LEGWORK: A python package for computing the evolution and detectability of stellar-origin gravitational-wave sources with space-based detectors

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Summary

LEGWORK (LISA Evolution and Gravitational Wave Orbit Kit) is an open-source Python package for making predictions about stellar-origin gravitational wave sources and their detectability in LISA or other space-based gravitational wave detectors. LEGWORK can be used to evolve the orbits of sources due to gravitational wave emission, calculate gravitational wave strains (using post-Newtonian approximations), compute signal-to-noise ratios and visualise the results. It can be applied to a variety of potential sources, including binaries consisting of white dwarfs, neutron stars and black holes. Although we focus on double compact objects, in principle LEGWORK can be used for any system with a user-specified orbital evolution, such as those affected by a third object or gas drag. We optimised the package to make it efficient for use in population studies which can contain tens-of-millions of sources. We hope that LEGWORK will enable and accelerate future studies triggered by the rapidly growing interest in gravitational wave sources. This paper is jointly submitted to ApJ, see Wagg et al. (2021).

Statement of need

The planned space-based gravitational wave detector LISA (Laser Interferometer Space Antenna, Amaro-Seoane et al. (2017)) will present an entirely new view of gravitational waves by focusing on lower frequencies ($10^{-5} < f/\,\mathrm{Hz} < 10^{-1}$) than ground-based detectors. This will enable the study of many new source classes including mergers of supermassive black holes (e.g. Begelman et al. (1980); Klein et al. (2016); Bellovary et al. (2019)), extreme mass ratio inspirals (e.g. Berti et al. (2006); Barack & Cutler (2007); Babak et al. (2017); Moore+2017), and cosmological GW backgrounds (e.g. Bartolo et al. (2016); Caprini et al. (2016); Caldwell et al. (2019)). However, this frequency regime is also of interest for the detection of local stellar-mass binaries during their inspiral phase. LISA is expected to detect Galactic stellar-origin binaries containing combinations of white dwarfs, neutron stars, and black holes, ranging from the numerous double white dwarf population, to the rare but loud double black hole population.

The potential to detect stellar-origin sources with LISA has been studied in the past (e.g. Nelemans et al. (2001); Liu (2009); Liu & Zhang (2014); Ruiter et al. (2010); Belczynski et al. (2010); Nissanke et al. (2012)). More recently, the direct detection of gravitational waves with ground-based detectors (Abbott et al., 2016) has led to renewed interest in this topic with many recent papers addressing the issue (e.g. Christian & Loeb (2017); Kremer et al. (2017); Kremer et al. (2018); Korol et al. (2017); Korol et al. (2018); Korol et al. (2019); Korol et al. (2020); Lamberts et al. (2018); Lamberts et al. (2019); Fang et al. (2019);

Andrews et al. (2020); Lau et al. (2020); Breivik, Coughlin, et al. (2020); Breivik, Mingarelli, et al. (2020); Roebber et al. (2020); Chen et al. (2020); Sesana et al. (2020); Shao & Li (2021)).

Each of these studies require making estimates of the signal-to-noise ratio of individual binary systems and possibly the slow gravitational wave inspiral that lead to the present-day parameters. So far, most studies made use of custom made codes which have not been made publicly available.

We believe that the large renewed interest in LISA and the stellar-origin sources it may detect will lead to many more studies in the near future that would need similar computations. This leads to a significant amount of redundancy which, at best results in extra work for each individual and at worst leads to an increased chance of introducing mistakes and inconsistencies when translating the necessary expressions to software.

LEGWORK is a Python package designed to streamline the process of making predictions of LISA detection rates for stellar-origin binaries such that it is as fast, reliable and simple as possible. This goal makes LEGWORK unique among other implementations of gravitational-wave tools in the literature, which focus on a more broad coverage of the gravitational-wave spectrum and source classes, rather than an optimised approach for certain sources (e.g. Moore et al. (2015); Yi et al. (2021)). With LEGWORK one can evolve the orbits of a binary or a collection of binaries and calculate their strain amplitudes for any range of frequency harmonics. One can compute the sensitivity curve for LISA or other future gravitational wave detectors (e.g. TianQin (Luo et al., 2016), or a user-defined custom instrument) and use it to compute the signal-to-noise ratio of a collection of sources. Furthermore, LEGWORK provides tools to visualise all of the results with easy-to-use plotting functions. Finally, LEGWORK is fully tested to check for consistency in the derivations described in the ApJ paper (Wagg et al., 2021).

Specifically, we implement the expressions by Peters & Mathews (1963) and Peters (1964) for the evolution of binary orbits due to the emission of gravitational waves, equations for the strain amplitudes and signal-to-noise ratios of binaries from various papers (e.g. Flanagan & Hughes (1998); Finn & Thorne (2000); Cornish & Larson (2003); Barack & Cutler (2004); Moore et al. (2015)) and approximations for the LISA and TianQin sensitivity curves given in Robson et al. (2019) and Huang et al. (2020) respectively. This lowest-order post-Newtonian implementation of gravitational radiation does not include the effects of higher-order terms in the post-Newtonian expansion, including spin-orbit coupling or radiation reaction. The strain calculations in LEGWORK also incorporate averages over the detector motion as well as sky position and inclination in order to remain completely analytically solvable. Work which requires the incorporation of a full LISA detector simulation should consider tools like lisacattools or ldasoft (Littenberg et al., 2020). For non-stellar-origin sources, tools like the Gravitational Wave Universe Toolbox are more appropriate (Yi et al., 2021).

The open-source nature of the project means that new users as well as seasoned experts in the field can work together in a collaborative setting to consider new features and enhancements to the package as well as check the implementation. At the same time, with our thorough online documentation, derivations and tutorials, we hope LEGWORK can make this functionality more accessible to the broader scientific community.

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