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Fermi and eROSITA bubbles

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ABSTRACT

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1. INTRODUCTION

2. METHODOLOGY

2.1. *Assumptions and Numerical Techniques*

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 Fermi and eROSITA bubbles. GAMER-SR adopts a new algorithm (Tseng et al. 2021) to convert between primitive and conserved variables, significantly reducing numerical error caused by catastrophic cancellations that commonly occur within the regions with high Mach number. i.e. 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 code.

The simulation box is $14 \times 14 \times 28$ kpc, slightly larger than the size of eROISTA bubbles, with a root grid $N = 16 \times 16 \times 32$. We resolve the jet source located at the center of the simulation domain, cells are refined to level 11, leading to a finest spatial resolution of 0.4 pc.

To save computational costs further, we restrict the refinement level is 7 within the cold disk so that a molecular colud can be adequately resolved by approximately 30 cells along their diameter, 100 pc.

We treat CRs as a second fluid and solve directly for the evolution of CR pressure p_{cr} as a function of $\mathbf{r}$ and t. We did not model the CR energy spectrum and neglect the cooling and heating processes of CRs, such as energy losses due to synchrotron and inverse Compton emission, and reacceleration in shocks.

We have assumed cosmic-ray is passive. (i.e. $p_{\mathrm{cr}} \ll p_{\mathrm{gas}}$)

We have ignored the $\mathbf{B}$ field within the simulation box as the field inside the bubbles should be weak due to adiabatic expansion, and thus the magnetic fields has little effect on the overall dynamics.

We also assumed the magnetic field is highly entangled on small-scale (how small?), resulting in the negligible cosmic-ray diffusion.

GAMER-SR solves the mass and energy-momentum conservation laws of special relativistic ideal fluid including CR advection, and dynamical coupling between the thermal gas and CRs. The governing equations can be written as

1. Assumptions on hydrodynamics:
    (a) Ideal fluid with TM EoS (Taub 1948; Mathews 1971).
2. Assumptions on gravity:
    (a) We use the potential of isothermal slab, symmetric about $z = 0$ and supported by gas pressure and by under its own self-gravity, to mimic the realistic potential of Galactic bulge.
    (b) We still use Newtonian gravity, as the relativistic fluid ejected by the jet source is quickly slowed down by heavy disk in a short time, and the relativistic fluid accounts

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for a little minority of total mass inside the simulation box.

(c) The ISM disk and atmosphere are subjected to the fixed external potential due to a disk bulge and dark matter halo.

(d) In addition to the gravitational interaction, we ignore other interactions between stars and gases.

(e) We also ignore the self-gravity of the ISM disk and of the atmosphere.

(f) We ignore the centrifugal force of Milky Way rotation acting on the bubbles.

(g) We use the potential of isothermal slab to mimic the gravitational potential due to the stellar bulge.

(h) The interface between cold ISM disk and atmosphere is parallel to the Galactic plane and is pressure balanced.

We simulate 3D special relativistic hydrodynamics with passive CR injections from the GC using the special hydrodynamics GPU code GAMER-SR (Tseng et al. 2021).

GAMER-SR solves mass and energy-momentum conservation laws of a special relativistic ideal fluid with CR.

The CRs are advected with the thermal gas, but the gas cannot react to the CR pressure. In this approach, the CRs are treated as a single species without distinction between electrons and protons. We did not model the CR energy spectrum, 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.

$$\partial_t D + \partial_j \left(DU^j/\gamma\right) = 0, \tag{1a}$$

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

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

$$\partial_t \left(\gamma e_{\rm cr}\right) + \partial_j \left(e_{\rm cr} U^j\right) = -p_{\rm cr}\partial_j U^j, \tag{1d}$$

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. γ and U^j are the temporal and spatial component of four-velocity of gas. ρ is the gas density in the local rest frame defined by D/γ. $p_{\rm gas}$ is the gas pressure. $p_{\rm cr}$ and $e_{\rm cr}$ are the CR pressure and CR energy density measured in the local rest frame. Φ is the gravitation potential. c is the speed of light, and δ^{ij} is the Kronecker delta notation. Throughout this paper, Latin indices run from 1 to 3, except when stated otherwise.

2.2. *The Galactic Model*

1. Fixed external gravitational potential:

   (a) Bulge potential:

      i. Peak density: $\rho_{\rm bulge}^{\rm peak} = 4 \times 10^{-24}$ g/cm^3.

      ii. Potential (isothermal slab):

$$\Phi_{\rm bulge} = 2\sigma_{\rm bulge}^2 \ln\cosh\left(z\sqrt{\frac{2\pi G\rho_{\rm bulge}^{\rm peak}}{\sigma_{\rm bulge}^2}}\right), \tag{2}$$

      where $\sigma_{\rm bulge} = \sqrt{\frac{k_B T_{\rm bulge}}{m}} = 100$ km/s (Valenti et al. 2018).

   (b) Dark logarithmic halo potential:

$$\Phi_{\rm halo} = v_{\rm halo}^2 \ln\left(z^2 + d_{\rm h}^2\right), \tag{3}$$

   where $v_{\rm halo} = 131.5$ km/s, $d_{\rm h} = 12$ kpc (Yang et al. 2013).

   (c) Total potential: $\Phi_{\rm total} = \Phi_{\rm bulge} + \Phi_{\rm halo}$.

2. Clumpy cold disk:

   (a) Dimension: 14×14×0.2 kpc. i.e. Scale height, $z_0 = 100$ pc. (Ferrière 2001)

   (b) Peak mass density: $\rho_{\rm disk}^{\rm peak} = 10^{-23}$ g/cm^3. (Ferrière 2001)

   (c) Average temperature: $T_{\rm disk} = 10^3$ K. (Ferrière 2001)

   (d) Average mass density:

$$\rho_{\rm disk} = \rho_{\rm disk}^{\rm peak} \exp\left[-\frac{\Phi_{\rm total}}{k_B T_{\rm disk}/m}\right]. \tag{4}$$

   (e) Pressure: $p_{\rm disk} = \rho_{\rm disk} T_{\rm disk}$.

   (f) The clumpy cuboid, using the publicly available pyFC code[1], are described by a log-normal distribution with mean 1.0 and variance 5.0. Also, the power spectrum of the clumpy cuboid is characterized by $k_{\rm min}$ and β, where $k_{\rm min}$ sets the maximum cloud size within the clumpy cuboid, and β is the slope of power spectrum in Fourier space. In this

[1] https://pypi.python.org/pypi/pyFC

paper, we set $\beta = -5/3$ and $k_{\rm min} = 375$ to follow the Kolmogorov spectrum and to limits the maximum size of an individual cloud to approximately 25 pc.

(g) The clumpy disk is then constructed by multiplying a fractal cuboid with Equation (4).

(h) The clouds and voids within clumpy disk are pressure balanced.

3. Isothermal atmosphere:

(a) The region outside the clumpy cold disk is atmosphere.

(b) $T_{\rm atmp} = 10^6$ K. (Miller & Bregman 2013)

(c) Density:

$$\rho_{\rm atmp} = \rho_{\rm atmp}^{\rm peak} \exp\left[-\frac{\Phi_{\rm total}}{k_B T_{\rm atmp}/m}\right], \quad (5)$$

where $\rho_{\rm atmp}^{\rm peak}$ can be obtained by assuming that pressure and gravitational potential are continuous at the interface ($z = \pm z_0$) between disk and atmosphere.

2.3. *Jet injection*

1. Why the overall structure is insensitive to jet direction?

(a) Jet source size.

(b) Cold disk.

(c) Large pressure gradient along z-dircetion.

2.4. *X-ray and Gamma-ray emission*

1. X-ray:

(a) Thermal bremsstrahlung: The X-ray emissivity in an energy range 1.4–1.6 keV is calculated 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.

2. Gamma-ray:

(a) Leptonic process:
The gamma-ray emission is produced by inverse Comptom scattering of the ISRF by CRe.

(b) Hadronic process:
In the hadronic model, CRp undergo hadronic collisions with thermal gas protons and produce γ-ray via pion decay. The volume emissivity of the emission can be written as

$$\epsilon \propto U_{\rm CRp} n_p \sigma_p \kappa_{pp}. \quad (6)$$

Note that the observed X-ray emission is contributed by all the gas in the Milky Way halo, which likely extends to a radius of ~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 (Miller & Bregman 2013).

Inverse Compton scattering

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

$$f(q,\Gamma) = 2q\ln q + (1+2q)(1-q) + 0.5(1-q)\frac{(\Gamma q)^2}{1+\Gamma q}, \quad (8)$$

$$\Gamma = \frac{4\epsilon\gamma_{\rm e}}{m_{\rm e}c^2} \quad (9)$$

$$q = \frac{\epsilon_1/\gamma_{\rm e} m_{\rm e} c^2}{\Gamma\,(1-\epsilon_1/\gamma_{\rm e} m_{\rm e} c^2)}. \quad (10)$$

Hadronic process

$$\frac{dE}{dtd\epsilon_1 dV} = c n_H p C \left(\frac{\epsilon_1}{m_{\rm p} c^2}\right)^{-p} \int_0^1 \sigma(\epsilon_{\rm p}) F(x,\epsilon_{\rm p}) x^p dx. \quad (11)$$

$$\sigma(\epsilon_{\rm p}) = 34.3 + 1.88L + 0.25L^2 \text{ mb}. \quad (12)$$

$$F(x,\epsilon_{\rm p}) = B\frac{d}{dx}\left[\ln(x)\left(\frac{1-x^\beta}{1+kx^\beta(1-x^\beta)}\right)^4\right], \quad (13)$$

where $B = 1.30 + 0.14L + 0.011L^2$, $\beta = \left(1.79 + 0.11L + 0.008L^2\right)^{-1}$, $\left(0.801 + 0.049L + 0.014L^2\right)^{-1}$, $L = \ln\left(\epsilon_{\rm p}/1 \text{ TeV}\right)$.

3. TO-DO-LIST

1. Predict cold inner bubbles, emitting OIII or OII spectrum.

4. CONCLUSIONS

DATA AVAILABILITY

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

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APPENDIX