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iharm3D: Vectorized General Relativistic Magnetohydrodynamics

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`iharm3D` Functionality and Purpose

`iharm3D`[1] is an open-source C code for simulating black hole accretion systems in arbitrary stationary spacetimes using ideal general-relativistic magnetohydrodynamics (GRMHD). It is an implementation of the HARM ("High Accuracy Relativistic Magnetohydrodynamics") algorithm outlined in Gammie et al. (2003) with updates as outlined in McKinney & Gammie (2004) and Noble et al. (2006). The code is most directly derived from Ryan et al. (2015) but but with radiative transfer portions removed. HARM is a conservative finite-volume scheme for solving the equations of ideal GRMHD, a hyperbolic system of partial differential equations, on a logically Cartesian mesh in arbitrary coordinates.

Statement of Need

Numerical simulations are crucial in modeling observations of active galactic nuclei, such as the recent horizon-scale results from the Event Horizon Telescope and GRAVITY collaborations. The computational simplicity of ideal GRMHD enables the generation of long, high-resolution simulations and broad parameter-exploration studies that can be compared to observations for parameter inference.

Multiple codes already exist for solving the ideal GRMHD equations on regular Eulerian meshes in 3D, including:

- Athena++ (Stone et al. (2020), White et al. (2016))
- BHAC (Porth et al. (2017))
- Cosmos++ (Anninos et al. (2005), Fragile et al. (2012), Fragile et al. (2014))
- ECHO (Londrillo & Zanna (2000), Londrillo & Zanna (2004))
- H-AMR (M. Liska et al. (2020), Matthew Liska et al. (2019), Chatterjee+ 2019?)
- HARM-Noble (Noble et al. (2006), Noble et al. (2009), Noble et al. (2012), Zilhão & Noble (2014), Bowen et al. (2018))
- IllinoisGRMHD (Etienne et al. (2015))

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[1] https://github.com/AFD-Illinois/iharm3d

- KORAL (Sądowski et al. (2013), Sądowski et al. (2014))

The emphasis of `iharm3D` development is to provide a simple, fast, and scalable open update to the original open-source implementation of HARM (Gammie et al. (2003)).

Implementation Notes

In MHD, uncorrected discretization errors inevitably lead to violations of the no-monopoles condition $\nabla \cdot B = 0$. As in the original HARM implementation, `iharm3D` uses the "Flux-CT" scheme for cell-centered constrained transport outlined in Tóth (2000).

`iharm3D` also retains numerical evaluation of all metric-dependent quantities, allowing trivial modification of the coordinate system or background spacetime so long as the line element is available in analytic form. This can be used as a form of static mesh refinement, since the coordinates can be adapted to place resolution in areas of interest (e.g., an accretion disk midplane).

In GRMHD, "conserved" variables (energy and momentum density) are complicated analytic functions of "primitive" variables (density, pressure, and velocity). Conserved variables are stepped forward in time and then inversion to primitives is done numerically. `iharm3d` uses the "$1D_W$" scheme outlined in Noble et al. (2006).

To model a collisionless plasma, `iharm3D` implements an optional scheme that provides a means of tracking and partitioning dissipation into ions and electrons (Ressler et al. (2015)). The code implements the turbulent cascade models of Howes (2010) and Kawazura et al. (2019), but new models are easy to implement and welcome.

To avoid catastrophic failures caused by discretization error, especially in low density regions, fluid variables are bounded at the end of each step. Typical `iharm3D` bounds in black hole accretion problems are enforced as follows:

- Density $\rho > 10^{-6}k$, for $k \equiv \frac{1}{r^2(1+r/10)}$, with radius r in units of gravitational radius r_g of the central object,
- Internal energy $u > 10^{-8}k^{\gamma}$ where $\gamma \equiv$ adiabatic index,
- ρ and u are incremented until $\sigma \equiv \frac{2P_b}{\rho} < 400$ and $\beta \equiv \frac{P_{gas}}{P_b} > 2.5 \times 10^{-5}$ where $P_b \equiv \frac{b^2}{2}$ is the magnetic pressure,
- ρ is incremented until $\frac{u}{\rho} < 100$,
- When evolving electron temperatures, u is decremented until $\frac{P_{gas}}{\rho^{\gamma}} < 3$,
- Velocity components are downscaled until Lorentz factor $\Gamma \equiv \frac{1}{\sqrt{1-v^2}} < 50$.

Global disk simulations inevitably invoke these bounds, most frequently those on σ and Γ.

Tests

The convergence properties of HARM are well-studied in Gammie et al. (2003). `iharm3D` implements most of the tests presented in that paper as integration and regression tests. Figure 1 shows convergence results for linear modes and for un-magnetized Bondi flow.

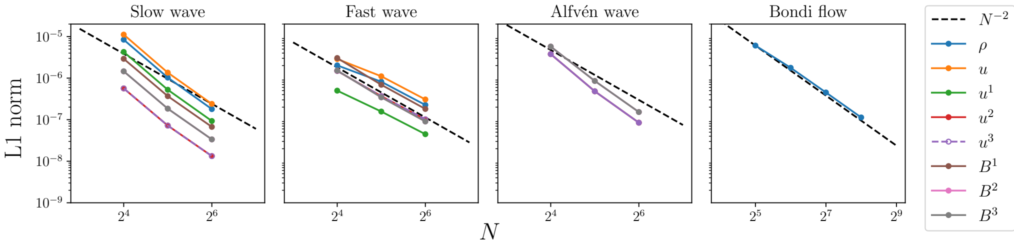

Figure 1: Results of convergence tests with `iharm3d`'s main branch, plotting L1 norm of the computed solution vs. the analytic or stable result with increasing domain size. Wave solutions were performed on a 3D cubic grid N zones to one side, the Bondi accretion problem was performed on a logically Cartesian 2D square grid N zones on one side.

`iharm3D` implements three additional tests which check that fluid evolution is identical under different domain decompositions: one which initializes a new fluid state, one which restarts from a checkpoint file, and one comparing the initialized state to an equivalent checkpoint file.

Scaling

Key `iharm3D` routines are highly vectorized and have efficient memory access patterns. Originally developed for Intel Knights Landing (KNL) chips on the Stampede2 supercomputer at Texas Advanced Computing Center (TACC), `iharm3D` also runs efficiently on TACC's Frontera CPU nodes.

Figure 2 presents scaling results for `iharm3D` on both Stampede2 and Frontera.

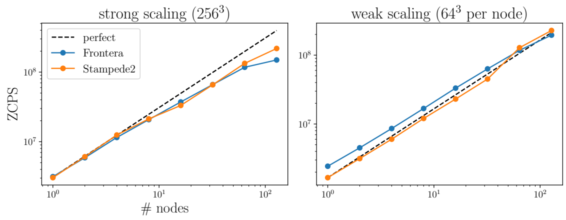

Figure 2: Strong scaling performance of iharm3D. Performance is measured in zones advanced by one cycle each second (Zone-Cycles per Second), when a problem with 256^3 zones is split among N nodes

Research projects using iharm3D

`iharm3D` is one of several GRMHD codes used by the EHT Collaboration to produce its library of fluid simulations. Images produced from this library were used for validation tests in Event Horizon Telescope Collaboration et. al. (2019a) and Event Horizon Telescope Collaboration et. al. (2021a) and for interpretation of the M87 EHT results in total intensity (Event Horizon Telescope Collaboration et. al. (2019b), Event Horizon Telescope Collaboration et. al. (2019c)) and polarization (Event Horizon Telescope Collaboration et. al. (2021b)).

`iharm3D` simulations have also been used in Porth et al. (2019), Johnson et al. (2020), Gold et al. (2020), Palumbo et al. (2020), Lin et al. (2020), Ricarte et al. (2020), Wielgus et al. (2020), Tiede et al. (2020), and Gelles et al. (2021).

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