Draft version November 5, 2021
Typeset using LaTeX **twocolumn** style in AASTeX631

Fermi and eROSITA bubbles

Po-Hsun Tseng [1] H.-Y. Karen Yang [2] Hsi-Yu Schive [1,3,4,5] and Tzihong Chiueh [1,3,4]

[1] Institute of Astrophysics, National Taiwan University, Taipei 10617, Taiwan
[2] Institute of Astronomy and Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
[3] Department of Physics, National Taiwan University, Taipei 10617, Taiwan
[4] Center for Theoretical Physics, National Taiwan University, Taipei 10617, Taiwan
[5] Physics Division, National Center for Theoretical Sciences, Taipei 10617, Taiwan

ABSTRACT

Keywords: keywords

1. INTRODUCTION

2. METHODOLOGY

2.1. *Assumptions and Numerical Techniques*

1. Numerical features:
   - (a) GPU acceleration with GAMER-SR code.
   - (b) Special relativistic hydrodynamics.
   - (c) We use 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.
   - (d) To further alleviate the numerical error due to high Mach number, GAMER-SR also adaptively reduce the min-mod coefficient (Tseng et al. 2021) inside the failed patch. Doing so provides an elegant way to avoid the use of pressure/density floor, which is unnatural but widely used in almost publicly available code.
2. Assumptions on hydrodynamics:
   - (a) Ideal fluid with TM EoS (Taub 1948; Mathews 1971).
3. Assumptions on cosmic-ray:
   - (a) We treat CRs as a second fluid and solve directly for the evolution of CR pressure $p_{\rm cr}$ as a function of $\mathbf{r}$ and t.
   - (b) We did not model the CR energy spectrum.
   - (c) We neglected the cooling and heating processes of CRs, such as energy losses due to synchrotron and inverse Compton emission, and reacceleration in shocks.
   - (d) We have assumed cosmic-ray is passive. (i.e. $p_{\rm cr} \ll p_{\rm gas}$)
   - (e) We have ignored the **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.
4. 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 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.

Corresponding author: Po-Hsun Tseng
zengbs@gmail.com

(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 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.

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

(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*

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 writen as

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

3. CONCLUSIONS

DATA AVAILABILITY

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

REFERENCES

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

Ferrière K. M., 2001, Rev. Mod. Phys., 73, 1031

Kaastra J. S., Mewe R., 1993, A&AS, 97, 443

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

Miller M. J., Bregman J. N., 2013, The Astrophysical Journal, 770, 118

Taub A. H., 1948, Physical Review, 74, 328

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

Yang H.-Y. K., Ruszkowski M., Zweibel E., 2013, Monthly Notices of the Royal Astronomical Society, 436, 2734

APPENDIX