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Fermi and eROSITA bubbles

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ABSTRACT

Keywords: keywords

1. INTRODUCTION

2. METHODOLOGY

2.1. *Assumptions and Numerical Techniques*

1. Numerical features:
   (a) GPU acceleration with the GAMER-SR code.
   (b) Special relativistic hydrodynamics.
   (c) Using a new algorithm dedicated to the conversion between primitive and conserved variable, significantly reducing numerical error caused by the non-relativistic cold disk.
2. 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 assumed $\mathbf{B}$ is zero 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. It might somewhat affect the instabilities near the bubble's surface, but that's a secondary effect.
   (f) Since $\mathbf{B}$ is zero, we can also ignore the effect of cosmic-ray diffusion.
3. Assumptions on gravity:
   (a) We have assumeed relativistic gravity is insignificant.
   (b) The ISM disk and atmosphere are subjected to the fixed external potential contributed by disk bulge and dark matter halo.
   (c) In addition to the gravitational interaction, we ignore other interactions between stars and gases.
   (d) We also ignore the self-gravity of the ISM disk and of the atmosphere.
   (e) We ignore the Milky Way rotation.
   (f) We use the potential of isothermal slab to mimic the fixed gravitational potential of the stellar bulge.
   (g) The interface between cold ISM disk and atmosphere is parallel to 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

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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.

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

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

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

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

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 externel 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.

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

2. Clummpy cold disk:

   (a) Scale height: $z_0 = 100$ pc. (Ferrière 2001)

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

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

   (d) 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) The fractal density is created using the publicly available pyFC code[1].

3. Isothermal atmosphere:

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

   (b) Density:

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

   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:

2. Gamma-ray:

   (a) Hadronic process:

3. CONCLUSIONS

DATA AVAILABILITY

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

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APPENDIX