The Journal of Open Source Software

METISSE: METhod of Interpolation for Single Star Evolution

Poojan Agrawal [1], **Katelyn Breivik** [3], **Jarrod Hurley** [4,5], **Carl Rodriguez** [2], **Simon Stevenson** [4,5], **Alex Kemp** [1], and **Dorottya Szécsi** [6]

1 Institute of Astronomy, KU Leuven, Celestijnenlaan 200D, B-3001, Leuven, Belgium **2** Department of Physics and Astronomy, University of North Carolina at Chapel Hill, 120 E. Cameron Avenue, Chapel Hill, NC 27599, USA **3** McWilliams Center for Cosmology & Astrophysics, Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA **4** Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, VIC 3122, Australia **5** OzGrav-The ARC Centre of Excellence for Gravitational Wave Discovery, Hawthorn, VIC 3122, Australia **6** Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100, Torun, Poland

DOI: 10.21105/joss.08817

Software

- Review
- Repository
- Archive

Editor: Josh Borrow

Reviewers:

- @ddhendriks
- @TomWagg

Submitted: 28 February 2025
Published: 14 December 2025

Summary

METISSE is an open-source stellar evolution tool specifically designed to be integrated with binary evolution and population synthesis codes. Unlike traditional rapid stellar evolution schemes based on fitting formulae (e.g. SSE, Hurley et al., 2000), METISSE interpolates between pre-computed stellar models to quickly derive stellar parameters for population synthesis codes. This approach makes it straightforward to incorporate the latest stellar models and explore the effects of different input physics. METISSE can be easily integrated with any population synthesis code that currently uses the popular Fortran code SSE to calculate stellar parameters. While METISSE can also be used in standalone mode to evolve single stellar populations, its primary purpose is to act as an interpolation engine within existing population synthesis codes for modelling binary stars and star clusters. Written in modern Fortran, METISSE is both fast and robust, making it well-suited for large-scale population studies that require realistic stellar evolution input. The full documentation for METISSE is available at metisse.readthedocs.io.

Statement of need

Stars, especially those with masses greater than eight solar masses (massive stars), play a pivotal role in shaping stellar populations. The best way of computing stellar evolution involves solving equations of stellar structure and evolution through detailed stellar evolution codes such as MESA (Jermyn et al., 2023). One drawback is that the inherent uncertainties in stellar evolution cause stellar codes to adopt different physical inputs, leading to significant differences in the predictions for the evolution of stars and stellar populations (Agrawal et al., 2022). Moreover, computational requirements and robustness issues render these codes impractical for direct use in large population synthesis simulations.

Rapid stellar evolution codes such as SSE (Hurley et al., 2000), which rely on fitting formulae manually calibrated to specific stellar models, have long provided a fast and efficient way to calculate stellar population properties. However, because the formulae must be recalculated manually for each new set of stellar models, they cannot be easily updated to incorporate advances in stellar evolution, limiting their flexibility and applicability to modern studies.

In recent years, interpolation-based rapid stellar evolution codes such as TRILEGAL (Girardi et al., 2005), ComBinE (Kruckow et al., 2018), SEVN (Iorio et al., 2023), and MINT (Rees et al., 2025), along with machine-learning–based frameworks like POSYDON (Fragos et al., 2023), have become increasingly common as alternatives to SSE. However, these tools can not be easily incorporated into existing frameworks: binary population codes such as BSE (Hurley et al., 2002) and COSMIC (Breivik et al., 2020), or star cluster codes such as CMC (Rodriguez et al., 2022) and NBODY6 (Aarseth, 2003), that continue to rely on standard SSE routines.

METISSE matches other interpolation-based codes in performance and includes SSE-style subroutines for easy integration into existing binary and population synthesis frameworks, with full Fortran 77 compatibility. It comes with an example set of MESA stellar models and can also use other published grids, such as MIST (Choi et al., 2016) and BoOST (Szécsi et al., 2022). Its interpolation framework allows stellar model grids to be swapped easily and explore how stellar parameters affect population outcomes. METISSE thus provides a flexible and efficient framework for stellar evolution calculations in population synthesis, offering greater flexibility than fitting formulae without the computational cost of full stellar structure models.

METISSE has already been employed in several scientific publications. For instance, it has been used to demonstrate the impact of core overshooting—one of the major uncertainties in stellar evolution—on the evolutionary outcomes of binary systems (Agrawal et al., 2023). Additionally, it has been used with stellar models from MESA as well as models from the Bonn Code (via the BoOST project, Szécsi et al., 2022) to conduct a systematic study study of how different physical parameters affect the evolutionary properties of massive single stars (Agrawal et al., 2020).

Multiple ongoing projects use METISSE alongside the binary population synthesis code COSMIC (Breivik et al., 2020) to investigate the population properties of black-hole-X-ray binaries, LISA white dwarf binaries, and GAIA black hole-star systems. In the era of big-data astronomy, driven by high-quality observational data from both ground-based and space-based telescopes, as well as gravitational wave and multi-messenger detectors, METISSE facilitates the seamless incorporation of updates in stellar evolution into simulations that model stellar populations and their interactions.

Acknowledgements

We thank Duncan Maclean, Christopher Crow, Runqiu Ye, and Steven Rieder for their help with testing METISSE. PA acknowledges support from the European Research Council (ERC) under the Horizon Europe programme (Synergy Grant agreement 101071505: 4D-STAR). While partially funded by the European Union, views and opinions expressed are however those of the author only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. PA, JH and SS acknowledge support from the Australian Research Council Centre of Excellence for Gravitational Wave Discovery (OzGrav), through project numbers CE170100004 and CE230100016. CR acknowledges support from the Alfred P. Sloan Foundation and the David and Lucile Packard Foundation. AK acknowledges financial support from the Flemish Government under the long-term structural Methusalem funding program by means of the project SOUL: Stellar evolution in full glory, grant METH/24/012 at KU Leuven. SS is supported by the ARC Discovery Early Career Research Award DE220100241. DSz acknowledges support from the National Science Center (NCN), Poland under grant number OPUS 2021/41/B/ST9/00757.

References

Aarseth, S. J. (2003). *Gravitational N-body simulations: Tools and algorithms*. Cambridge University Press. https://doi.org/10.1017/CBO9780511535246

Agrawal, P., Hurley, J., Stevenson, S., Rodriguez, C. L., Szécsi, D., & Kemp, A. (2023). Modelling stellar evolution in mass-transferring binaries and gravitational-wave progenitors with METISSE. *Monthly Notices of the Royal Astronomical Society*, *525*(1), 933–951. https://doi.org/10.1093/mnras/stad2334

Agrawal, P., Hurley, J., Stevenson, S., Szécsi, D., & Flynn, C. (2020). The fates of massive stars: Exploring uncertainties in stellar evolution with METISSE. *Monthly Notices of the Royal Astronomical Society*, *497*(4), 4549–4564. https://doi.org/10.1093/mnras/staa2264

Agrawal, P., Szécsi, D., Stevenson, S., Eldridge, J. J., & Hurley, J. (2022). Explaining the differences in massive star models from various simulations. *Monthly Notices of the Royal Astronomical Society*, *512*(4), 5717–5725. https://doi.org/10.1093/mnras/stac930

Breivik, K., Coughlin, S., Zevin, M., Rodriguez, C. L., Kremer, K., Ye, C. S., Andrews, J. J., Kurkowski, M., Digman, M. C., Larson, S. L., & Rasio, F. A. (2020). COSMIC variance in binary population synthesis. *The Astrophysical Journal*, *898*(1), 71. https://doi.org/10.3847/1538-4357/ab9d85

Choi, J., Dotter, A., Conroy, C., Cantiello, M., Paxton, B., & Johnson, B. D. (2016). Mesa Isochrones and Stellar Tracks (MIST). I. Solar-scaled models. *The Astrophysical Journal*, *823*, 102. https://doi.org/10.3847/0004-637X/823/2/102

Fragos, T., Andrews, J. J., Bavera, S. S., Berry, C. P. L., Coughlin, S., Dotter, A., Giri, P., Kalogera, V., Katsaggelos, A., Kovlakas, K., Lalvani, S., Misra, D., Srivastava, P. M., Qin, Y., Rocha, K. A., Román-Garza, J., Serra, J. G., Stahle, P., Sun, M., … Zevin, M. (2023). POSYDON: A general-purpose population synthesis code with detailed binary-evolution simulations. *The Astrophysical Journal Supplement Series*, *264*(2), 45. https://doi.org/10.3847/1538-4365/ac90c1

Girardi, L., Groenewegen, M. A. T., Hatziminaoglou, E., & da Costa, L. (2005). Star counts in the Galaxy. Simulating from very deep to very shallow photometric surveys with the TRILEGAL code. *Astronomy & Astrophysics*, *436*(3), 895–915. https://doi.org/10.1051/0004-6361:20042352

Hurley, J. R., Pols, O. R., & Tout, C. A. (2000). Comprehensive analytic formulae for stellar evolution as a function of mass and metallicity. *Monthly Notices of the Royal Astronomical Society*, *315*(3), 543–569. https://doi.org/10.1046/j.1365-8711.2000.03426.x

Hurley, J. R., Tout, C. A., & Pols, O. R. (2002). Evolution of binary stars and the effect of tides on binary populations. *Monthly Notices of the Royal Astronomical Society*, *329*(4), 897–928. https://doi.org/10.1046/j.1365-8711.2002.05038.x

Iorio, G., Mapelli, M., Costa, G., Spera, M., Escobar, G. J., Sgalletta, C., Trani, A. A., Korb, E., Santoliquido, F., Dall'Amico, M., Gaspari, N., & Bressan, A. (2023). Compact object mergers: Exploring uncertainties from stellar and binary evolution with SEVN. *Monthly Notices of the Royal Astronomical Society*, *524*(1), 426–470. https://doi.org/10.1093/mnras/stad1630

Jermyn, A. S., Bauer, E. B., Schwab, J., Farmer, R., Ball, W. H., Bellinger, E. P., Dotter, A., Joyce, M., Marchant, P., Mombarg, J. S. G., Wolf, W. M., Sunny Wong, T. L., Cinquegrana, G. C., Farrell, E., Smolec, R., Thoul, A., Cantiello, M., Herwig, F., Toloza, O., … Timmes, F. X. (2023). Modules for Experiments in Stellar Astrophysics (MESA): Time-dependent convection, energy conservation, automatic differentiation, and infrastructure. *The Astrophysical Journal Supplement Series*, *265*(1), 15. https://doi.org/10.3847/1538-4365/acae8d

Kruckow, M. U., Tauris, T. M., Langer, N., Kramer, M., & Izzard, R. G. (2018). Progenitors of gravitational wave mergers: Binary evolution with the stellar grid-based code ComBinE. *Monthly Notices of the Royal Astronomical Society*, *481*, 1908–1949. https://doi.org/10.1093/mnras/sty2190

Rees, N. R., Izzard, R. G., & Hendriks, D. D. (2025). A stellar evolutionary grid for binary population synthesis: From the main sequence to helium ignition. *arXiv e-Prints*, arXiv:2503.17772. https://doi.org/10.48550/arXiv.2503.17772

Rodriguez, C. L., Weatherford, N. C., Coughlin, S. C., Amaro-Seoane, P., Breivik, K., Chatterjee, S., Fragione, G., Kıroğlu, F., Kremer, K., Rui, N. Z., Ye, C. S., Zevin, M., & Rasio, F. A. (2022). Modeling dense star clusters in the Milky Way and beyond with the Cluster Monte Carlo code. *The Astrophysical Journal Supplement Series*, *258*(2), 22. https://doi.org/10.3847/1538-4365/ac2edf

Szécsi, D., Agrawal, P., Wünsch, R., & Langer, N. (2022). Bonn Optimized Stellar Tracks (BoOST). Simulated populations of massive and very massive stars for astrophysical applications. *Astronomy & Astrophysics*, *658*, A125. https://doi.org/10.1051/0004-6361/202141536