

## The symmetry problem of the *Fermi* and eROSITA bubbles: A proof-of-concept study

PO-HSUN TSENG <sup>1</sup>, H.-Y. KAREN YANG <sup>2, 3, 4</sup>, HSI-YU SCHIVE <sup>1, 5, 6, 4</sup>, CHUN-YEN CHEN,<sup>7</sup> AND TZIHONG CHIUH <sup>1, 5, 6</sup>

<sup>1</sup>*Institute of Astrophysics, National Taiwan University, Taipei 10617, Taiwan*

<sup>2</sup>*Institute of Astronomy, National Tsing Hua University, Hsinchu 30013, Taiwan*

<sup>3</sup>*Center for Informatics and Computation in Astronomy, National Tsing Hua University, Hsinchu 30013, Taiwan*

<sup>4</sup>*Physics Division, National Center for Theoretical Sciences, Taipei 10617, Taiwan*

<sup>5</sup>*Department of Physics, National Taiwan University, Taipei 10617, Taiwan*

<sup>6</sup>*Center for Theoretical Physics, National Taiwan University, Taipei 10617, Taiwan*

<sup>7</sup>*Institute of physics, National Taiwan University, Taipei 10617, Taiwan*

### ABSTRACT

*Keywords:* keywords

#### 1. INTRODUCTION

The detection of the *Fermi* bubbles (Su & Finkbeiner 2012; Ackermann et al. 2014; Narayanan & Slatyer 2017), two large bubbles symmetrically extending about 50 degrees above and below the Galactic plane, is one of the great discoveries made with *Fermi* Large Area Telescope (Atwood et al. 2009).

The gamma-ray emission of the *Fermi* bubbles is observed in the energy range of  $1 \lesssim E_\gamma \lesssim 100$  GeV and has an almost spatially uniform hard spectrum, sharp edges and an approximately flat brightness distribution.

Over the course of a decade, the first all-sky X-ray survey with high-spatial resolution (Predehl et al. 2021) from eROSITA (Predehl et al. 2020) also reveals a giant hourglass-shaped structure (eROSITA bubbles hereafter) at the GC, but extending about twice as large as the *Fermi* bubbles. The large-scale X-ray structure shows that the intrinsic size of the bubbles is 14 kiloparsecs across (Predehl et al. 2021), and displays morphological symmetry about the Galactic plane as the *Fermi* bubbles.

Their symmetry about the GC suggests that they originate from powerful energy injections from the GC, possibly related to nuclear star formation (Crocker & Aharonian 2011; Carretti et al. 2013) or past active galactic nucleus (AGN) activity (Guo & Mathews 2012; Yang & Ruszkowski 2017).

Early attempts (Sarkar et al. 2015; Yang & Ruszkowski 2017; Zhang & Guo 2020) to model the symmetric *Fermi* and eROSITA bubbles (collectively we call the Galactic bubbles) assumed that the jet is vertical to the Galactic plane. However, observation (Gallimore et al. 2006) has proposed that there is a lack of preferred orientation of jets with respect to a disc normal. In contrast, a number of galaxies in which the jets are tilted to the disc normal (e.g. NGC 3079, Cecil et al. 2001; NGC 1052, Dopita et al. 2015), including galaxies in which the jets lie in the plane of the disc (e.g. IC 5063, Morganti et al. 2015).

To this end, this work introduces a dense thin disc of interstellar medium around a jet source to deflects and decelerates the inclined jets, in an attempt to remedy the symmetry problem of the Galactic bubbles.

The main purpose of this study is to use three-dimensional special relativistic hydrodynamics simulations involving CR jet injections from the central SMBH in the Galaxy to investigate whether the *inclined* jet scenario is able to produce the *symmetric* Galactic bubbles that are consistent with the observed features, including the shape, the surface brightness (for eROSITA bubbles), and the spectra (for *Fermi* bubbles).

This paper is organized as follows. In Section 2, we describe the numerical techniques and initial conditions employed. We directly compare the morphology of the Galactic bubbles with observation, and also show the simulated gamma-ray and microwave spectra compared with observations in Section 3. Finally, we summarize our findings in Section 4.

## 2. METHODOLOGY

We used the GPU-accelerated special relativistic hydrodynamics AMR code (GAMER-SR) developed at the National Taiwan University (Schive et al. 2010, 2018; Tseng et al. 2021) to carry out the simulations of the Galactic bubbles by CR and relativistic fluid injections from the GC.

The CRs are advected with the thermal gas, and in return the velocities of gas can react to the gradients of the CR pressure via the source term containing spatial divergence of fluid velocities.

Although the high-energy CRe (10 – 100 GeV) plays a crucial role in reproducing the  $\gamma$ -ray map within the range of 1 – 100 GeV, we assume the pressure of CRe is much less than that of gas throughout the simulation so that we , and the *Fermi* bubbles can be outlined against the eROSITA bubbles.

As stressed by Yang et al. (2012), CR diffusion has an insignificant effect on the overall morphology of the *Fermi* bubbles, but only sharpens the edges of the simulated bubbles by the interplay between anisotropic CR diffusion and magnetic fields with suppressed perpendicular diffusion across the bubble surface. Moreover, the bubbles should be weak due to adiabatic expansion, and thus the magnetic fields has a little effect on the overall dynamics. For these two reasons, we have ignored the CR diffusion and the magnetic field throughout the simulation.

We do not simulate the spectral evolution of the CR, and we neglected the cooling and heating processes of CRs, such as energy losses due to synchrotron and inverse Compton emission, and reacceleration in shocks.

In this approach, we treat CRs as a single species without distinction between electrons and protons, that cannot react to the gas via the application of CRe pressure, and solve directly for the evolution of CR energy density  $e_{\text{cr}}$  as a function of  $\mathbf{r}$  and  $t$ .

Since the relativistic fluid ejected by the jet source is quickly stalled off and slowed down by a dense ISM disc in a short time, and the relativistic fluid accounts for a little minority of total mass inside the simulation box, we still use the Newtonian gravity to attack this problem.

The governing equations solving the special relativistic ideal fluid including CR advection, and dynamical coupling between the thermal gas and CRs without CR diffusion can be written a succinct form as

$$\partial_t D + \partial_j (D U^j / \gamma) = 0, \quad (1a)$$

$$\partial_t M^i + \partial_j (M^i U^j / \gamma + p_{\text{gas}} \delta^{ij}) = -\rho \partial_i \Phi, \quad (1b)$$

$$\partial_t \tilde{E} + \partial_j [(\tilde{E} + p_{\text{gas}}) U^j / \gamma] = 0, \quad (1c)$$

$$\partial_t (\gamma e_{\text{cr}}) + \partial_j (e_{\text{cr}} U^j) = -p_{\text{cr}} \partial_j U^j, \quad (1d)$$

where the five conserved quantities of gas  $D$ ,  $M^i$ , and  $\tilde{E}$  are the mass density, the momentum densities, and the reduced energy density, respectively. The reduced energy density is defined by subtracting the rest mass energy density of gas from the total energy density of gas.  $\gamma$  and  $U^j$  are the temporal and spatial component of four-velocity of gas.  $\rho$  is the gas density in the local rest frame defined by  $D/\gamma$ .  $p_{\text{gas}}$  is the gas pressure.  $p_{\text{cr}}$  and  $e_{\text{cr}}$  are the CR pressure and CR energy density measured in the local rest frame.  $\Phi$  is the gravitation potential.  $c$  is the speed of light, and  $\delta^{ij}$  is the Kronecker delta notation. Throughout this paper, Latin indices run from 1 to 3, except when stated otherwise.

The set of Equation (1) is closed by using the Taub-Mathews equation of state (Taub 1948; Mathews 1971) that approximates the exact EoS (Synge 1957) for ultra-relativistically hot gases coexisting with non-relativistically cold gases.

GAMER-SR adopts a new algorithm (Tseng et al. 2021) to convert between primitive ( $\rho$ ,  $U^j$ ,  $p$ ) and conserved variables ( $D$ ,  $M^j$ ,  $\tilde{E}$ ), significantly reducing numerical error caused by catastrophic cancellations that commonly occur within the regions with high Mach number flows. e.g., jet-ISM interaction zones.

GAMER-SR also adaptively and locally reduce the min-mod coefficient (Tseng et al. 2021) within the failed patch group. Doing so provides an elegant way to avoid the use of pressure/density floor, being unnatural but widely used in almost publicly available codes.

### 2.1. The Galactic and Disk Models

As a proof-of-concept study, we approximate conventionally axisymmetric stellar potential of Milky Way by a plane-parallel potential that is symmetric about the mid-plane  $z = 0$  in a simulation box size of  $14 \times 14 \times 28$  kpc, slightly larger than the size of eROISTA bubbles.

The plane-parallel potential is fixed throughout our simulations and given by

$$\Phi_{\text{total}}(z) = \Phi_{\text{bulge}}(z) + \Phi_{\text{halo}}(z), \quad (2)$$

where

$$\Phi_{\text{bulge}}(z) = 2\sigma_{\text{bulge}}^2 \ln \cosh \left( z \sqrt{\frac{2\pi G \rho_{\text{bulge}}^{\text{peak}}}{\sigma_{\text{bulge}}^2}} \right) \quad (3)$$



**Figure 1.** The density profile of the isothermal disc (red pluses) and atmosphere (blue crosses) along the positive  $z$ -axis. The density distribution is derived from hydrostatic equilibrium, the interface ( $z = 0.1$ ) between the isothermal disc and the atmosphere is pressure balanced.

is the potential of an isothermal slab mainly contributed by stars around the Galactic bulge, and  $\Phi_{\text{halo}}(z) = v_{\text{halo}}^2 \ln(z^2 + d_h^2)$  is a plane-parallel dark logarithmic halo potential.

With the help of the isothermal and hydrostatic equilibrium conditions, and assuming the interfaces between isothermal disc and atmosphere are in thermal pressure equilibrium, we can write the steady-state gaseous density distributions, confined in the total potential, of the disc and the Galactic atmosphere as

$$\rho_{\text{isoDisk}}(z) = \rho_{\text{isoDisk}}^{\text{peak}} \exp \left[ -\frac{\Phi_{\text{total}}(z)}{k_B T_{\text{isoDisk}}/m_p} \right] \quad (4a)$$

, if  $|z| < z_0$

$$\rho_{\text{atmp}}(z) = \rho_{\text{atmp}}^{\text{peak}} \exp \left[ -\frac{\Phi_{\text{total}}(z)}{k_B T_{\text{atmp}}/m_p} \right] \quad (4b)$$

, otherwise,

where  $m_p$  is the proton mass,  $T_{\text{isoDisk}}$  and  $T_{\text{atmp}}$  is the temperature of the isothermal disc and atmosphere,  $\rho_{\text{isoDisk}}^{\text{peak}}$  and  $\rho_{\text{atmp}}^{\text{peak}}$  is the peak mass density of the disc and atmosphere on the mid-plane  $z = 0$ .

We tabulate parameters in the first four categories of Table 1, except for  $\rho_{\text{atmp}}^{\text{peak}}$  that can be derived from the other known parameters and thermal pressure equilibrium condition on the interfaces ( $z = \pm z_0$ ) between the disc and atmosphere.

The density profile of Equation (4) is shown in Figure 1. Beyond the core radius ( $\sim 2$  kpc) the gaseous density decreases rapidly as a power-law.

To quantify the synchrotron radiation as a function of position, it is essential to start the simulation with a more realistic magnetic field distribution. To this end, for our fixed magnetic field we adopt the default exponential model in GALPROP (Strong et al. 2007) which has the following spatial dependence:

$$|\mathbf{B}(R, z)| = B_0 \exp\{-z/z_0\} \exp\{-R/R_0\}, \quad (5)$$

where  $R = \sqrt{x^2 + y^2}$ ,  $B_0$  is the average field strength at the GC and  $z_0$  and  $R_0$  are the characteristic scales in the vertical and radial directions, respectively. We adopt  $z_0 = 2$  kpc and  $R_0 = 10$  kpc, which are best-fitting values in the GALPROP model to reproduce the observed large-scale 408 MHz synchrotron radiation in the Galaxy. We choose  $B_0 = 50 \mu\text{G}$  based on the observed field strength at the GC (Crocker et al. 2010).

## 2.2. The Clumpy Multiphase Interstellar Medium

A crucial component in our work is the clumpy ISM disc initialized by the publicly available pyFC code <sup>1</sup>.

pyFC randomly generates dimensionless 3D scalar field  $f(\mathbf{x})$  that obeys the log-normal probability distribution with mean  $\mu$  and dispersion  $\sigma$ , and follows the power-law Kolmogorov spectrum

$$D(\mathbf{k}) = \int k^2 \hat{f}(\mathbf{k}) \hat{f}^*(\mathbf{k}) d\Omega \propto k^{-\beta}, \quad (6)$$

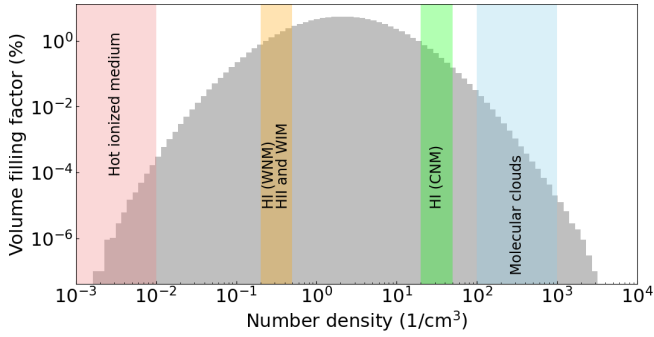
where  $\hat{f}(\mathbf{k})$  is the Fourier transform of  $f(\mathbf{x})$ . The spectrum  $D(\mathbf{k})$  in the Fourier space is characterized by the power-law index  $\beta = 5/3$ , the Nyquist limit  $k_{\text{max}}$ , and the lower cutoff wave number  $k_{\text{min}}$ .  $k_{\text{max}}$  is one-half of the spatial resolution within disc, and  $k_{\text{min}}$  is 375.0, corresponding to the maximum size of an individual clump  $\sim 20$  pc. Lewis & Austin (2002) and Wagner et al. (2012) have outlined a detailed procedure for constructing a clumpy scalar field, and we do not repeat here.

The density of clumpy disc can thus be obtained by taking the scalar products of  $f(\mathbf{x})$  with  $\rho_{\text{isoDisk}}(z)$  over all cells within the disc, i.e.,  $\rho_{\text{ismDisk}}(\mathbf{x}) = f(\mathbf{x}) \rho_{\text{isoDisk}}(z)$ . Also, the thermal pressure equilibrium within the clumpy disc implies that the temperature of disc is  $T_{\text{ismDisk}}(\mathbf{x}) = T_{\text{isoDisk}}(z) \rho_{\text{isoDisk}}(z) / \rho_{\text{ismDisk}}(\mathbf{x})$ .

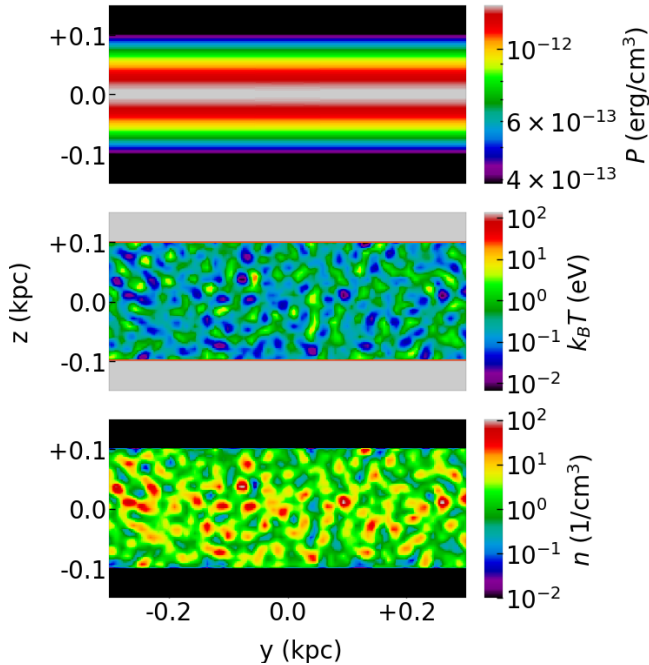
Table 1 summarize the parameters of the clumpy disc and their references.

On the basis of this setup, we cover the AMR base level with  $16 \times 16 \times 32$  root cells, refined progressively on the mid-plane  $z = 0$  based on the gradient of mass density. We also restrict the refinement level at 7 within

<sup>1</sup> <https://pypi.python.org/pypi/pyFC>



**Figure 2.** The volume filling factor as a function of initial number density within the disc without jet source. The vertical bands from left to right depict the allowable number densities (Ferrière 2001) for hot ionized, warm neutral (WNM), warm ionized (WIM), cold neutral mediums (CNM), and molecular clouds.



**Figure 3.** Close-up view of the initial pressure (top), temperature (middle), and number density (bottom) slices in the y-z plane through the center of the disc.

the cold disc so that a molecular cloud can be adequately resolved by approximately 30 cells along their diameter, 20 pc.

Figure 3 shows a close-up view of the pressure, temperature, and number density slices in the y-z plane through the center of the disc.

Figure 2 plots the volume filling factor as a function of initial number density within the disc without jet source.

### 2.3. Inclined jet injection

Motivated by these observations, we simulate the jet with an inclination angle  $45^\circ$  with respect to the

Galactic plane in order to release the caveat that the jet direction must be perpendicular to the Galactic plane, and in particular to investigate the effect of the jet-disc misalignment on the symmetry of bubbles.

A few additional quantities are used to characterize the jets: the density contrast between the thermal gas contained in the jet source and the ambient gas,  $\rho_{\text{jet}}/\rho_{\text{amb}} = 10^{-3}$ , the temperature contrast,  $T_{\text{jet}}/T_{\text{amb}} = 2 \times 10^4$ , the pressure ratio of CR to gas is 0.18, and the flow 4-velocity inside the jet source  $\beta\gamma = 0.6$  along the symmetric axis of cylinder. The jet power is thus  $3.2 \times 10^{42}$  erg/s, resulting in the Eddington ratio 0.008.

Note that as we inject the jets at the center of the clumpy disc, we define the ambient gas density by the peak density of the isothermal disc on the mid-plane  $z = 0$  (i.e.  $\rho_{\text{isoDisk}}^{\text{peak}}$ ), as opposed to the *clumpy* density around the jet source, to avoid ambiguous definition.

The bipolar jets are constantly ejected from a cylindrical source within a jet duration time  $t = 0 - 1.2$  Myr, allowing the total ejected energy  $1.2 \times 10^{56}$  erg is between  $8 \times 10^{55}$  erg and  $1.3 \times 10^{56}$  erg, estimated by Predehl et al. (2020).

The diameter and height of cylindrical source are 4 pc, leading to the source volume  $\sim 50 \text{ pc}^3$  is much smaller than that of an individual clump by a factor of about 83. By intentionally reducing the volume ratio of the jet source to an individual clump, we can mitigate the effect of the randomness of the clumps on the bubbles. Moreover, we resolve the jet source with the highest refinement level 11, bringing the finest spatial resolution up to 0.4 pc.

## 3. RESULTS

### 3.1. Morphology

Figure 4 shows the slices of pressure (top), temperature (middle), number density (bottom) at the end of simulation  $t = 12.39$  Myr. The slices pass through the bipolar jet source injecting along  $z = -y$  direction for a duration  $t = 0 - 1.2$  Myr. Comparison between the clumpy (first column from left) and the smooth disc (second) in a stratified atmosphere shows that the initial density distribution of the dense disc has an insignificant effect on the overall dynamics of bubbles. However, the outermost bubbles arising from the smooth disc in an uniform atmosphere (third) is spherical-shape, suggesting the stratification facilitates the outermost bubbles elongation significantly. Also, the two rightmost columns reveal that the development of the innermost bubbles (dashed box) is always associated with the disc, and without the disc, the outermost bubbles and the turbulent region will be tilted, indicating the dense disc

Parameter	Description	Value	Reference
<b>Static stellar potential</b>			
$\sigma_{\text{bulge}}$	Velocity dispersion of bulge	100 km·s <sup>-1</sup>	(Valenti et al. 2018)
$\rho_{\text{bulge}}^{\text{peak}}$	Peak average density of bulge	$4 \times 10^{-24}$ g·cm <sup>-3</sup>	N/A
<b>Static dark halo potential</b>			
$v_{\text{halo}}$		131.5 km·s <sup>-1</sup>	(Johnston et al. 1995)
$d_{\text{h}}$	Core radius	12 kpc	"
<b>Atmosphere</b>			
$T_{\text{atmp}}$	Temperature of atmosphere	10 <sup>6</sup> K	(Tepper-García et al. 2015)
<b>Isothermal disc</b>			
$z_0$	Scale height of disc	100 pc	(Ferrière 2001)
$T_{\text{isoDisk}}$	Temperature of disc	10 <sup>3</sup> K	"
$\rho_{\text{isoDisk}}^{\text{peak}}$	Peak mass density of disc	$10^{-23}$ g·cm <sup>-3</sup>	"
<b>Clumpy disc</b>			
$\dagger k_{\text{min}}$	Cutoff wave number	375.0	(Ferrière 2001)
$\mu$	Mean of scalar field	1.0	N/A
$\ddagger \sigma$	Dispersion of scalar field	5.0	(Federrath et al. 2010)
$\beta$	Power law index	-5/3	N/A

$\dagger k_{\text{min}} = 375.0$  leads to the size of an individual molecular cloud  $\sim 100$  pc.

$\ddagger$  In numerical simulations of turbulence, Federrath et al. (2010) find  $\sigma \sim 3.6$  and 35 for solenoidal (divergence-free) and compressive (curl-free) driving force, respectively, so that our adopted value of 5 is closer to their solenoidal result.

**Table 1.** Parameters of the disc, atmosphere, and gravitational potential in the simulation.

is crucial for the symmetry of the Galactic bubbles and for the innermost bubbles formation.

### 3.2. X-ray

The X-ray emissivity in an energy range 0.6 – 1.0 keV is computed for each computational volume cell using the MEKAL model (Mewe et al. 1985; Kaastra & Mewe 1993; Liedahl et al. 1995) implemented in the utility XSPEC (Arnaud 1996), assuming solar metallicity. The X-ray intensity map are then generated by projecting the emissivities along lines of sight with resolutions of 0.5 degrees from the solar position at  $(x, y, z) = (8, 0, 0)$  kpc across the sky.

We point out that the projections throughout this paper is ‘perspective’, which has the effect of making distant object appear smaller than the same object in the near distance, in order to facilitate a reliable interpretation of simulated all-sky map, and also that the observed X-ray emission is contributed by all the gas in the Milky Way halo, which likely extends to a radius of  $\sim 250$  kpc (Blitz & Robishaw 2000; Grcevich & Putman 2009), much bigger than our simulation box. Therefore, we first compute the X-ray emissivity from the simulated gas within a radius of 25 kpc away from the GC. Then, beyond 25 kpc the gas is assumed to be isothermal with  $T = 10^6$  K and follows out to a radius of 250 kpc the observed density profile of (Tepper-García et al. 2015).

Figure 5(a) shows the simulated photon count rate (top) in the 0.6–1.0 keV range at the present time, overlaid with the red arrow representing the direction of the bipolar jet, compared with the observed count rate (bottom) in the same energy bin.

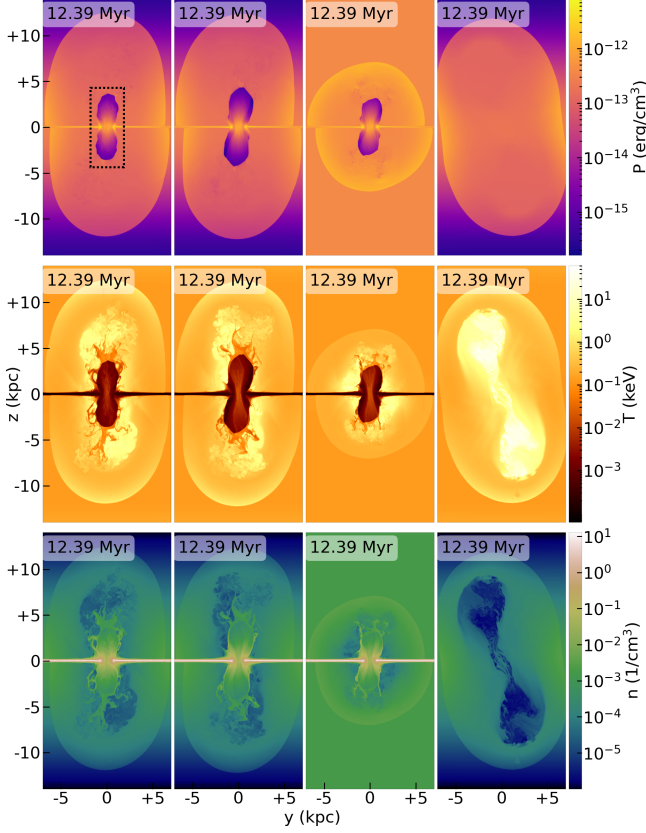
### 3.3. Gamma-ray and microwave spectra: constraint on the CRe spectral index

In this section, we give the constraint on the CRe spectral index by comparing the simulated gamma-ray and microwave spectra with the observed spectra of the Fermi bubbles Ackermann et al. (2014) and the microwave haze (Dobler & Finkbeiner 2008), respectively.

The simulated gamma-ray and microwave spectra is based on the IC scattering and synchrotron from CRe, in which the CRe spectrum follows a power-law distribution ranging from  $m_e c^2$  (0.5 MeV) to  $1.1 \times 10^6 m_e c^2$  (562.1 GeV), where  $m_e c^2$  is the rest mass energy of an electron.

The IC emissivity of the upscattered photons at the energy  $\epsilon_1$  is computed for each computational cell in our simulations using the Klein-Nishina IC cross-section (Jones 1968; Blumenthal & Gould 1970) to handle the scattering between ultra-relativistic CRe and ISRF:





**Figure 4.** The slices of pressure (top), temperature (middle), and number density (bottom) at the end of simulation  $t = 12.39$  Myr. The slices pass through a bipolar jet source injecting along  $z = -y$  direction for a duration  $t = 0$ – $1.2$  Myr. Comparison between the clumpy (first column from left) and the smooth disc (second) in a stratified atmosphere shows that the initial density distribution of the dense disc has an insignificant effect on the overall dynamics of bubbles. However, the outermost bubbles arising from the smooth disc in an uniform atmosphere (third) is spherical-shape, suggesting the stratification facilitates the outermost bubbles elongation significantly. Also, the two rightmost columns reveal that the development of the innermost bubbles (dashed box) is always associated with the disc, and without the disc, the outermost bubbles and the turbulent region will be tilted, indicating the dense disc is crucial for the symmetry of the Galactic bubbles and for the innermost bubbles formation.

$$\frac{dE}{dt d\epsilon_1 dV} = \frac{3}{4} \sigma_T c \mathbb{C} \epsilon_1 \int_{\epsilon_{\min}}^{\epsilon_{\max}} \frac{n(\epsilon)}{\epsilon} d\epsilon \int_{\gamma_{\min}(\epsilon)}^{\gamma_{\max}} \gamma^{-(p+2)} f(q, \Gamma) d\gamma, \quad (7a)$$

$$f(q, \Gamma) = 2q \ln q + (1 + 2q)(1 - q) + 0.5(1 - q) \frac{(\Gamma q)^2}{1 + \Gamma q}, \quad (7b)$$

$$q = \frac{\epsilon_1 / \gamma m_e c^2}{\Gamma (1 - \epsilon_1 / \gamma m_e c^2)}, \quad (7c)$$

$$\Gamma = \frac{4\epsilon\gamma}{m_e c^2}, \quad (7d)$$

$$\gamma_{\min}(\epsilon) = 0.5 \left( \frac{\epsilon_1}{m_e c^2} + \sqrt{\left( \frac{\epsilon_1}{m_e c^2} \right)^2 + \frac{\epsilon_1}{\epsilon}} \right), \quad (7e)$$

where  $\sigma_T$  is the Thomson cross section,  $c$  speed of light,  $n(\epsilon)$  the energy distribution of the photon number density in ISRF given by Porter et al. (2017),  $\gamma$  the Lorentz factor of CRe,  $\mathbb{C}$  and  $p$  are the normalization constant and spectral index of CRe power-law spectrum.  $\gamma_{\min}(\epsilon)$  is the minimum Lorentz factor of CRe that allows incident photons to scatter from energy  $\epsilon$  to  $\epsilon_1$ .  $\gamma_{\max}$  is the maximum CRe Lorentz factor in the spectrum.

We perform the double integration in Equation (7) on each cell over the range of CRe Lorentz factor, and the range of incident photon energy between  $\epsilon_{\min} = 1.13 \times 10^{-4}$  eV (cosmic microwave background radiation) and  $\epsilon_{\max} = 13.59$  eV (optical starlight) to obtain the simulated IC emissivities.

The synchrotron emissivity with an isotropic electron pitch angle distribution is given by Blumenthal & Gould (1970):

$$\frac{dE}{dt dv dV} = \frac{4\pi \mathbb{C} e^3 B^{0.5(p+1)}}{m_e c^2} \left( \frac{3e}{4\pi m_e c} \right)^{0.5(p-1)} a(p) v^{-0.5(p-1)}, \quad (8a)$$

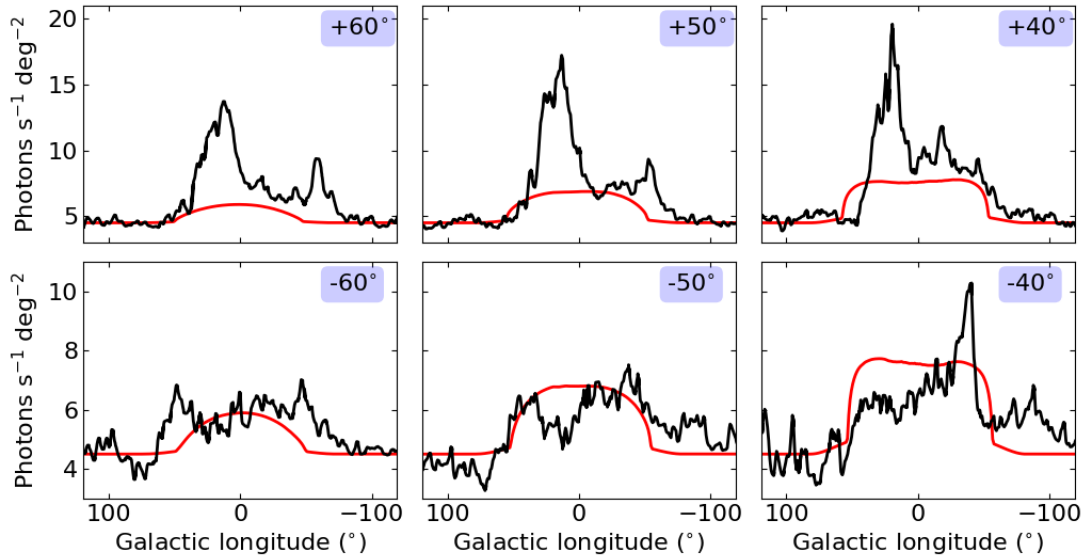
$$a(p) = \frac{2^{0.5(p-1)} \sqrt{3} \Gamma[(3p-1)/12] \Gamma[(3p+9)/12] \Gamma[(p+5)/4]}{8 \sqrt{\pi} (p+1) \Gamma[(p+7)/4]}, \quad (8b)$$

where  $\Gamma$  is gamma function,  $B$  is the magnetic field strength defined in Equation (5).

For a given longitude and latitude range, the simulated spectra are computed by projecting



(a) Simulated (top) and observed (bottom; [Predehl et al. 2020](#)) count rate ( $\text{photons s}^{-1} \text{deg}^{-2}$ ) in the 0.6-1.0 keV range. Throughout this paper we show sky maps in Galactic coordinates centered on the Galactic center using a Hammer-Aitoff projection, and observed from the solar system. The red arrow at the center of the top panel depicts the direction of the bipolar jet, constantly ejecting at an angle of  $45^\circ$  to the disc normal in 1.2 Myr.



(b) Comparison of simulated (red) and observed (black; [Predehl et al. 2020](#)) one-dimensional count rate profiles in the same energy band as Figure 5(a), cut at various Galactic latitudes (as labelled).

Figure 5.

emissivities as we project X-ray emissivities in Section 3.2, and then we average the spectra over all the sight lines within the region on sky.

Figure 6 shows the simulated microwave (left) and gamma-ray (right) spectra averaged over the different patches (shown in the legends) of the sky. The row from top to bottom shows the microwave (left) and gamma-ray (right) spectra with CRe spectral index 2.2, 2.4 and 2.6, respectively.

We find that the simulated gamma-ray spectra are well fitted by the CRe spectral index 2.4 (the middle row), and display several similar features as observed.

First, the simulated and observed spectra of the *Fermi* bubbles is nearly latitude independent, and characterized by a broad bump that roughly peaks around  $\sim 10$  GeV. However, the high-latitude spectrum tends to be slightly dimmer than low-latitude probably because the optical intensity in ISRF decays with increasing latitude.

Second, the gamma-ray spectra for all latitudes exhibit a spectral cutoff around energies 400–500 GeV, consistent with the observed cutoff energy. This is expected since the upscattered high-energy photons ( $\epsilon_1 \sim 450$  GeV) mainly arise from the relativistic scatterings between the high-energy CRe ( $\gtrsim 408$  GeV) and optical starlight ( $\epsilon \sim 10$  eV), and therefore Equation (7e) can be reduced to  $\epsilon_1 \sim \gamma m_e c^2$  in the Klein–Nishina limit (i.e.  $\epsilon_1 \gg (m_e c^2)^2$ ), implying most of the CRe energy is carried away by the upscattered photons.

We display the morphology of the *Fermi* bubbles that emit gamma-rays from the inverse Compton scattering of ISRF by CRe.

Figure 7 shows the simulated gamma-ray photon flux compared with the observed one in the energy bin 76.8 – 153.6 GeV. One can see that the symmetric of the *Fermi* bubbles can also be realized by tilted jets as the eROSITA bubbles.

The correlation between the multi-wavelength simulation suggest that the *Fermi* bubbles are produced by high-energy electrons via an inverse Compton scattering process, as the same electrons can also simultaneously produce synchrotron radiations in the presence of magnetic fields.

#### 4. CONCLUSIONS

We have found qualitative similarities between the results our simulations and the observed spectrum and morphological structure of the Galactic bubbles.

Since the jets encounter a larger column depth of clouds along their path, they interact more strongly with the dense ISM. The jets do not immediately clear a channel along the inclined axis of launch. Rather, the dense clouds deflect the jets, which then decelerate and launch a sub-relativistic outflow along the minor axis following the path of least resistance.

Assuming that a relativistic electron population of spectral index  $x = 2.2$  gives rise to the microwave haze via synchrotron emission.

#### DATA AVAILABILITY

The data underlying this article are available in the article and in its online supplementary material.

#### REFERENCES

- Ackermann M., et al., 2014, *The Astrophysical Journal*, 793, 64
- Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, *Astronomical Society of the Pacific Conference Series* Vol. 101, *Astronomical Data Analysis Software and Systems V*. p. 17
- Atwood W. B., et al., 2009, *The Astrophysical Journal*, 697, 1071
- Blitz L., Robishaw T., 2000, *J. 10.1086/309457*, 541, 675
- Blumenthal G. R., Gould R. J., 1970, *Reviews of Modern Physics*, 42, 237
- Carretti E., et al., 2013, *Nature*, 493, 66
- Cecil G., Bland-Hawthorn J., Veilleux S., Filippenko A. V., 2001, *The Astrophysical Journal*, 555, 338
- Crocker R. M., Aharonian F., 2011, *Phys. Rev. Lett.*, 106, 101102
- Crocker R. M., Jones D. I., Melia F., Ott J., Protheroe R. J., 2010, *Nature*, 463, 65
- Dobler G., Finkbeiner D. P., 2008, *The Astrophysical Journal*, 680, 1222
- Dopita M. A., et al., 2015, *The Astrophysical Journal Supplement Series*, 217, 12
- Federrath C., Roman-Duval J., Klessen R. S., Schmidt W., Low M.-M. M., 2010, *Astronomy and Astrophysics*, 512, A81
- Ferrière K. M., 2001, *Rev. Mod. Phys.*, 73, 1031
- Gallimore J. F., Axon D. J., O’Dea C. P., Baum S. A., Pedlar A., 2006, *The Astronomical Journal*, 132, 546
- Greevich J., Putman M. E., 2009, *J. 10.1088/0004-637x/696/1/385*, 696, 385
- Guo F., Mathews W. G., 2012, *The Astrophysical Journal*, 756, 181

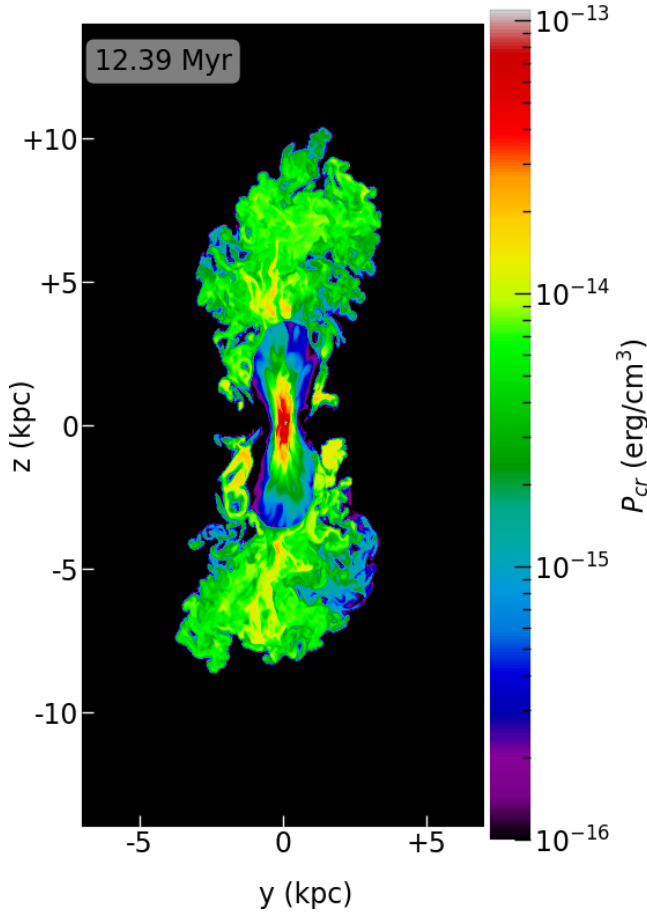




**Figure 6.** Simulated microwave spectra (colored lines in left) averaged over  $20^\circ < |b| < 30^\circ$ ,  $|l| < 10^\circ$ . The data point represents the *WMAP* data in the 23 GHz K band and the shaded bow-tie area indicates the range of synchrotron spectral indices allowed for the *WMAP* haze (Dobler & Finkbeiner 2008). Simulated gamma-ray spectra (colored lines in right column) of the *Fermi* bubbles calculated for a longitude range of  $|l| < 10^\circ$  for different latitude bins. The gray band represents the observational data of Ackermann et al. (2014). The row from top to bottom shows the microwave (left) and gamma-ray (right) spectra with CRe spectral index 2.2, 2.4 and 2.6, respectively. The CRe cutoff energy is  $1.1 \times 10^6 m_e c^2$  in all cases.



**Figure 7.** The observed (left) and simulated (right) photon flux in the energy bin 76.8 – 153.6 GeV. Note that the left panel is the photon flux of the diffuse component reconstructed by the D<sup>3</sup>PO algorithm (Selig et al. 2015) that analyzes the photon data from the *Fermi* Large Area Telescope (Atwood et al. 2009) and removes the contribution from point-like component. The red arrow at the center of the right panel depicts the direction of the bipolar jet, constantly ejecting at an angle of  $45^\circ$  to the disc normal in 1.2 Myr.



**Figure 8.** The slice of CR...

Johnston K. V., Spergel D. N., Hernquist L., 1995, *The Astrophysical Journal*, 451, 598  
 Jones F. C., 1968, *Physical Review*, 167, 1159  
 Kaastra J. S., Mewe R., 1993, *A&AS*, **97**, 443  
 Lewis G. M., Austin P. H., 2002, 1th Conference on Atmospheric Radiation  
 Liedahl D. A., Osterheld A. L., Goldstein W. H., 1995, *ApJL*, 438, L115  
 Mathews W. G., 1971, *ApJ*, **165**, 147  
 Mewe R., Gronenschild E. H. B. M., van den Oord G. H. J., 1985, *A&AS*, **62**, 197

Morganti R., Oosterloo T., Oonk J. B. R., Frieswijk W., Tadhunter C., 2015, *Astronomy & Astrophysics*, 580, A1  
 Narayanan S. A., Slatyer T. R., 2017, *Monthly Notices of the Royal Astronomical Society*, 468, 3051  
 Porter T. A., Jóhannesson G., Moskalenko I. V., 2017, *The Astrophysical Journal*, 846, 67  
 Predehl P., et al., 2020, *Nature*, 588, 227  
 Predehl P., et al., 2021, *Astronomy & Astrophysics*, 647, A1  
 Sarkar K. C., Nath B. B., Sharma P., 2015, *Monthly Notices of the Royal Astronomical Society*, 453, 3828  
 Schive H.-Y., Tsai Y.-C., Chiueh T., 2010, *The Astrophysical Journal Supplement Series*, 186, 457  
 Schive H.-Y., ZuHone J. A., Goldbaum N. J., Turk M. J., Gaspari M., Cheng C.-Y., 2018, *Monthly Notices of the Royal Astronomical Society*, 481, 4815  
 Selig M., Vacca V., Oppermann N., Enßlin T. A., 2015, *Astronomy & Astrophysics*, 581, A126  
 Strong A. W., Moskalenko I. V., Ptuskin V. S., 2007, *Annual Review of Nuclear and Particle Science*, 57, 285  
 Su M., Finkbeiner D. P., 2012, *The Astrophysical Journal*, 753, 61  
 Synge J. L., 1957, North-Holland Pub. Co.; Interscience Publishers  
 Taub A. H., 1948, *Physical Review*, **74**, 328  
 Tepper-García T., Bland-Hawthorn J., Sutherland R. S., 2015, *The Astrophysical Journal*, 813, 94  
 Tseng P.-H., Schive H.-Y., Chiueh T., 2021, *Monthly Notices of the Royal Astronomical Society*, 504, 3298  
 Valenti E., et al., 2018, *A&AS*, 616, A83  
 Wagner A. Y., Bicknell G. V., Umemura M., 2012, *The Astrophysical Journal*, 757, 136  
 Yang H.-Y. K., Ruszkowski M., 2017, *The Astrophysical Journal*, 850, 2  
 Yang H.-Y. K., Ruszkowski M., Ricker P. M., Zweibel E., Lee D., 2012, *The Astrophysical Journal*, 761, 185  
 Zhang R., Guo F., 2020, *The Astrophysical Journal*, 894, 117