The Journal of Open Source Software

iharm3D: Vectorized General Relativistic Magnetohydrodynamics

Ben S. Prather[*1, 2], **George N. Wong**[1, 2], **Vedant Dhruv**[1, 2], **Benjamin R. Ryan**[3], **Joshua C. Dolence**[3], **Sean M. Ressler**[5], and **Charles F. Gammie**[1, 2, 4]

1 Physics Department, University of Illinois at Urbana–Champaign, 1110 West Green Street, Urbana, IL 61801, USA **2** Illinois Center for Advanced Studies of the Universe **3** CCS-2, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA **4** Astronomy Department, University of Illinois at Urbana–Champaign, 1002 West Green Street, Urbana, IL 61801, USA **5** Kavli Institute for Theoretical Physics, University of California Santa Barbara, Kohn Hall, Santa Barbara, CA 93107, USA

DOI: DOIunavailable

Software

- Review
- Repository
- Archive

Editor: Pending Editor

Reviewers:

- @Pending Reviewers

Submitted: N/A
Published: N/A

`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++ (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. T. P. Liska et al. (2018), M. 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))
- 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)).

*bprathr2@illinois.edu
[1] https://github.com/AFD-Illinois/iharm3d

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. (2018), 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.

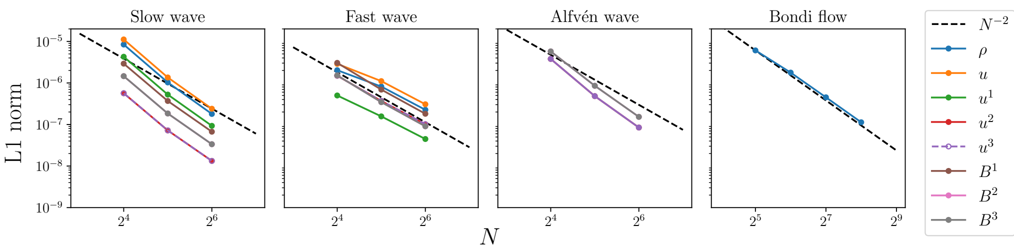

Figure 1: Results of convergence tests with `iharm3d`'s main branch, plotting L1 norm of the computed solution vs. the analytic or stable result with increasing domain size. Wave solutions were performed on a 3D cubic grid N zones to one side, the Bondi accretion problem was performed on a logically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

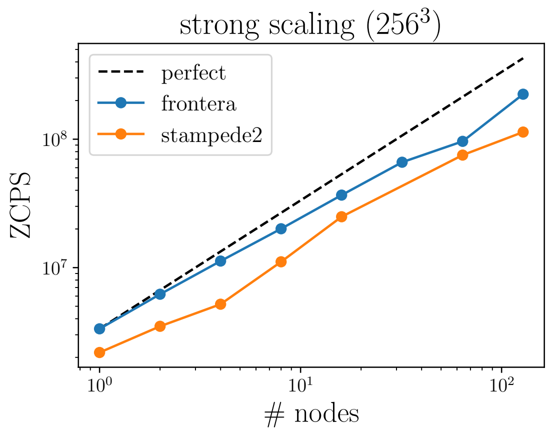

Figure 2: Strong scaling performance of iharm3D. Performance is measured in zones advanced by one cycle each second (Zone-Cycles per Second), when a problem with 256^3 zones is split among N nodes

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), Yao-Yu Lin et al. (2020), Ricarte et al. (2020), Wielgus et al. (2020), Tiede et al. (2020), and Gelles et al. (2021).

Acknowledgements

This work was supported by National Science Foundation grants AST 17-16327, OISE 17-43747, AST 20-07936, AST 20-34306, and PHY 17-48958, by a Donald C. and F. Shirley Jones Fellowship to G.N.W., by the Gordon and Betty Moore Foundation through Grant GBMF7392, and by the US Department of Energy through Los Alamos National Laboratory. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear

Security Administration of the US Department of Energy (Contract No. 89233218CNA000001). This work has been assigned a document release number LA-UR-21-23714.

References

Anninos, P., Fragile, P. C., & Salmonson, J. D. (2005). Cosmos++: Relativistic Magnetohydrodynamics on Unstructured Grids with Local Adaptive Refinement. *The Astrophysical Journal*, *635*(1), 723. https://doi.org/10.1086/497294

Bowen, D. B., Mewes, V., Campanelli, M., Noble, S. C., Krolik, J. H., & Zilhão, M. (2018). Quasi-periodic Behavior of Mini-disks in Binary Black Holes Approaching Merger. *The Astrophysical Journal Letters*, *853*(1), L17. https://doi.org/10.3847/2041-8213/aaa756

Etienne, Z. B., Paschalidis, V., Haas, R., Mösta, P., & Shapiro, S. L. (2015). IllinoisGRMHD: An open-source, user-friendly GRMHD code for dynamical spacetimes. *Classical and Quantum Gravity*, *32*(17), 175009. https://doi.org/10.1088/0264-9381/32/17/175009

Event Horizon Telescope Collaboration et. al. (2021a). First M87 Event Horizon Telescope Results. VII. Polarization of the Ring. *910*(1), L12. https://doi.org/10.3847/2041-8213/abe71d

Event Horizon Telescope Collaboration et. al. (2021b). First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon. *910*(1), L13. https://doi.org/10.3847/2041-8213/abe4de

Event Horizon Telescope Collaboration et. al. (2019a). First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole. *875*(1), L4. https://doi.org/10.3847/2041-8213/ab0e85

Event Horizon Telescope Collaboration et. al. (2019b). First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring. *875*(1), L5. https://doi.org/10.3847/2041-8213/ab0f43

Event Horizon Telescope Collaboration et. al. (2019c). First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole. *875*(1), L6. https://doi.org/10.3847/2041-8213/ab1141

Fragile, P. C., Gillespie, A., Monahan, T., Rodriguez, M., & Anninos, P. (2012). Numerical Simulations of Optically Thick Accretion onto a Black Hole. I. Spherical Case. *The Astrophysical Journal Supplement Series*, *201*, 9. https://doi.org/10.1088/0067-0049/201/2/9

Fragile, P. C., Olejar, A., & Anninos, P. (2014). Numerical Simulations of Optically Thick Accretion onto a Black Hole. II. Rotating Flow. *The Astrophysical Journal*, *796*, 22. https://doi.org/10.1088/0004-637X/796/1/22

Gammie, C. F., McKinney, J. C., & Tóth, G. (2003). HARM: A Numerical Scheme for General Relativistic Magnetohydrodynamics. *The Astrophysical Journal*, *589*(1), 444. https://doi.org/10.1086/374594

Gelles, Z., Prather, B. S., Palumbo, D. C. M., Johnson, M. D., Wong, G. N., & Georgiev, B. (2021). The Role of Adaptive Ray Tracing in Analyzing Black Hole Structure. *arXiv e-Prints*, arXiv:2103.07417. http://arxiv.org/abs/2103.07417

Gold, R., Broderick, A. E., Younsi, Z., Fromm, C. M., Gammie, C. F., Mościbrodzka, M., Pu, H.-Y., Bronzwaer, T., Davelaar, J., Dexter, J., Ball, D., Chan, C., Kawashima, T., Mizuno, Y., Ripperda, B., Akiyama, K., Alberdi, A., Alef, W., Asada, K., … Event Horizon Telescope Collaboration. (2020). Verification of Radiative Transfer Schemes for the EHT. *897*(2), 148. https://doi.org/10.3847/1538-4357/ab96c6

Howes, G. G. (2010). A prescription for the turbulent heating of astrophysical plasmas. *Monthly Notices of the Royal Astronomical Society*, *409*, L104–L108. https://doi.org/10.1111/j.1745-3933.2010.00958.x

Johnson, M. D., Lupsasca, A., Strominger, A., Wong, G. N., Hadar, S., Kapec, D., Narayan, R., Chael, A., Gammie, C. F., Galison, P., Palumbo, D. C. M., Doeleman, S. S., Blackburn, L., Wielgus, M., Pesce, D. W., Farah, J. R., & Moran, J. M. (2020). Universal interferometric signatures of a black hole's photon ring. *Science Advances*, *6*(12), eaaz1310. https://doi.org/10.1126/sciadv.aaz1310

Kawazura, Y., Barnes, M., & Schekochihin, A. A. (2018). Thermal disequilibration of ions and electrons by collisionless plasma turbulence. *arXiv:1807.07702 [Astro-Ph, Physics:physics]*. http://arxiv.org/abs/1807.07702

Liska, M., Chatterjee, K., Tchekhovskoy, A., Yoon, D., Eijnatten, D. van, Hesp, C., Markoff, S., Ingram, A., & Klis, M. van der. (2019). H-AMR: A New GPU-accelerated GRMHD Code for Exascale Computing With 3D Adaptive Mesh Refinement and Local Adaptive Time-stepping. *arXiv e-Prints*, *1912*, arXiv:1912.10192. http://adsabs.harvard.edu/abs/2019arXiv191210192L

Liska, M. T. P., Tchekhovskoy, A., & Quataert, E. (2018). Large-Scale Poloidal Magnetic Field Dynamo Leads to Powerful Jets in GRMHD Simulations of Black Hole Accretion with Toroidal Field. *arXiv:1809.04608 [Astro-Ph, Physics:physics]*. http://arxiv.org/abs/1809.04608

Londrillo, P., & Zanna, L. D. (2000). High-Order Upwind Schemes for Multidimensional Magnetohydrodynamics. *The Astrophysical Journal*, *530*(1), 508. https://doi.org/10.1086/308344

Londrillo, P., & Zanna, L. del. (2004). On the divergence-free condition in Godunov-type schemes for ideal magnetohydrodynamics: The upwind constrained transport method. *Journal of Computational Physics*, *195*, 17–48. https://doi.org/10.1016/j.jcp.2003.09.016

McKinney, J. C., & Gammie, C. F. (2004). A Measurement of the Electromagnetic Luminosity of a Kerr Black Hole. *The Astrophysical Journal*, *611*(2), 977. https://doi.org/10.1086/422244

Noble, S. C., Gammie, C. F., McKinney, J. C., & Del Zanna, L. (2006). Primitive Variable Solvers for Conservative General Relativistic Magnetohydrodynamics. *The Astrophysical Journal*, *641*, 626–637. https://doi.org/10.1086/500349

Noble, S. C., Krolik, J. H., & Hawley, J. F. (2009). DIRECT CALCULATION OF THE RADIATIVE EFFICIENCY OF AN ACCRETION DISK AROUND A BLACK HOLE. *The Astrophysical Journal*, *692*(1), 411–421. https://doi.org/10.1088/0004-637X/692/1/411

Noble, S. C., Mundim, B. C., Nakano, H., Krolik, J. H., Campanelli, M., Zlochower, Y., & Yunes, N. (2012). Circumbinary Magnetohydrodynamic Accretion into Inspiraling Binary Black Holes. *The Astrophysical Journal*, *755*, 51. https://doi.org/10.1088/0004-637X/755/1/51

Palumbo, D. C. M., Wong, G. N., & Prather, B. S. (2020). Discriminating Accretion States via Rotational Symmetry in Simulated Polarimetric Images of M87. *The Astrophysical Journal*, *894*(2), 156. https://doi.org/10.3847/1538-4357/ab86ac

Porth, O., Chatterjee, K., Narayan, R., Gammie, C. F., Mizuno, Y., Anninos, P., Baker, J. G., Bugli, M., Chan, C., Davelaar, J., Del Zanna, L., Etienne, Z. B., Fragile, P. C., Kelly, B. J., Liska, M., Markoff, S., McKinney, J. C., Mishra, B., Noble, S. C., … Collaboration, T. E. H. T. (2019). The Event Horizon General Relativistic Magnetohydrodynamic Code Comparison Project. *arXiv:1904.04923 [Astro-Ph, Physics:gr-Qc]*. https://doi.org/10.3847/1538-4365/ab29fd

Porth, O., Olivares, H., Mizuno, Y., Younsi, Z., Rezzolla, L., Moscibrodzka, M., Falcke, H., & Kramer, M. (2017). The Black Hole Accretion Code. *Computational Astrophysics and Cosmology*, *4*(1). https://doi.org/10.1186/s40668-017-0020-2

Ressler, S. M., Tchekhovskoy, A., Quataert, E., Chandra, M., & Gammie, C. F. (2015). Electron thermodynamics in GRMHD simulations of low-luminosity black hole accretion. *Monthly Notices of the Royal Astronomical Society*, *454*, 1848–1870. https://doi.org/10.1093/mnras/stv2084

Ricarte, A., Prather, B. S., Wong, G. N., Narayan, R., Gammie, C., & Johnson, M. (2020). Decomposing the Internal Faraday Rotation of Black Hole Accretion Flows. *arXiv:2009.02369 [Astro-Ph]*. http://arxiv.org/abs/2009.02369

Ryan, B. R., Dolence, J. C., & Gammie, C. F. (2015). Bhlight: General Relativistic Radiation Magnetohydrodynamics with Monte Carlo Transport. *The Astrophysical Journal*, *807*(1), 31. https://doi.org/10.1088/0004-637X/807/1/31

Sądowski, A., Narayan, R., McKinney, J. C., & Tchekhovskoy, A. (2014). Numerical simulations of super-critical black hole accretion flows in general relativity. *Monthly Notices of the Royal Astronomical Society*, *439*(1), 503. https://doi.org/10.1093/mnras/stt2479

Sądowski, A., Narayan, R., Tchekhovskoy, A., & Zhu, Y. (2013). Semi-implicit scheme for treating radiation under M1 closure in general relativistic conservative fluid dynamics codes. *Monthly Notices of the Royal Astronomical Society*, *429*(4), 3533. https://doi.org/10.1093/mnras/sts632

Tiede, P., Broderick, A. E., & Palumbo, D. C. M. (2020). Variational Image Feature Extraction for the EHT. *arXiv e-Prints*, arXiv:2012.07889. http://arxiv.org/abs/2012.07889

Tóth, G. (2000). The $\nabla \cdot$ B=0 Constraint in Shock-Capturing Magnetohydrodynamics Codes. *Journal of Computational Physics*, *161*(2), 605–652. https://doi.org/10.1006/jcph.2000.6519

White, C. J., Stone, J. M., & Gammie, C. F. (2016). An Extension of the Athena++ Code Framework for GRMHD Based on Advanced Riemann Solvers and Staggered-mesh Constrained Transport. *The Astrophysical Journal Supplement Series*, *225*(2), 22. https://doi.org/10.3847/0067-0049/225/2/22

Wielgus, M., Akiyama, K., Blackburn, L., Chan, C., Dexter, J., Doeleman, S. S., Fish, V. L., Issaoun, S., Johnson, M. D., Krichbaum, T. P., Lu, R.-S., Pesce, D. W., Wong, G. N., Bower, G. C., Broderick, A. E., Chael, A., Chatterjee, K., Gammie, C. F., Georgiev, B., … Zhu, Z. (2020). Monitoring the Morphology of M87* in 2009-2017 with the Event Horizon Telescope. *901*(1), 67. https://doi.org/10.3847/1538-4357/abac0d

Yao-Yu Lin, J., Wong, G. N., Prather, B. S., & Gammie, C. F. (2020). Feature Extraction on Synthetic Black Hole Images. *arXiv e-Prints*, arXiv:2007.00794. http://arxiv.org/abs/2007.00794

Zilhão, M., & Noble, S. C. (2014). Dynamic fisheye grids for binary black hole simulations. *Classical and Quantum Gravity*, *31*(6), 065013. https://doi.org/10.1088/0264-9381/31/6/065013