc and spiral arms filled with rSNRs would be a subject for the future.

3.11 Fluttering filaments: a wind from GC

We also point out that the observed radio GCFs near the galactic plane at $l \sim -0.5^{\circ}$ to -1.5° in Fig. 18 are systematically fluttering towards the west and run almost horizontally. Interesting, the fluttering phenomenon is lopsided, appearing only in the negative longitude side of GC, but not observed at positive longitudes. Such fluttering is not explained by the present SNR model, and is not seen in the simulation as shown in Fig. 18. A possible mechanism for causing such fluttering would be a radial flow or expansion of gas from inside the SF ring or a nuclear wind from Sgr A that pushes and blows down the vertical filaments. Alternatively, they may be blown segments of filaments by the wind that are being caught by the molecular ring. In either case, the east-west lopsidedness remains also as a question.

4 DISCUSSION

4.1 The limitation of model

We simulated the evolution of rSNR (relic of SNR) as fully evolved expanded SNRs, and mimicked them by heavily deformed MHD disturbances. The disturbance is approximated by the fast-mode compression MHD wave in the magnetized hot plasma around the



Figure 13. [Top] Same as Fig. 11, but for the central region after BGF (2 pixels). [Middle] MHD wave simulation of rSNRs in the past 10 t_{unit} , during which 10 SF regions were born, each associated with 5–15 SNe in $\sim 0.5 t_{unit}$. [Bottom] Same, but a result for a longer duration (past 20 t_{unit}) and time interval for SNe in a wider SF ring. The MeerKATdata are from Heywood et al. (2022).



Figure 14. (a) 'Harp' G+0.30–0.27, and (b) 'flying mini-harps', as revealed in the 1.28 GHz map with extended structures subtracted (produced from the MeerKAT archival data; Heywood et al. 2022). (c) Simulation of the mini-harp by MHD waves originating from a cluster of 10 SNe that exploded 8–9 t_{unit} ago in an SF region as marked by the small front shells at $t = 0.05t_{unit}$. Projection on the (*x*,*z*) plane ($3L_{unit} \times 3L_{unit}$); (d) projection on the (*x*, *y*) projection. (e) Same, but close-up.



Figure 15. (a) Radio arc from MeerKAT 1.28 GHz image (Heywood et al. 2022), where extended structures are subtracted. The prominent harp feature suggests that the structure is due to an SN cluster associated with a recent (within \sim 1 Myr) mini starburst in the CMZ. (b) MHD wave simulation of the radio arc (*x*,*z*) plane, (c) same, but close-up, and (d) projection on the (*x*, *y*) plane.

GC where the low-plasma $\beta = (c_s/V)^2 < 1$ condition is satisfied, and the wave propagates at the Alfvén velocity.

The linear wave theory is a powerful tool for finding such new types of phenomena as the cylindrical focusing of the MHD disturbances from the SF ring and Galactic disc on to the rotation axis of the Galaxy. On the other hand, this method cannot handle the actual magnetic field compression and cosmic ray acceleration required to calculate the radio brightness. Therefore, we have so far limited our discussion to the morphological properties of the GCF. None the less, the simulations suggest many aspects about the GCF to consider, and below we attempt a qualitative and speculative discussion of the potentially non-linear phenomena expected from the model.

4.2 Magnetic fields

In our previous paper, we showed that the wave model eases the magnetic strength necessary for the radio synchrotron emission by a factor of 3 compared to the string model (Sofue 2020a). From detailed analyses based on the assumption of the pressure equilibrium between magnetic and cosmic rays, the mean field strength of GCF

has been shown to range from 0.1 to 0.4 mG (Yusef-Zadeh et al. 2022a). If the present wave sheet model is assumed, the field strength would be decreased to 0.03–0.13 mG and the magnetic pressure by an order of magnitude, which also eases the acceleration problem of cosmic rays.

The Eikonal equations used to trace the MHD waves do not include the magnetic configuration or direction, as the wave propagation depends only on the distribution of the scalar value of Alfvén speed. Even if the ambient fields are oblique and not parallel to the filaments, the magnetic fields in the compressed front will become locally parallel to the wavefront, when they emit the synchrotron radiation. Namely, the linear polarization observed towards the filaments (Tsuboi et al. 1986; Sofue et al. 1987; Lang, Morris & Echevarria 1999b) would represent locally compressed field direction, but does not necessarily represent the background (undisturbed) field direction. In fact, the large and strongly varying Faraday rotation measures observed towards the radio arc and some bright filament (Tsuboi et al. 1986; Sofue et al. 1987; Lang et al. 1999a) indicate that the magnetic fields are significantly inclined and twisted from the z-axis direction.





Figure 16. [Top] Loop filament G+0.0+0.3 at 1.28 GHz map (from MeerKAT archive), drawing a loop as illustrated by the finding chart. [Middle] MHD wavefront projected on the (x,z) plane at $t = 8t_{unit}$ due to an SN exploded at $r = 0.5L_{unit}$ inside CMZ. Frame size is $2L_{unit} \times 2L_{unit}$. The front is largely stretched in the *z*-direction, and looped at both the tops. [Bottom] Same, but on the (x, y) plane.

Figure 17. [Top] Perpendicular filaments crossing at G-0.55-0.1 in the BGF2 image. They are apparently running near Sgr C at G-0.56-0.08. [Middle] (*x*,*z*) projection of simulated MHD wavefronts at $t = 10t_{unit}$ due to three SNe exploded at $r = 0.5L_{unit}$ inside CMZ. The fronts are largely deformed, some are looped, and some are crossing perpendicularly. [Bottom] Same, but on the (*x*, *y*) plane.



Figure 18. [Top] MeerKAT 1.28 GHZ BGF map near G359+0.0, showing the 'spaghetti' (Yusef-Zadeh et al. 2022a) in the tangential region of the warping SF ring (Sofue 2022). Numerous filaments are tangling in the ring and are fluttering towards the west. [Bottom] Tangential projection of MHD wavefronts trapped by the molecular ring, mimicking the spaghetti.

Considering the origin of GC magnetic field (Fig. 2), the accumulated vertical magnetic field in the GC must be strongly twisted by the differential rotation of the disc and halo (Sofue et al. 2010). However, the GCFs are not observed to be twisted so strongly, as shown in Figs 11 and 13. This fact may manifest such situation that the directions of the undisturbed field and the wavefront are not necessarily be aligned, as assumed in the present MHD-wave model. Namely, the observed GCFs may not strictly represent the Galactic magnetic field structure.

Here, we recall that the equations used in the present model do not include the magnetic vectors. This means that the model does not necessarily require a vertical field orientation as illustrated in Fig. 2. That is, if the V distribution is fixed, any field, including twisted ones as expected for magnetic towers (Kato, Mineshige & Shibata 2004), or even spiral and ring fields are equally allowed and the same result is obtained. In other words, the present model cannot give constraint on the magnetic orientation, although a vertical configuration looks natural in the simple view of the MeerKAT image inside the GC.

4.3 Unique morphology

The present SNR model can explain not only the vertical filaments, but also many other filaments and threads having peculiar morphology (Anantharamaiah et al. 1991; Lang et al. 1999a; Paré et al. 2019; Yusef-Zadeh et al. 2021, 2022a), which are attributed to various types of projections of the wavefronts. They include the bent radio arc, horizontal, bifurcated, and crossing threads as due to projection of multiple fronts on the line of sight. The tightly bunched filaments of the radio arc and the 'flying harps' (Fig. 14) are simulated by MHD wavefronts due to a cluster of multiple SNe exploded in an SF region. Threads having kinks, knots, and mouse-like spots can be explained by superposition of obliquely corrugated or twisted fronts (Sofue 2020a). We mention that, if they were real strings, some of the thousands threads would be aligned parallel to the line of sight, which should appear as exceptionally bright spots, but no such object is reported. We stress that the similarity between the GCFs and the thin filaments of Galactic SNRs as typically observed in the Cygnus Loop (Blair, Sankrit & Raymond 2005) may also support the SNR model.

4.4 Energetics and SN rate

The magnetic energy contained in a single thread is estimated to be

$$E \sim (B^2/8\pi)a_1a_2a_3 \sim 4 \times 10^{47} \text{erg},$$
 (20)

where $B \sim 0.1$ mG, $a_1 \sim 0.1$ pc is the filament thickness, $a_2 \sim 70$ pc (~0.5° for the long threads) is the length, and $a_3 \sim 4$ pc is the depth on the line of sight for the thickness a_1 and curvature a_2 . Therefore, only ~0.1 per cent of the released kinetic energy by a single core-collapse SN (10⁵¹ erg) is sufficient to drive one thread.

Using the background-filtered MeerKAT map shown in Figs 11 and 13, we roughly count $\sim 10^2$ filaments inside the supposed magnetic cylinder at $|l| \leq \sim 0.5^{\circ}$ and $|b| \leq \sim 1^{\circ}$. Detailed statistics of the filaments reports an order of greater number, $\sim 10^3$, including fainter filaments (Yusef-Zadeh et al. 2022a).

So, the total energy possessed by the entire filaments is of the order of $\sim 10^{50-51}$ erg, or one SN is sufficient to supply the entire energy. However, considering the dissipation and dilution of the waves, a larger number of SNe, or about ~ 100 SNe in the present model, may have been necessary (and sufficient) to excite the observed filaments.

The current SF rate in the CMZ has been estimated to be $R_{\rm SF} \sim 0.07 \, {\rm M_{\odot}} \, {\rm yr^{-1}}$ (Henshaw et al. 2022). The SN efficiency per born-stellar mass is estimated by $\eta_{\rm SN} = \int_{10 \, {\rm M_{\odot}}}^{\infty} \mathcal{M}(m) {\rm d}m / \int_{0.1 \, {\rm M_{\odot}}}^{10 \, {\rm M_{\odot}}} \mathcal{M}(m) {\rm d}m \sim 1.9 \times 10^{-3}$, which is equal to the high-mass stars' mass density over the mass density of all stars with $\mathcal{M}(m) \propto m^{-2.36}$ being the mass function of the stellar mass *m*. Combining with the SF rate, this SN fraction yields an SN rate of $R_{\rm SN} \sim 1.3 \times 10^{-4} \, {\rm yr^{-1}}$ in the CMZ. This rate agrees with the SN rate $(2 \times 10^{-4} \, {\rm yr^{-1}})$ assumed in the simulation in Fig. 11 within a factor of 2. The agreement between the counting of filaments (rSNRs) and the SF rate would be in favour for the SNR model.

4.5 SN History and the high density of SNR

The thus estimated SN rate is consistent with that assumed in the simulations of the SNR model for GCF. Fig. 19 shows the frequency of SN explosions in the past $10-20t_{unit}$ as assumed in the intermittent SF/SN model shown in the previous subsection (Figs 11 and 13). Fig. 20 panel (a) enlarges one of the SF periods from panel (b) of Fig. 19, showing a cluster of ~10 SNe within ~ 10^4 yr. This diagram may be compared with the cross-section of the mini-harps of GCF. In panel (b), we show a horizontal cross-section of the radio intensity distribution of the mini-harp G+0.30–0.26 as read from Fig. 14. By our interpretation, each peak corresponds to an rSNR, so that the spatial separation of filaments represents the time interval of SN explosions. In this diagram, seven filaments are counted, spanning for 70 arcsec with the mean separation of $\Delta L \sim 0.4$ pc, so that the profile indicates SN explosions at a mean interval of ~ 2×10^3 yr in a period of 1.4×10^4 yr.



Figure 19. (a) Random occurrence of SNe in the past $20t_{unit} \sim 1$ Myr for MHD simulation of the intermittent SN/SF model used in Fig. 11). (b) Same, but for Fig. 13, middle panel. (c) Same, but for Fig. 13, bottom panel.



Figure 20. (a) Enlargement of one of the SN clusters from panel (b) of Fig. 19 with the horizontal axis converted to time. (b) Horizontal cross-section of Harp G+03-0.2 from Fig. 14 with the filament separation converted to time in year for an assumed front velocity of 200 km s⁻¹.

According to the present model, the spatial density of rSNRs in the central 100 pc of the GC is as high as $n_{\rm SNR} \sim 10^2 (\pi (100 \, {\rm pc})^2 \times 100 \, {\rm pc})^{-1} \sim 4 \times 10^4 \, {\rm kpc}^{-3}$. This density may be compared with the density of SNRs in the Galactic disc of $\sim 300 - 1000 (\pi (10 \, {\rm kpc})^2 \times 0.1 \, {\rm kpc})^{-3} \sim 10{\rm -}30 \, {\rm kpc}^{-3}$ (Anderson et al. 2017; Green 2019).

The high (r)SNR density in the GC than that in the disc would be due to several reasons as follows:

(i) The intrinsic SN rate per unit volume in the GC is higher than that in the disc.

(ii) The GC SNRs are accumulated towards the centre by the focusing effect of the wave propagation in the magnetized cylinder filled with the plasma. This effect acts to keep the old SNRs in the restricted area in the GC from diluting away.

(iii) The disc SNRs have been searched for by assuming a spherical shape. In other words, old SNRs that lost their spherical shape are difficult to discover due to both the irregular shape and faintness.

(iv) Mismatch of the number of SNRs and the SF rate in the Galactic disc (Anderson et al. 2017) would be due to such reasons.

(v) Therefore, the GC is a special region for the SNR research, because most of the SNRs (rSNR) younger than ~ 0.5 Myr are visible in this restricted area. This makes a contrast to the current SNR research in the Galactic disc, where the majority is not found yet or not visible.

(vi) GC is also special, because the (r)SNRs are closely associated with the SF sites and molecular clouds in the small volume of $r \sim 100$ pc area. This also makes contrast to the rare or almost no spatial correlation of the catalogued SNRs to their parent SF regions in the Galactic disc.

4.6 SNR-SNR collision

The GCFs as rSNRs through their dissipation will act as the heating source of the hot plasma with thermal energy of the order of $\sim 10^{51-52}$ (Nakashima et al. 2019; Ponti et al. 2019). The present model offers an efficient energy supply from the SNe exploded in the SF ring not only due to the focusing of the waves towards the centre, but also by frequent SNR-SNR collisions.

As discussed in Section 2.4, the dissipation length is of the order of several tens to ~ 100 pc in the magnetized X-ray hot plasma. So, the waves are diluted inside the magnetic cylinder, and heat the hot plasma filling the GCL (Sofue & Handa 1984). On the other hand, the damping distance is much longer in the molecular ring with higher density. Therefore, the waves trapped in the SF ring survive for much longer life and propagate along the ring, drawing the complicated patterns as displayed in the simulations shown in Figs 11, 13, and 18.

The high density of rSNRs inside the magnetic cylinder causes frequent collision of the wave fronts. The collision frequency per one rSNR is estimated to be on the order of $f_{col} = 1/t_{col} \sim 2 \times 10^{-5} y^{-1}$ for $N \sim 10^2$ SNRs (sheets) moving at $V \sim 500$ kms with a mean cross section $\sigma_{\text{SNR}} \sim 50 \text{pc} \times 50 \text{pc} \sim 2.5 \times 10^3 \text{pc}^2$, which yields a mean free path $l_{col} \sim 1/(n_{\text{SNR}}\sigma) \sim 13 \text{pc}$ and $t_{col} = l_{col}/V \sim 2.6 \times 10^4$ y. So, the total SNR-SNR collision (SSC) frequency in the GC is on the order of $f_{\text{total}} = N f_{col} \sim 4 \times 10^{-3} \text{y}^{-1}$. The frequency is highest near the rotation axis due to the focusing effects from different and even from counter directions. The SSC is therefore quite frequent in the particular circumstance of GC.

In so far as the waves are linear with small amplitude, they penetrate through each other, and are indeed observed as the crossing filaments. However, when they are focused around the magneticcylinder axis, the fronts will be amplified and become non-linear



Figure 21. Number of GCFs as a function of spectral index α given by Yusef-Zadeh et al. (2022a) compared with that for Galactic SNRs (histogram and approximate fit by Gaussian profile) as constructed from the SNR catalogue by Green (2019). Plotted values are $dN/d\alpha$ per $\delta \alpha = 0.1$.

shock waves. The collision of the shock fronts will cause more effective heating of the plasma as well as the acceleration of cosmic rays. The acceleration takes place not only by the direct collision, but also by the Mach stem, wiping a wider area with the amplified strength (Hartigan et al. 2016; Vieu, Gabici & Tatischeff 2020).

4.7 Radio spectrum

In Fig. 21, we reproduce the distribution diagrams of the radio spectral index α ($\Sigma \propto \nu^{\alpha}$ with Σ the radio brightness and ν the frequency) of GCFs obtained by the large-scale statistical analysis of the MeerKAT data (Yusef-Zadeh et al. 2022a). The GCFs with length >66 arcsec have indices of $\alpha = -0.62 \pm 0.5$ and long GCFs with >132 arcsec have steeper index of -0.82 ± 0.4 . We compare them with the distribution of spectra taken from the catalogue of Galactic SNRs (Green 2019), which shows $\alpha = -0.5 \pm 0.2$. Therefore, the spectral indices of GCFs and SNRs coincide with each other within their dispersion, and are consistent with the idea that GCFs are rSNRs. It is also noticeable that the mean value of α decreases from SNR to GCF and from GCF to long GCF. This is reasonable in view that the longer the filament or the larger the SNR, the older the filament and the steeper the cosmic ray electron spectrum due to aging. In this sense, the GCFs are similar to such extended SNRs like Vela X, Y, Z having $\alpha = -0.4$ to -0.8 (Alvarez et al. 2001) and old SNR S147 with $\alpha = -0.3$ to -1.3 (Sofue, Furst & Hirth 1980; Fuerst & Reich 1986; Xiao et al. 2008).

Another important aspect in Fig. 21 is the wider dispersion of α for the GCF compared to that of the SNR. This is understandable for two reasons. One reason is that, as mentioned earlier, GCF is much older. Another is that the count of old SNRs is missing due to the difficulty of detection at a larger diameter (Green 1984). Nevertheless, the question remains why the GCF can have both such steep and mild tails that reach $\alpha \sim -2$ and +0.5. This requires extremely sharp energy spectrum of cosmic rays reaching $\beta_{CR} \sim -4$ as well as very flat spectrum reaching to \sim -1.5. This problem would be a

 Table 1. Approximate parameters of a GCF as an SNR compared with the SNR S147.

Object	GCF ¹	S147 ^{2, 3, 4}
Shape	Filaments	Shell
$\Sigma_{1 \text{GHz}}^{a}$	$3.9 \times 10^{-22} \text{ b}$	$4.1 \times 10^{-22} \text{ c}$
Spectral index	-0.6 to -0.8	-0.3 to -1
θ (ang. dia. $^{\circ}$)	-	2.5×2.8
D (dia., pc)	103	101 (5)
Distance (kpc)	(8.2)	2.2
Age (Myr)	0.1-0.5 ^d	$0.4 \ (\sim \frac{2}{3} \frac{D}{2} / V_{expa})$
$V_{\rm expa} ({\rm km} {\rm s}^{-1})$	100-1000 ^d	80
B (mG)	0.1	0.02

Notes. (1) Yusef-Zadeh et al. (2022a); (2) Xiao et al. (2008); (3) Fuerst & Reich. (1986); (4) Sofue et al. (1980); (5) Σ –*D* relation (Case & Batthacharya 1998).

 $a(w m^{-2} Hz^{-1} str^{-1}).$

 $^bSide-on\ \Sigma_{1\,GHz}$ for $\Sigma_{1.3\,GHz}=0.1\ mJy\,4\ arcsec\ beam^{-1}$ and radius-to-width ratio =100.

°Total flux 69 Jy over $2.5^{\circ} \times 2.8^{\circ}$ dia. ellipse.

^dAlfvén velocity.

challenging subject for the acceleration mechanism of cosmic rays in the GC.

To summarize, the steeper spectra of GCFs (rSNR) would indicate that they are older than galactic SNRs (10^2-10^4 yr) . This agrees with the result that the simulated GCFs focused around the rotation axis are more aged than $\sim 10^5$ yr. In a similar context, but in terms of the distance from the explosion centre instead of age, the observed steepening of α of GCFs with the increasing latitudes (Yusef-Zadeh et al. 2022a) may be explained by the cooling (instead of aging) effect of the filaments. Namely, the more distant is the filament from the excitation centre (SN) in the CMZ, the steeper the spectrum.

4.8 Surface brightness-diameter relation

We examine whether the radio brightness of the GCF is consistent with that expected for SNRs using the Σ -D (surface brightnessdiameter) relation for SNRs. If we take the brightness of typical GCFs to be $\Sigma \sim 0.1 \text{ mJy beam}^{-1}$ (Yusef-Zadeh et al. 2022a), the expected mean brightness over a suspected area of its side projection is estimated as $\Sigma_{1 \text{ GHz}} = \Sigma (1 \text{ GHz}/1.3 \text{ GHz})^{-0.6} \times (w_{\text{fila}}/r_{\text{shell}})^{1/2} \sim$ 4×10^{-22} w m⁻² Hz⁻¹ str⁻¹ for a spectral index of -0.6. Here, $w_{\rm fila}$ is the tangential width of the filament and $r_{\rm shell} = 1/2D$ is the radius of supposed shell, and we assume here that $r_{\rm fila}/r_{\rm shell} \sim 0.01$. According to the $\Sigma_{1 \text{ GHz}}$ -D relation (Case & Bhattacharya 1998), this brightness yields a linear diameter of $D \sim 103$ pc. Note, however, that this estimation may include uncertainty by an order of magnitude because of the uncertainty of the assumed width-to-depth ratio and also due to the fact that each filament is a small portion of the largely deformed rSNR. So, we can only state that the radio brightness of GCFs is not inconsistent with the Σ -D relation. For comparison, we estimate the same for the old shell-type SNR S147. This SNR is observed to have a total flux of $S_{1\,{
m GHz}} \sim 69$ Jy over a round area of diameters of $2.5^{\circ} \times 3^{\circ}$ (Xiao et al. 2008). This leads to the surface brightness of $\Sigma 1 \text{ GHz} = 4.1^{-22} \text{ w m}^{-2} \text{ Hz}^{-1} \text{ str}^{-1}$ (Xiao et al. 2008), and the diameter is estimated to be $D \sim 101$ pc and the distance of 2.2 kpc from the Σ -D relation. So, the GCF in view of the SNR model is similar to the old shell-type SNR S147 (Sofue et al. 1980; Alvarez et al. 2001). We compare the parameters derived for the GCF in the regime of SNR with those observed for S147 in Table 1.

4.9 AGN origin versus SNR origin

In our previous paper (Sofue 2020a), we showed that the GCF can be produced as the result of puffing AGN activity at the nucleus or by SNe near Sgr A, where we assumed a similar, but more off-centre oblique cylinder of magnetic field. In the present paper, we showed that the observed brightness of individual GCF as averaged over the supposed wave area is consistent with the brightness of old SNRs satisfying the Σ –*D* relation. This means that the source energy of each filament is regulated on the order of that of one SN, ~10⁵¹ erg, supporting the SNR origin scenario. On the other hand, the AGN activity hypothesis does not necessarily require such regulation of the released energy.

As to the location of the SN explosions, either in Sgr A or in CMZ, the latter seems more natural for the following reasons, although we cannot exclude the possibility that some SNe exploded in/near Sgr A are contaminated. First, the number of the filaments distributing over the wide area (Yusef-Zadeh et al. 2022b) is consistent with the present SNR model at the SN rate as expected for the SF rate in the CMZ (Henshaw et al. 2022). Secondly, the surface brightness averaged over the area covered by the supposed line-of-sight depth is consistent with that for an SNR from the Σ -*D* relation. Thirdly, the filament's intensity is regulated around ~mJy beam⁻¹ within a factor of 10 (Yusef-Zadeh et al. 2022a), consistent with the rSNR scenario, but such regulated intensity would be difficult to explain by AGN events.

4.10 Relation to GC bubbles

According to the SNR model, the GCFs are objects with lifetimes less than ~ 0.5 Myr and total energy of the order of $\sim 10^{53}$ erg (~ 100 SNe) during the ordinary phase of SF in the CMZ (Henshaw et al. 2022). The outflow phenomena that produced GCL (Sofue & Handa 1984; Heywood et al. 2019) and X-ray hot plasma (Nakashima et al. 2019; Ponti et al. 2019) may have occurred prior to or in parallel to the current SF activity.

On the other hand, the GC experienced more energetic explosion and outflow \sim 5–20 Myr ago with the released energy of \sim 10⁵⁵ erg (Sofue 1977, 2000; Bland-Hawthorn & Cohen 2003; Sofue et al. 2016; Kataoka et al. 2018), as evidenced by the detection of the giant bubbles of radii a few to \sim 10 kpc in the radio (Haslam et al. 1982), X-ray (Snowden et al. 1997; Predehl et al. 2020), and gamma-ray emissions (Su, Slatyer & Finkbeiner 2010). However, such 'ancient' events at $t \gtrsim$ 5 Myr should have no longer direct effect on the 'recent' SF activity at $t \lesssim$ 0.5 Myr in the CMZ, because the regulation timescale there is comparable to the Galactic rotation period of a couple of Myr (Sormani & Li 2020).

In fact, the GCFs are coherently aligned to each other and are not strongly disturbed. The globally regular morphology would manifest a rather undisturbed and quiet ISM condition in the recent (≤ 1 Myr) CMZ and its surroundings. The milder outflows such as the GCL and hot plasma of ~100 pc scale and ~10⁵³ erg can be coexisting inside the ring of the CMZ and SF ring in their basic states.

4.11 Proper motion of the filaments

Finally, we comment on the proper motion of the filaments. In the present model, the wavefronts are moving at Alfvén velocity of $\sim 100-1000$ km s⁻¹. This would cause proper motion between the overlapping filaments of $\sim 3-30$ mas yr⁻¹. Mutual velocities between the overlapped filaments in the near and far sides of the GC would be

even higher. If they are obliquely crossing, the crossing points will move much faster along the filaments.

Analysis of the mutual positional displacements of the filaments with respect to the neighbouring point sources (Yusef-Zadeh et al. 2022c) at different epochs would be an ideal method to detect the proper motion by regarding the point sources as the reference, which are supposed to be at cosmological distances.

5 SUMMARY

We have simulated the evolution of rSNRs in the Galactic Centre in the presence of a vertical magnetic cylinder filled with hot plasma by tracing the propagation of fast-mode MHD waves. The waves are shown to be focused around the Galactic rotation axis, and form cylindrical sheets whose tangential projection on the sky constitutes the vertical filaments. The GCFs are therefore explained as old relic of SNRs that exploded in the SF ring in the past ~10⁵ yr at an SN rate of approximately several × 10⁻⁴ yr⁻¹. The SNR model can explain not only the morphology, but also the steep radio spectrum, the smoothed brightness over the distribution area that satisfies the surface brightness–diameter relation of SNRs, and the heating energy source of the hot plasma in the GC.

We thus conclude that the GCFs are old relic of SNRs similar to the well-known shell-type SNRs such as the Cygnus Loop, except that they are significantly deformed in the particular circumstance of the GC. According to the SNR model, we need not to assume any unknown, uncertain, or sophisticated mechanism such as ejection, magnetic inflation, and/or instabilities to create the magnetic threads. The only difficulty with this model may be that we have to abandon the common sense that the shell SNRs are spherical.

The rSNR hypothesis would thus open a new era of an integrated study of the ISM composed of the molecular clouds, SF regions, and SNRs (SNe) that are all visible in the same field of view at the precise distance in the GC, well observed at the same time in radio (from molecular lines to continuum), infrared (lines and continuum), X-rays, and gamma-ray emissions. We therefore emphasize from a new point of view that the GC is a particular place in the Milky Way for the study of the ordinary ISM and its evolution with SF feedback via the rSNRs.

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DATA AVAILABILITY

The MeerKAT radio data were downloaded from https://archive-gw -1.kat.ac.za/public/repository/10.48479/fyst-hj47/index.html.

REFERENCES

Alvarez H., Aparici J., May J., Reich P., 2001, A&A, 372, 636 Anantharamaiah K. R. et al., 1991, MNRAS, 249, 262 Anderson L. D. et al., 2017, A&A, 605, A58 Barkov M. V., Lyutikov M., 2019, MNRAS, 489, L28 Blair W. P., Sankrit R., Raymond J. C., 2005, AJ, 129, 2268 Bland-Hawthorn J., Cohen M., 2003, ApJ, 582, 246 Boldyrev S., Yusef-Zadeh F., 2006, ApJ, 637, L101

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- Case G. L., Bhattacharya D., 1998, ApJ, 504, 761
- Dahlburg R. B. et al., 2002, ApJ, 568, 220
- Fuerst E., Reich W., 1986, A&A, 163, 185
- Green D. A., 1984, MNRAS, 209, 449
- Green D. A., 2019, J. Astrophys. Astron., 40, 36
- Hartigan P. et al., 2016, ApJ, 823, 148
- Hasegawa T., Sato F., Whiteoak J. B., Miyawaki R., 1994, ApJ, 429, L77
- Haslam C. G. T., Salter C. J., Stoffel H., Wilson W. E., 1982, A&AS, 47, 1
- Henshaw J. D., Barnes A. T., Battersby C., Ginsburg A., Sormani M. C., Walker D. L., 2022, preprint (arXiv:2203.11223)
- Heywood I. et al., 2019, Nature, 573, 235
- Heywood I. et al., 2022, ApJ, 925, 165
- Kataoka J., Sofue Y., Inoue Y., Akita M., Nakashima S., Totani T., 2018, Galaxies, 6, 27
- Kato Y., Mineshige S., Shibata K., 2004, ApJ, 605, 307
- Kumar N., Kumar P., Singh S., 2006, A&A, 453, 1067
- Lang C. C., Anantharamaiah K. R., Kassim N. E., Lazio T. J. W., 1999a, ApJ, 521, L41
- Lang C. C., Morris M., Echevarria L., 1999b, ApJ, 526, 727
- LaRosa T. N., Nord M. E., Lazio T. J. W., Kassim N. E., 2004, ApJ, 607, 302
- Morris M., Yusef-Zadeh F., 1985, AJ, 90, 2511
- Nakashima S., Koyama K., Wang Q. D., Enokiya R., 2019, ApJ, 875, 32
- Paré D. M., Lang C. C., Morris M. R., Moore H., Mao S. A., 2019, ApJ, 884, 170
- Ponti G. et al., 2019, Nature, 567, 347
- Ponti G., Morris M. R., Churazov E., Heywood I., Fender R. P., 2021, A&A, 646, A66
- Porter L. J., Klimchuk J. A., Sturrock P. A., 1994, ApJ, 435, 482
- Predehl P. et al., 2020, Nature, 588, 227
- Snowden S. L. et al., 1997, ApJ, 485, 125
- Sofue Y., 1977, A&A, 60, 327
- Sofue Y., 1978, A&A, 67, 409
- Sofue Y., 1980, PASJ, 32, 79
- Sofue Y., 1995, PASJ, 47, 527

- Sofue Y., 2000, ApJ, 540, 224
- Sofue Y., 2013, PASJ, 65, 118
- Sofue Y., 2020a, PASJ, 72, L4
- Sofue Y., 2020b, MNRAS, 498, 1335
- Sofue Y., 2022, MNRAS, 516, 907
- Sofue Y., Furst E., Hirth W., 1980, PASJ, 32, 1
- Sofue Y., Habe A., Kataoka J., Totani T., Inoue Y., Nakashima S., Matsui H., Akita M., 2016, MNRAS, 459, 108
- Sofue Y., Handa T., 1984, Nature, 310, 568
- Sofue Y., Machida M., Kudoh T., 2010, PASJ, 62, 1191
- Sofue Y., Reich W., 1979, A&AS, 38, 251
- Sofue Y., Reich W., Inoue M., Seiradakis J. H., 1987, PASJ, 39, 95
- Sormani M. C., Li Z., 2020, MNRAS, 494, 6030
- Su M., Slatyer T. R., Finkbeiner D. P., 2010, ApJ, 724, 1044
- Tsuboi M., Inoue M., Handa T., Tabara H., Kato T., Sofue Y., Kaifu N., 1986, AJ, 92, 818
- Uchida Y., 1970, PASJ, 22, 341
- Uchida Y., 1974, Sol. Phys., 39, 431
- Vieu T., Gabici S., Tatischeff V., 2020, MNRAS, 494, 3166
- Xiao L., Fürst E., Reich W., Han J. L., 2008, A&A, 482, 783
- Yusef-Zadeh F. et al., 2021, MNRAS, 500, 3142
- Yusef-Zadeh F. et al., 2022a, ApJ, 925, L18
- Yusef-Zadeh F., Arendt R. G., Wardle M., Boldyrev S., Heywood I., Cotton W., Camilo F., 2022b, MNRAS, 515, 3059
- Yusef-Zadeh F., Arendt R. G., Wardle M., Heywood I., Cotton W., 2022c, MNRAS, 517, 294
- Yusef-Zadeh F., Morris M., Chance D., 1984, Nature, 310, 557
- Yusef-Zadeh F., Wardle M., 2019, MNRAS, 490, L1
- Zhang M., Li Z., Morris M. R., 2021, ApJ, 913, 68

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