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

Chun Huang [1], **Tuhin Malik** [2], **João Cartaxo** [2], **Shashwat Sourav** [1], **Wenli Yuan** [3], **Tianzhe Zhou** [4], **Xuezhi Liu**[5], **John Groger** [1], **Nicole Osborn**[1], **Nathan Whitsett**[1], **Xieyuan Dong**[6], **Zhiheng Wang** [1], **Constança Providência** [2], **Micaela Oertel** [7], **Alexander Y. Chen** [1], **Laura Tolos** [10], and **Anna Watts** [11]

1 Physics Department and McDonnell Center for the Space Sciences, Washington University in St. Louis, MO 63130, USA 2 CFisUC, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal 3 School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China 4 Department of Physics, Tsinghua University, Beijing 100084, China 5 Physics Department, Central China Normal University, Luoyu Road, 430030, Wuhan, China 6 School of Physics, Nankai University, Tianjin 300071, China 7 Laboratoire Univers et Théories, CNRS, Observatoire de Paris, Université PSL, Université Paris Cité, 5 place Jules Janssen, 92195 Meudon, France 8 Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Can Magrans, 08193, Barcelona, Spain 9 Institut d'Estudis Espacials de Catalunya (IEEC), 08860 Castelldefels (Barcelona), Spain 10 Frankfurt Institute for Advanced Studies, Ruth-Moufang-Str. 1, 60438 Frankfurt am Main, Germany 11 Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1090 GE Amsterdam, the Netherlands

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 (χEFT). 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 provided seven EOS choices, a Tolman–Oppenheimer–Volkoff (TOV) equation solver, enabling solve Mass Radius and Tidal deformability as observables, and a comprehensive Bayesian inference workflow module, including a whole pipeline of implementing EOS Bayesian inference. Each component can be independently utilized in various scientific research contexts, like nuclear physics and astrophysics. Additionally, CompactObject is designed to synergize with existing software such as CompOSE, enabling the use of the CompOSE EOS database to expand the available EOS options.

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 its core densities exceeding several time 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 and meta-models of neutron star EOSs but also strange star and quark star EOSs, 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 facilitate 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 science 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 Tolos et al. ([2017](#)) and its density-dependent variant Char & Banik ([2014](#)). We 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 a strange star EOS based on the strangeon model (**?**…596L..59X) and the widely used MIT bag model ([Chodos et al., 1974](#)) for quark stars.

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](#)) ([Providência et al., 2023](#)) and χEFT ([Hebeler et al., 2013](#)) ([Huth & others, 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, Raaijmakers, et al., 2024](#)) and hyperonic RMF models \citep([Huang, Tolos, et al., 2024](#)). Ongoing projects include constraining the strangeon star EOS and exploring phase transitions and twin stars. Additionally, various nuclear and astrophysical constraints on RMF model with density-dependent couplings are being developed ([Malik et al., 2022](#))

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, Malick, et al., 2024](#)). 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 (Walt et al., 2011), MPI for Python (Dalcín et al., 2008), Numba (Lam et al., 2015), NumbaMinpack (Wogan, 2023), Matplotlib (Hunter, 2007), Jupyter (?…87K), UltraNest (?….6.3001B), emcee (Foreman-Mackey et al., 2013), SciPy (Virtanen et al., 2020), Seaborn (Waskom, 2021), corner.py (Foreman-Mackey, 2016)

References

Char, P., & Banik, S. (2014). Massive neutron stars with antikaon condensates in a density-dependent hadron field theory. *Physical Review C*, *90*(1). https://doi.org/10.1103/physrevc.90.015801

Chodos, A., Jaffe, R. L., Johnson, K., Thorn, C. B., & Weisskopf, V. F. (1974). New extended model of hadrons. *Phys. Rev. D*, *9*, 3471–3495. https://doi.org/10.1103/PhysRevD.9.3471

Dalcín, L., Paz, R., Storti, M., & D'Elía, J. (2008). MPI for python: Performance improvements and MPI-2 extensions. *Journal of Parallel and Distributed Computing*, *68*(5), 655–662. https://doi.org/https://doi.org/10.1016/j.jpdc.2007.09.005

Foreman-Mackey, D. (2016). Corner.py: Scatterplot matrices in python. *The Journal of Open Source Software*, *1*(2), 24. https://doi.org/10.21105/joss.00024

Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. (2013). <Tt>emcee</tt>: The MCMC hammer. *Publications of the Astronomical Society of the Pacific*, *125*(925), 306–312. https://doi.org/10.1086/670067

Gorda, T., Komoltsev, O., & Kurkela, A. (2023). Ab-initio QCD Calculations Impact the Inference of the Neutron-star-matter Equation of State. *Astrophys. J.*, *950*(2), 107. https://doi.org/10.3847/1538-4357/acce3a

Hebeler, K., Lattimer, J. M., Pethick, C. J., & Schwenk, A. (2013). Equation of state and neutron star properties constrained by nuclear physics and observation. *Astrophys. J.*, *773*, 11. https://doi.org/10.1088/0004-637X/773/1/11

Hempel, M., & Schaffner-Bielich, J. (2010). A statistical model for a complete supernova equation of state. *Nuclear Physics A*, *837*(3–4), 210–254. https://doi.org/10.1016/j.nuclphysa.2010.02.010

139 Huang, C., Malick, T., Cartaxo, J., Sourav, S., Yuan, W., Zhou, T., Liu, X., Groger, J.,
140 Osborn, N., Whitsett, N., Wang, Z., Providência, C., Oertel, M., Chen, A. Y., Tolos, L.,
141 & Watts, A. L. (2023). CompactObject: An open-source package for neutron star whole
142 workflow bayesian nference constraining neutron star EOS package. In *Github repository*.
143 Github. https://github.com/ChunHuangPhy/EoS_inference/tree/v.1.9

144 Huang, C., Malick, T., Cartaxo, J., Sourav, S., Yuan, W., Zhou, T., Liu, X., Groger, J.,
145 Osborn, N., Whitsett, N., Wang, Z., Providência, C., Oertel, M., Chen, A. Y., Tolos, L.,
146 & Watts, A. L. (2024). *ChunHuangPhy/EoS_inference: Compact-object EOS inference*
147 *package (v.1.9)*. Zenodo. https://doi.org/10.5281/zenodo.10927600

148 Huang, C., Raaijmakers, G., Watts, A. L., Tolos, L., & Providência, C. (2024). Constraining a
149 relativistic mean field model using neutron star mass–radius measurements I: nucleonic
150 models. *Mon. Not. Roy. Astron. Soc.*, *529*(4), 4650–4665. https://doi.org/10.1093/
151 mnras/stae844

152 Huang, C., Tolos, L., Providência, C., & Watts, A. (2024). *Constraining a relativistic*
153 *mean field model using neutron star mass-radius measurements II: Hyperonic models*.
154 https://arxiv.org/abs/2410.14572

155 Hunter, J. D. (2007). Matplotlib: A 2D graphics environment. *Computing in Science &*
156 *Engineering*, *9*(3), 90–95. https://doi.org/10.1109/MCSE.2007.55

157 Huth, S., & others. (2022). Constraining Neutron-Star Matter with Microscopic and Macro-
158 scopic Collisions. *Nature*, *606*, 276–280. https://doi.org/10.1038/s41586-022-04750-w

159 Lam, S. K., Pitrou, A., & Seibert, S. (2015). Numba: A LLVM-based python JIT compiler.
160 *Proceedings of the Second Workshop on the LLVM Compiler Infrastructure in HPC*.
161 https://doi.org/10.1145/2833157.2833162

162 Malik, T., Ferreira, M., Agrawal, B. K., & Providência, C. (2022). Relativistic Description
163 of Dense Matter Equation of State and Compatibility with Neutron Star Observables:
164 A Bayesian Approach. *Astrophys. J.*, *930*(1), 17. https://doi.org/10.3847/1538-4357/
165 ac5d3c

166 Oliphant, T. E. (2007). Python for scientific computing. *Computing in Science and Engg.*,
167 *9*(3), 10–20. https://doi.org/10.1109/MCSE.2007.58

168 Providência, C., Malik, T., Albino, M. B., & Ferreira, M. (2023). *Neutron star equation of state:*
169 *identifying hadronic matter characteristics*. https://doi.org/10.1201/9781003306580-5

170 Raaijmakers, G., Rutherford, N., Timmerman, P., Salmi, T., Watts, A. L., Prescod-Weinstein,
171 C., Svensson, I., & Mendes, M. (2023). NEoST: A python package for nested sampling of
172 the neutron star equation of state. *JOSS Submitted*.

173 Tolos, L., Centelles, M., & Ramos, A. (2016). EQUATION OF STATE FOR NUCLEONIC
174 AND HYPERONIC NEUTRON STARS WITH MASS AND RADIUS CONSTRAINTS. *The*
175 *Astrophysical Journal*, *834*(1), 3. https://doi.org/10.3847/1538-4357/834/1/3

176 Tolos, L., Centelles, M., & Ramos, A. (2017). The equation of state for the nucleonic and
177 hyperonic core of neutron stars. *Publications of the Astronomical Society of Australia*, *34*,
178 e065. https://doi.org/10.1017/pasa.2017.60

179 Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D.,
180 Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson,
181 J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., … SciPy
182 1.0 Contributors. (2020). SciPy 1.0: Fundamental Algorithms for Scientific Computing in
183 Python. *Nature Methods*, *17*, 261–272. https://doi.org/10.1038/s41592-019-0686-2

184 Walt, S. van der, Colbert, S. C., & Varoquaux, G. (2011). The NumPy array: A structure
185 for efficient numerical computation. *Computing in Science & Engineering*, *13*(2), 22–30.
186 https://doi.org/10.1109/mcse.2011.37

187 Waskom, M. L. (2021). Seaborn: Statistical data visualization. *Journal of Open Source Software*, *6*(60), 3021. https://doi.org/10.21105/joss.03021

189 Wogan, N. (2023). *NumbaMinpack*. https://github.com/Nicholaswogan/NumbaMinpack.