The Journal of Open Source Software

COMPAS: A rapid binary population synthesis suite

Team COMPAS[1], Jeff Riley[2,3], Poojan Agrawal[4,3], Jim W. Barrett[5], Kristian N. K. Boyett[6], Floor S. Broekgaarden[7], Debatri Chattopadhyay[8,4,3], Sebastian M. Gaebel[9], Fabian Gittins[10], Ryosuke Hirai[2,3], George Howitt[11], Stephen Justham[12,13,14], Lokesh Khandelwal[12], Floris Kummer[12], Mike Y. M. Lau[2,3], Ilya Mandel[2,3,5], Selma E. de Mink[14,12,7], Coenraad Neijssel[5,3], Tim Riley[2,3], Lieke van Son[7,12,14], Simon Stevenson[4,3], Alejandro Vigna-Gómez[15,16], Serena Vinciguerra[12], Tom Wagg[7,14], and Reinhold Willcox[2,3]

1 The public COMPAS code is a product of work by the entire COMPAS collaboration over many years; we therefore kindly request that, in recognition of this team effort, the paper is cited as Team COMPAS - J. Riley et al. **2** School of Physics and Astronomy, Monash University, Clayton, Victoria 3800, Australia **3** OzGrav, Australian Research Council Centre of Excellence for Gravitational Wave Discovery, Australia **4** Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, VIC 3122, Australia **5** Institute of Gravitational Wave Astronomy and School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT **6** Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK **7** Center for Astrophysics |Harvard & Smithsonian, 60 Garden St., Cambridge, MA 02138, USA **8** School of Physics and Astronomy, Cardiff University, Cardiff, CF24 3AA, United Kingdom **9** Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Callinstrasse 38, D-30167 Hannover, Germany **10** Mathematical Sciences and STAG Research Centre, University of Southampton, Southampton SO17 1BJ, UK **11** School of Physics, University of Melbourne, Parkville, Victoria, 3010, Australia **12** Anton Pannekoek Institute of Astronomy and GRAPPA, Science Park 904, University of Amsterdam, 1098XH Amsterdam, The Netherlands **13** School of Astronomy & Space Science, University of the Chinese Academy of Sciences, Beijing 100012, China **14** Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany **15** DARK, Niels Bohr Institute, University of Copenhagen, Jagtvej 128, 2200, Copenhagen, Denmark **16** Niels Bohr International Academy, The Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark

DOI: 10.21105/joss.03838

Software

- Review
- Repository
- Archive

Editor: Christina Hedges

Reviewers:

- @katiebreivik
- @HeloiseS

Submitted: 12 October 2021
Published: 06 November 2021

In partnership with

AMERICAN ASTRONOMICAL SOCIETY

This article and software are linked with research article DOI

Summary

Most massive stars—those with initial masses greater than 8 $M_\odot$—are born with another massive star as a companion (Moe & Di Stefano, 2017; Sana et al., 2012). Massive binary stars are responsible for producing many exotic astrophysical phenomena, such as the observed diversity of supernovae, binary pulsars, X-ray binaries and merging compact objects. The latter are now regularly observed by the ground-based gravitational wave observatories Advanced LIGO and Virgo (B. P. Abbott et al., 2016; R. Abbott et al., 2020). Population models of massive binary evolution make it possible to interpret existing observations and to make predictions for future observing campaigns.

Statement of need

Binary population synthesis generates population models of isolated stellar binaries under a set of parametrized assumptions. These models permit comparisons against observational data sets, such as X-ray binaries of gravitational-wave mergers.

In particular, rapid binary population synthesis is needed in order to efficiently explore a broad parameter space of uncertain assumptions about the physics of stellar and binary evolution, including supernova remnant masses and natal kicks, mass transfer efficiency and stability, and the outcome of common-envelope events.

A range of binary population synthesis codes have been developed over the last three decades. These include the Scenario Machine (Lipunov et al., 1996), IBiS (Tutukov & Yungelson, 1996), SeBa (**Seba?**), BSE (Hurley et al., 2002), StarTrack (Belczynski et al., 2008), binary_c (Izzard et al., 2004), MOBSE (Giacobbo et al., 2018) and COSMIC (Breivik et al., 2020). These codes range from private to semi-public to fully public, and differ in the range of available tools, computational complexity, and speed of execution.

COMPAS is a rapid binary population synthesis suite. It parametrizes complex astrophysical processes with prescriptions calibrated to detailed models. COMPAS is designed to allow for flexible modifications as evolutionary models improve. All code is fully public and, including pre-processing and post-processing tools. COMPAS is computationally efficient, with a focus on the statistical analysis of large populations, particularly but not exclusively in the context of gravitational-wave astronomy.

Details

The core engine of COMPAS—responsible for calculating the evolution of single (Hurley et al., 2000) and binary (Hurley et al., 2002) stars—is written in object oriented C++ for speed and flexibility. COMPAS is able to simulate the evolution of a typical binary over 10 Gyr in approximately 10 milliseconds.

A detailed description of the implementation of the COMPAS suite can be found in Team COMPAS: Riley et al. (2021).

In addition to the core stellar and binary evolution engine, we provide Python scripts for both pre- and post-processing COMPAS outputs. Post-processing can account for integrating populations formed throughout cosmic history (Neijssel et al., 2019) and methods to account for gravitational-wave selection effects (Barrett et al., 2018). A set of examples is also provided.

COMPAS is *embarrassingly* parallel and can be trivially run on high performance computers and distributed on cloud computing.

COMPAS was initially designed to focus on studies of merging binaries containing neutron stars and black holes that are being observed through gravitational waves (Stevenson et al., 2017; Vigna-Gómez et al., 2018). In recent years, the scope of systems investigated with COMPAS has expanded to incorporate, e.g., Be X-ray binaries (Vinciguerra et al., 2020) and luminous red novae (Howitt et al., 2020) (see Team COMPAS: Riley et al. (2021) or the COMPAS collaboration website for a summary of COMPAS publications to date.)

COMPAS development happens on Github. We maintain a Zenodo community where data from many publications using COMPAS is publicly available.

Acknowledgements

Multiple authors are supported by the Australian Research Council Centre of Excellence for Gravitational Wave Discovery (OzGrav), through project number CE170100004. Multiple authors were funded in part by the National Science Foundation under Grant No. (NSF grant number 2009131), the Netherlands Organization for Scientific Research (NWO) as part of the Vidi research program BinWaves with project number 639.042.728 and by the European

Union's Horizon 2020 research and innovation program from the European Research Council (ERC, Grant agreement No. 715063). FSB is supported in part by the Prins Bernard Cultuurfonds studiebeurs. IM is a recipient of an Australian Research Council Future Fellowship (FT190100574). AVG acknowledges funding support by the Danish National Research Foundation (DNRF132)

References

Abbott, B. P., Abbott, R., Abbott, T., Abernathy, M., Acernese, F., Ackley, K., Adams, C., Adams, T., Addesso, P., Adhikari, R., & others. (2016). Observation of gravitational waves from a binary black hole merger. *Physical Review Letters*, *116*(6), 061102.

Abbott, R., Abbott, T. D., Abraham, S., Acernese, F., & others. (2020). GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run. *arXiv e-Prints*, arXiv:2010.14527. http://arxiv.org/abs/2010.14527

Barrett, J. W., Gaebel, S. M., Neijssel, C. J., Vigna-Gomez, A., Stevenson, S., Berry, C. P. L., Farr, W. M., & Mandel, I. (2018). Accuracy of inference on the physics of binary evolution from gravitational-wave observations. *Mon. Not. Roy. Astron. Soc.*, *477*(4), 4685–4695. https://doi.org/10.1093/mnras/sty908

Belczynski, K., Kalogera, V., Rasio, F. A., Taam, R. E., Zezas, A., Bulik, T., Maccarone, T. J., & Ivanova, N. (2008). Compact Object Modeling with the StarTrack Population Synthesis Code. *174*(1), 223–260. https://doi.org/10.1086/521026

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. *898*(1), 71. https://doi.org/10.3847/1538-4357/ab9d85

Giacobbo, N., Mapelli, M., & Spera, M. (2018). Merging black hole binaries: the effects of progenitor's metallicity, mass-loss rate and Eddington factor. *474*, 2959–2974. https://doi.org/10.1093/mnras/stx2933

Howitt, G., Stevenson, S., Vigna-Gómez, A. ro, Justham, S., Ivanova, N., Woods, T. E., Neijssel, C. J., & Mandel, I. (2020). Luminous Red Novae: population models and future prospects. *492*(3), 3229–3240. https://doi.org/10.1093/mnras/stz3542

Hurley, J. R., Pols, O. R., & Tout, C. A. (2000). Comprehensive analytic formulae for stellar evolution as a function of mass and metallicity. *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. *329*(4), 897–928. https://doi.org/10.1046/j.1365-8711.2002.05038.x

Izzard, R. G., Tout, C. A., Karakas, A. I., & Pols, O. R. (2004). A new synthetic model for asymptotic giant branch stars. *350*, 407–426. https://doi.org/10.1111/j.1365-2966.2004.07446.x

Lipunov, V. M., Postnov, K. A., & Prokhorov, M. E. (1996). The Scenario Machine: restrictions on key parameters of binary evolution. *310*, 489–507.

Moe, M., & Di Stefano, R. (2017). Mind Your Ps and Qs: The Interrelation between Period (P) and Mass-ratio (Q) Distributions of Binary Stars. *230*(2), 15. https://doi.org/10.3847/1538-4365/aa6fb6

Neijssel, C. J., Vigna-Gómez, A., Stevenson, S., Barrett, J. W., Gaebel, S. M., Broekgaarden, F. S., de Mink, S. E., Szécsi, D., Vinciguerra, S., & Mandel, I. (2019). The effect of the metallicity-specific star formation history on double compact object mergers. *490*(3), 3740–3759. https://doi.org/10.1093/mnras/stz2840

Sana, H., de Mink, S. E., de Koter, A., Langer, N., Evans, C. J., Gieles, M., Gosset, E., Izzard, R. G., Le Bouquin, J.-B., & Schneider, F. R. N. (2012). Binary Interaction Dominates the Evolution of Massive Stars. *Science*, *337*, 444. https://doi.org/10.1126/science.1223344

Stevenson, S., Vigna-Gómez, A., Mandel, I., Barrett, J. W., Neijssel, C. J., Perkins, D., & de Mink, S. E. (2017). Formation of the first three gravitational-wave observations through isolated binary evolution. *Nature Communications*, *8*, 14906. https://doi.org/10.1038/ncomms14906

Team COMPAS: Riley, J., Agrawal, P., Barrett, J. W., Boyett, K. N. K., Broekgaarden, F. S., Chattopadhyay, D., Gaebel, S. M., Gittins, F., Hirai, R., Howitt, G., Justham, S., Khandelwal, L., Kummer, F., Lau, M. Y. M., Mandel, I., de Mink, S. E., Neijssel, C., Riley, T., van Son, L., … Willcox, R. (2021). Rapid stellar and binary population synthesis with COMPAS. *arXiv e-Prints*, arXiv:2109.10352. http://arxiv.org/abs/2109.10352

Tutukov, A., & Yungelson, L. (1996). Double-degenerate semidetached binaries with helium secondaries: cataclysmic variables, supersoft X-ray sources, supernovae and accretion-induced collapses. *280*(4), 1035–1045. https://doi.org/10.1093/mnras/280.4.1035

Vigna-Gómez, A., Neijssel, C. J., Stevenson, S., Barrett, J. W., Belczynski, K., Justham, S., de Mink, S. E., Müller, B., Podsiadlowski, P., Renzo, M., Szécsi, D., & Mandel, I. (2018). On the formation history of Galactic double neutron stars. *481*, 4009–4029. https://doi.org/10.1093/mnras/sty2463

Vinciguerra, S., Neijssel, C. J., Vigna-Gómez, A., Mandel, I., Podsiadlowski, P., Maccarone, T. J., Nicholl, M., Kingdon, S., Perry, A., & Salemi, F. (2020). Be X-ray binaries in the SMC as indicators of mass-transfer efficiency. *498*(4), 4705–4720. https://doi.org/10.1093/mnras/staa2177