Abstract

We present a new special relativistic hydrodynamics (SRHD) code capable of handling coexisting ultra-relativistically hot and non-relativistically cold gases. We achieve this by designing a new algorithm for conversion between primitive and conserved variables in the SRHD solver, which incorporates a realistic ideal-gas equation of state covering both the relativistic and non-relativistic regimes. The code can handle problems involving a Lorentz factor as high as 10^6 and optimally avoid the catastrophic cancellation. In addition, we have integrated this new SRHD solver into the code GAMER (`https://github.com/gamer-project/gamer`) to support adaptive mesh refinement and hybrid OpenMP/MPI/GPU parallelization. It achieves a peak performance of 7×10^7 cell updates per second on a single Tesla P100 GPU and scales well to 2048 GPUs. We apply this code to two interesting astrophysical applications: (1) an asymmetric explosion source on the relativistic blast wave and (2) the flow acceleration and limb-brightening of relativistic jets.

The *Fermi Gamma-Ray Space Telescope* reveals two large bubbles in the Galaxy, which extend nearly symmetrically $\sim 50^\circ$ above and below the Galactic center (GC). The recent discovery of giant eROSITA bubbles also shows such a symmetry about the GC, suggesting that they may originate from a single GC activity. Previous simulations of bubble formation that invoke active galactic nucleus (AGN) jets have assumed that the jets are vertical to the Galactic plane; however, in general there does not need to be a correlation between the jet orientation and the rotational axis of the Galactic

disk. Using three-dimensional (3D) special relativistic hydrodynamic (SRHD) simulations that include cosmic rays (CRs) and thermal gas, we show that the dense clumpy gas within disk interstellar medium disrupts jets collimation and confinement ("failed jets" hereafter), which in turn causes the failed jets to form hot bubbles. Subsequent bouyancy in the stratified atmosphere renders them vertical to form the symmetric *Fermi* and eROSITA bubbles (collectively, Galactic bubbles). Specifically, we find that (1) despite the relativistic jets emanated from the GC 12 Myr ago are at various angles $\leq 45^\circ$ with respect to the rotational axis of the Galaxy, the Galactic bubbles nonetheless appear aligned with the axis; the simulated Galactic bubbles are nearly symmetric about the GC albeit the bipolar jets are at an angle 45° with respect to the rotational axis of the Galaxy; (2) the edge of the eROSITA bubbles corresponds to a forward shock, driven by the hot bubble; (3) followed by the forward shock is a tangling contact discontinuity at the edge of the *Fermi* bubbles composed of turbulent and high-temperature (~ 2 keV) plasma in pressure balance with the external medium; (4) assuming a leptonic model we find that the observed gamma-ray bubbles and microwave haze can be reproduced with a best-fit CR power-law index of 2.4; (5) the 12 Myr time span between the present and the launch of short-lived jets appears to be the appropriate time scale for the observed GC Central Molecular Zone to form. The broad agreement between the simulated and the observed multi-wavelength features suggests that forming the Galactic bubbles by oblique AGN failed jets is a plausible scenario.

Keywords: relativistic hydrodynamics, numerical method, *Fermi*/eROSITA bubbles