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Magrathea v2: A planetary interior modeling platform in C++

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Software

- Review
- Repository
- Archive

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Summary

Magrathea is an open-source C++ code for modeling the internal structure of differentiated planets. The initial release, Huang et al. (2022), introduced the base solver, a modular framework for defining equations of state (EOSs) used within phase diagrams for each differentiated layer, and outlined a series of planned extensions. Many of those updates are now implemented. Magrathea v2 is a more versatile platform that supports a winder range of compositions, adds new tools for composition retrieval, and makes it easier for users to adapt the code to their own models.

Statement of need

Constraining a planet's composition is essential for understanding its formation and evolution. Observations of mass and radius alone are not sufficient, since many different interiors can yield the same bulk density. Interior structure solvers are therefore essential tools for constraining the possible compositions. With observational programs routinely measuring the densities of small to large planets, researchers require codes with models that are transparent and flexible—able to adapt to our changing understanding of planet mineralogy.

Magrathea is designed as such a platform. Rather than enforcing a fixed planet model, Magrathea provides a framework in which users can define their own phase diagrams, equations of state (EOSs), and thermal profiles. This adaptability has led to broad uptake: Magrathea has been used to generate mass–radius diagrams and infer interiors of observed planets (Daspute et al., 2025; Desai et al., 2024; Rice et al., 2025; Taylor et al., 2025), to connect theoretical composition models to observables (Childs et al., 2023; Dou et al., 2024; Steffen et al., 2025), and to incorporate new high-pressure equation of state (EOS) measurements into planetary modeling (Huang et al., 2021). A list of other open source interior models can be found in Acuña et al. (2025). With the continued expansion of the physics and usability, Magrathea helps the community keep up with the growing precision of exoplanet observations and experimental constraints on planetary materials.

Summary of the base code

The core solver of Magrathea is a one-dimensional, spherically symmetric integrator of the equations of hydrostatic equilibrium, mass continuity, and energy transport written in C++. For a user-defined planet consisting of up to four differentiated layers, the code integrates inward and outward solutions using a shooting-to-fitting-point method with adaptive Runge–Kutta–Fehlberg stepping. The solver returns the radius of the planet, the radii of each compositional boundary, and profiles of pressure, temperature, density, and phase as functions of enclosed mass. Solving one planet taskes approximately one second for most configurations.

A key design choice is **modularity**:

- A large variety of EOS forms are supported in `EOS.cpp`, including Birch–Murnaghan, Vinet, Holzapfel, Keane, van der Waals gases, and tabulated.
- Parameters for each material's EOS are defined and stored in a library of 70+ EOSs in `EOSlist.cpp`.
- Phase diagrams for each layer define which material is used at a given P-T condition in `phase.cpp`.

MAGRATHEA offers **nine run modes** through human-readable `.cfg` files:
1. **Full solver** takes masses for each layer and returns the planet's radius and interior profiles.
2. **Temperature-free solver** for isothermal interiors.
3. **Two-layer mode** for rapid mass–radius curves.
4. **Bulk mode** for ensembles of planets.
5. **Composition finder**: determine an unknown layer mass to match observed M and R.
6. **On-the-fly EOS modification** for testing parameter uncertainties.
7. **Iterated EOS modification** with two-layer solver.
8. **Iterated EOS modification** with full solver.
9. **MCMC composition retrieval** for probabilistic inference given mass, radius, and corresponding uncertainties.

This modularity and range of modes makes Magrathea not just a solver but a platform for exploring interior models.

Major updates in this version

Since the initial release (Huang et al., 2022), Magrathea has undergone expansions in physics, solvers, and usability.

New physical models and materials

- **Default Mantle:** Added upper-mantle polymorphs of Mg_2SiO_4 (forsterite, wadsleyite, ringwoodite) (Dorogokupets et al., 2015), see Figure 1.
- **Default Hydrosphere:** Updated H_2O EOSs and phase boundaries for ices (Journaux et al., 2020), liquid, gas (Wagner & Pruß, 2002), and supercritical (Mazevet et al., 2019, with 2021 entropy correction) largely inspired by the AQUA package (Haldemann et al., 2020), see Figure 1.
- **Additional Gas EOSs:** Including the solar-metalicity table for hydrogen/helium from (Chabrier & Debras, 2021) and van der Waals gases.
- **Carbon Mantles:** EOSs and phase diagrams for phases of carbon (Benedict et al., 2014) and silicon carbide (Miozzi et al., 2018), see Figure 1.
- **EOS library growth:** Including the AQUA table (Haldemann et al., 2020), fcc- and bcc-iron (Dorogokupets et al., 2017), and the mantle materials from Stixrude & Lithgow-Bertelloni (2011).

New functionality and solvers

- **Composition finders:**

  - A secant-method routine that determines the mass of a third unknown layer given a target mass, radius, and ratio between the other two layers looped over layer ratios and mass and radius posterior draws.
  - An Markov chain Monte Carlo based routine following Rogers & Seager (2010) and Dorn et al. (2015) for probabilistic composition inference given mass, radius, and associated uncertainties with Metropolis–Hastings method.
- **Tabulated EOSs:** Support for tabulated P–T–ρ–∇T_S EOS tables using bilinear interpolation.
- **Modular phase diagrams** Allow users to store multiple phase-diagram configurations and call them in the configuration file—for example, toggling between a silicate-based and carbon-based mantle phase diagram.

Usability

- **Input handling:** All input parameters migrated to `run/*.cfg` files with descriptive keys and documentation.
- **Parallelization:** Bulk runs and composition finder routines can exploit OpenMP in `compfind.cpp`, enabling execution with multiple threads.
- **Diagnostics:** More informative error messages when solutions fail to converge.
- **Tutorial and documentation:** A guided set of examples and practice problems resides in the `docs/` folder with online documentation at magrathea.readthedocs.io.

Together, these updates make Magrathea a platform for statistical inference of diverse exoplanet interiors. By expanding the physics library, adding composition retrieval solvers, and improving usability, the code enables a wider range of applications than in its initial release.

Planned future expansions include building versatile methods for mixing materials, adding treatments of thermal evolution, and coupling to an atmosphere model. Integrating new experimental and theoretical results will keep Magrathea a robust and adaptable tool for interpreting the increasing number and precision of exoplanet observations.

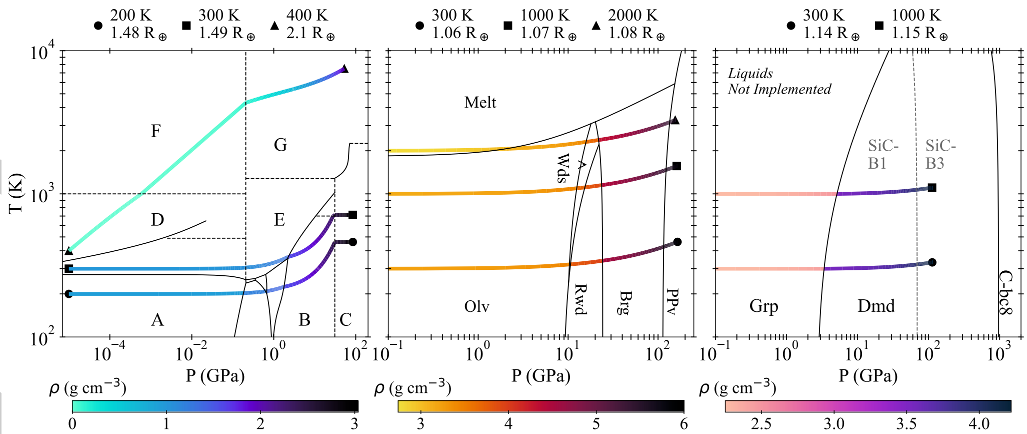

Figure 1: New phase diagrams in the code. Left, default hydrosphere compiled from many sources—A: low pressure ice/liquid (Journaux et al., 2020), B: ice-VII Sotin et al. (2007), C: ice-X (Grande et al., 2022), D: IAPWS-95 liquid/gas (Wagner & Pruß, 2002), E: supercritical (Brown, 2018), F: van der Waals gas, G: supercritical (Mazevet et al., 2019). Center, default mantle with lower pressure Mg_2SiO_4 phases. Right, carbon phase diagram in dark and SiC phase diagram in light grey. On each plot is shown the P-T conditions inside a 100% composition planet of one Earth-mass with two or three different outer temperatures. The density inside of the planet is shown by each plot's colorbar and the radius of the planet is denoted in the legend.

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