The Journal of Open Source Software

TSE: A triple stellar evolution code

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DOI: 10.21105/joss.07102

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Editor: Warrick Ball

Reviewers:

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Submitted: 17 July 2024
Published: 24 October 2024

Summary

Most massive stars are found in hierarchical triples or higher multiplicity systems in which a close inner binary is orbited by one or more distant companions (Moe & Di Stefano, 2017). A distant companion may significantly alter the evolution of the system by causing large-amplitude oscillations of the inner binary eccentricity (so-called von Zeipel-Kozai-Lidov oscillations; Naoz, 2016). These oscillations determine how close the inner binary stars pass each other at periapsis and are therefore essential for our understanding of interactions between massive binary stars (Sana et al., 2012) as well as their compact remnants. Understanding the role of tertiary companions for the evolution of massive stars requires an efficient numerical tool to simulate the complex interplay between the dynamics of hierarchical triples and their stellar evolution.

Statement of need

The evolutionary pathways of hierarchical stellar triples are determined by their gravitational three-body dynamics and the stellar physics that describes the changes in mass, radius, chemical composition, etc. as a function of time. In hierarchical triples, both aspects are closely intertwined. On the one hand, stellar effects such as mass-loss due to stellar winds, tidal forces between the stars, and natal kicks during a supernova explosion may alter the orbital evolution of a triple. On the other hand, the gravitational perturbation from a tertiary companion gives rise to large-amplitude oscillations of the inner binary eccentricity. Thus, by effectively reducing the periapsis of the inner binary stars it may facilitate the occurrence of a mass-transfer episode or stellar merger between them, or, if the inner binary stars developed compact remnants (black holes or neutron stars), promotes a gravitational-wave-driven inspiral. Various aspects of this complex interplay between dynamics and stellar physics of triples have been studied in previous work, yet computational tools that aim to recover the evolutionary plethora of stellar triples within one self-consistent framework are sparse.

`TSE` is a Python code to evolve hierarchical stellar triples by simultaneously taking into account the gravitational dynamics and the stellar physics. At its core, the secular equations of motions for the orbital elements of the inner and outer orbits (Liu et al., 2015) and the spin vectors of the inner binary stars (Hamers et al., 2021) are evolved using the initial value problem (IVP) solver implemented in `scipy.integrate`. Since it is a secular code, i.e., it employs the orbit-averaged equations of motion (as opposed to a direct N-body integrator), it is fast enough to be used as a population synthesis code. Optionally, TSE follows the trajectory of the triple barycentre throughout the Milky Way and includes the perturbative effect of Galactic tides on the orbital elements of the inner and outer binary (Bub & Petrovich, 2020; Stegmann et al., 2024). The evolution of stellar properties such as masses and radii are followed by using the stellar evolution code `MOBSE` (Giacobbo et al., 2018; Giacobbo & Mapelli, 2018) which builds upon the binary stellar evolution code `BSE` written in Fortran (Hurley et al., 2000, 2002). While integrating the equations of motion `TSE` constantly checks for events such as Roche-lobe overflow, supernova explosions, stellar or compact object mergers, orbital disruptions and other user-defined custom events. In either case, TSE either models the impact of the event on the triple, e.g., by simulating the result of Roche-lobe overflow using MOBSE, or terminates the evolution and stores the final outcome.

TSE was designed to study the impact of a tertiary companion on massive stellar evolution, and has been already used in a number of scientific publications (Stegmann, Antonini, Schneider, et al., 2022; Stegmann, Antonini, & Moe, 2022). While previous work mostly focused on the long-term evolution of black hole triples towards gravitational-wave sources (e.g., Rodriguez & Antonini, 2018), already including the dynamical effect of a tertiary companion during the lifetime of the progenitors has been largely neglected. Thus, TSE can be used to investigate the role of tertiary companions for a range of massive star phenomena, such as X-ray binaries, stellar mergers, and gravitational-wave sources. There are only few other codes published which combine the dynamical evolution of triples with that of stars in a comparable way than TSE (e.g. TRES, Toonen et al., 2016; MSE, Hamers et al., 2021). Comparing the outcomes of the codes will be an essential part in order to understand how different model assumptions determine the evolution of stellar triples.

Acknowledgements

We acknowledge contributions from Jordan Barber in reviewing and testing the code and support from Michela Mapelli and Max Moe during the genesis of this project. We thank the referees Katelyn Breivik and Steven Rieder and the editor Warrick Ball for improving the code and paper during the JOSS review. This work was largely carried out at Cardiff University and was funded by the STFC grants ST/V005618/1 and ST/P00492X/2, and in parts by the Netherlands Organisation for Scientific Research (NWO), as part of the Vidi research program BinWaves (project number 639.042.728, PI: de Mink). We acknowledge the support of the Supercomputing Wales project, which is part-funded by the European Regional Development Fund (ERDF) via Welsh Government.

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