

CompactObject: An open-source Python package for full-scope neutron star equation of state inference

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Summary

The CompactObject package is an open-source software framework developed to constrain the neutron star equation of state (EOS) through Bayesian statistical inference. It integrates astrophysical observational constraints from X-ray timing, gravitational wave events, and radio measurements, as well as nuclear experimental constraints derived from perturbative Quantum Chromodynamics (pQCD) and Chiral Effective Field Theory (χ EFT). The package supports a diverse range of EOS models, including meta-model like and several physics-motivated EOS models. It comprises three independent components: an EOS generator module that currently provides seven EOS choices, a Tolman–Oppenheimer–Volkoff (TOV) equation solver, that allows the determination of the Mass Radius and Tidal deformability as observables, and a comprehensive Bayesian inference workflow module, including a complete pipeline for implementing EOS Bayesian inference. Each component can be used independently in different scientific research contexts, such as nuclear physics and astrophysics. In addition, CompactObject is designed to work in synergy with existing software such as [CompOSE](#), allowing the use of the CompOSE EOS database [Typel et al. \(2015, 2022\)](#) to extend the EOS options available.

Statement of need

Understanding the equation of state (EOS) of neutron stars is important for understanding the fundamental physics governing ultra-dense matter. Neutron stars, with their core densities exceeding several times nuclear saturation density, have a crucial role to play in studying nuclear interactions under extreme conditions. However, inferring the EOS from observational and experimental data has significant challenges due to the complex interplay of astrophysical phenomena and nuclear physics. Many of these studies such as [Raaijmakers et al. \(2023\)](#) focus on EOS meta-models (which may be parameterized or non-parameterized) that attempt to span all reasonable mass-radius parameter space, rather than being driven by microphysics. In contrast, CompactObject achieves high accuracy and rapid computation for a family of physics-motivated EOSs, thereby enabling researchers to perform inferences based on physically motivated models and apply nuclear physics-related constraints derived from nuclear experiments.

CompactObject appears as a viable solution to these challenges by providing an open-source, robust platform designed for Bayesian inference on neutron star EOS constraints. Its comprehensive workflow integrates a wide range of EOSs, including not only physical microscopic models and meta-models of neutron star EOSs but also quark star EOSs, i.e., strange stars [Bodmer \(1971\)](#); [Witten \(1984\)](#), nonstrange stars [Holdom et al. \(2018\)](#) or strangeon star EOSs ([Xu, 2003](#)), which have been proposed to explain the nature of these compact objects, enabling a detailed exploration of dense matter physics. The package’s user-friendly interface and modular architecture facilitates a easy adoption and extension, allowing researchers to customize analyses and incorporate new EOSs as they become available. Furthermore, thorough documentation ensures that both novice and experienced users can effectively utilize the tool, promoting widespread accessibility and collaborative advancement in the field. By addressing the need for an integrated, flexible, and well-documented framework, CompactObject enhances the capability of nuclear astrophysicists to derive precise EOS constraints.

The CompactObject Package and scientific use

CompactObject is an open-source software package designed to apply astrophysical and nuclear physics constraints to EOS parameters. Currently, the available EOS options include polytropic EOSs and speed of sound model EOSs, both of which are meta-models. Additionally, the package supports physics-motivated models such as the Relativistic Mean Field (RMF) theory (Todd-Rutel & Piekarewicz, 2005; Tolos et al., 2016, 2017) and its density-dependent variant (Typel & Wolter, 1999; Hempel & Schaffner-Bielich, 2010; Char & Banik, 2014; Char et al., 2023). We have integrated features for users to define the density dependent variant form by themselves, and which span most of the possibility of this family of models. Beyond neutron star EOS models, CompactObject also includes the widely used MIT bag model (Chodos et al., 1974) and a strangeon matter EOS model (Xu, 2003) for quark stars, which are analytical and convenient for statistical analysis. Meanwhile, this package also includes the more advanced quark matter EOS derived from the Nambu-Jona-Lasinio (NJL) model Klevansky (1992); Buballa (2005), which is motivated by the basic symmetries of QCD. The package integrates various likelihood constraints, including routines for simulating mass-radius measurements from X-ray timing observations and analyzing mass-radius likelihoods from actual observational data. It also incorporates constraints from radio timing observations, gravitational wave observations related to tidal deformability, and nuclear physics constraints derived from saturation properties, pQCD Gorda et al. (2023), and χ EFT Hebeler et al. (2013); Huth et al. (2022).

Furthermore, CompactObject includes routines for EOS analysis that output additional properties of neutron stars, such as proton fraction and the number densities of different particles within the star. Other than these, CompactObject synergizes with the CompOSE database, allowing users to derive observational evidence directly into existing EOS models. The nested sampling pipeline implemented in CompactObject is based on UltraNest, providing a computational framework to extract Bayesian evidence for each integrated EOS model. For the inference pipeline, the package offers two sampling algorithm options: UltraNest (nested sampling) and emcee (Markov Chain Monte Carlo sampling)

CompactObject has been utilized to derive constraints on nucleonic RMF models (Huang et al., 2024a) and hyperonic RMF models (Huang et al., 2024b). Ongoing projects include constraining the strangeon star EOS Yuan et al. (2024) and exploring phase transitions and twin stars. Additionally, various nuclear and astrophysical constraints on RMF model with density-dependent couplings and non-linear mesonic terms have been implemented in Malik et al. (2022, 2023); Providência et al. (2023).

The released version of CompactObject is readily accessible through its GitHub repository (Huang et al., 2023) under the MIT license and is archived on Zenodo repository (Huang et al., 2024c). Comprehensive documentation and the complete workflow for implementing EOS inference are available in the GitHub repository. Future plans for CompactObject include expanding the range of available EOS options and conducting a detailed survey of existing EOS models to perform cross-comparisons of Bayesian evidence using current observational and experimental constraints.

Software: Python language (Oliphant, 2007), Numpy (van der Walt et al., 2011), MPI for Python (Dalcín et al., 2008), Numba (Lam et al., 2015), NumbaMinpack (Wogan, 2023), Matplotlib (Hunter, 2007), Jupyter (Kluyver et al., 2016), UltraNest (Buchner, 2021), emcee (Foreman-Mackey et al., 2013), SciPy (Virtanen et al., 2020), Seaborn (Waskom, 2021), corner.py

(Foreman-Mackey, 2016)

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