AMReX-Astrophysics Microphysics: A set of microphysics routines for astrophysical simulation codes based on the AMReX library

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Summary

The AMReX-Astrophysics Microphysics library provides a common set of microphysics routines (reaction networks and associated physics, equations of state, and various transport coefficients) as well as solvers (stiff ODE integrators, nonlinear system solvers) for astrophysical simulation codes built around the AMReX adaptive mesh refinement library (W. Zhang et al., 2019). Several multi-dimensional simulation codes, including the compressible hydrodynamics code Castro (Almgren et al., 2010), the low-Mach number hydrodynamics code MAESTROeX (Fan et al., 2019), and the radiation-hydrodynamics code Quokka (Wibking & Krumholz, 2022) use Microphysics to provide the physics and solvers needed to close the hydrodynamics systems that they evolve. The library is implemented in C++ with GPU-offloading a key design feature.

Statement of need

Astrophysical simulation codes need many different small-scale (microphysics) physics inputs to close the system of equations. There are many astrophysics simulation codes built around the AMReX library, with each specializing in different astrophysics phenomena. Each of these codes share some common needs. The Microphysics library was created to minimize developer effort across these codes and coordinate the approach to exascale compute architectures, in particular, GPU support for astrophysical simulation codes.

State of the field

Individual reaction networks and equations of state have been made available by authors for decades, including a wide variety from Cococubed.com. Flash (Fryxell et al., 2000) comes with a set of reaction networks and equations of state as well. The closest compilation to ours is the recent singularity-EOS library (Miller et al., 2024), which provides various equations of state. Microphysics predates this library, going back to at least 2013. Further, our design targets codes that use the AMReX library directly, and encompasses a wider set of physics.

Software design

The Microphysics project started in 2013 as a way to centralize the reaction networks and equations of state used by Castro and MAESTRO (Nonaka et al., 2010), the predecessor to MAESTROeX. Originally, Microphysics used Fortran and for a brief period, it was referred to as Starkiller Microphysics, which was an attempt to co-develop microphysics routines for the Castro and the Flash (Fryxell et al., 2000) simulation codes. As interest in GPUs grew (with early support added to Microphysics in 2015), Castro moved from a mix of C++

and Fortran to pure C++ to take advantage of GPU-offloading afforded by the AMReX library, and C++ ports of all physics routines and solvers were added to Microphysics. At this point, the project was formally named the AMReX-Astrophysics Microphysics library. Today, the library is completely written in C++ and relies heavily on the AMReX data structures to take advantage of GPUs. The GPU-enabled reaction network integrators led to the Quokka code adopting Microphysics for their simulations.

Microphysics provides several different types of physics: equations of state, reaction networks and screening methods, nuclear statistical equilibrium solvers and tabulations, thermal conductivities, and opacities, as well as the tools needed to work with them, most notably the suite of stiff ODE integrators for the networks. Several classic Fortran libraries have been converted to header-only C++ implementations, including the VODE integrator (Brown et al., 1989), the hybrid Powell method of MINPACK (Powell, 1970), and the Runge–Kutta–Chebyshev (RKC) integration method (Sommeijer et al., 1998). The code was modernized where possible, with many `go to` statements removed and additional logic added to support our applications (see for example the discussion on VODE in Zingale et al., 2022). We also make use of the C++ autodiff library (Leal, 2018) to compute thermodynamic derivatives required in the Jacobians of our reaction networks.

Microphysics uses header-only implementations of all functionality as much as possible to allow for easier compiler inlining, which is especially important in GPU kernels. We also leverage C++17 `if constexpr` templating to compile out unnecessary computations for performance. Generally, the physics routines and solvers are written to work on a single zone from a simulation code, and in AMReX, a C++ lambda-capturing approach is used to loop over zones (and offload to GPUs if desired). When used with an application code, this design permits the simulation state data to be allocated directly in GPU memory and left there for the entire simulation, with all physics run directly on the GPU. Since each zone in a simulation usually will have a different thermodynamic state, the integration of reaction networks can lead to thread divergence issues. To help mitigate this issue, we can cap the number of integration steps and either retry an integration on a zone-by-zone basis with different tolerances or Jacobian approximations or pass the failure back to the application code to deal with. This strategy has been successful for many large scale simulations (Zingale et al., 2025).

Another key design feature is the separation of the reaction network from the integrator. This allows us to easily experiment with different integration methods (such as the RKC integrator) and also support different modes of coupling reactions to a simulation code, including operator splitting and spectral deferred corrections (SDC; see, e.g., Zingale et al., 2022). The latter is especially important for explosive astrophysical flows. Tight integration with pynucastro (Smith et al., 2023; Willcox & Zingale, 2018) allows for the generation of custom reaction networks for a science problem.

There are two ways to use Microphysics: in a standalone fashion (via the unit tests) for simple investigations or as part of an (AMReX-based) application code. In both cases, the core (compile-time) requirement is to select a network—this defines the composition that is then used by most of the other physics routines. This compile-time requirement also allows Microphysics to provide the number of species as a `constexpr` value (which many application codes need), and greatly reduces the compilation time (due to the templating used throughout the library).

Research impact statement

Microphysics has been used for simulations of convective Urca (Boyd et al., 2025) and X-ray bursts (Guichandut et al., 2024) with MAESTROeX; and for simulations of nova (Smith Clark & Zingale, 2025), X-ray bursts (Harpole et al., 2021), thermonuclear supernovae (Zingale, Chen, Rasmussen, et al., 2024), and convection in massive stars (Zingale, Chen, Johnson, et al., 2024) with Castro. This Microphysics library has also enabled recent work in astrophysical machine learning to train deep neural networks modeling nuclear reactions (Fan et al., 2022; X. Zhang et al., 2025).

AI usage disclosure

No generative AI/LLM was used for producing code or documentation in the git repository or for this paper. We have experimented with using AI/LLM tools for code review and for suggesting places to focus our optimization efforts on, but the resulting coding, benchmarking, and testing is then done by humans.

Acknowledgements

The AMReX-Astro Microphysics library developers are an open scientific team with members contributing to various aspects of the library. We have thus chosen to display the members of our development team in the author list in alphabetical order. All developers who have contributed new features, substantial design input, and/or at least 3 commits were invited to be coauthors. The work at Stony Brook was supported by the US Department of Energy, Office of Nuclear Physics grant DE-FG02-87ER40317.

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