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Dyad: a binary-star dynamics and statistics library for Python

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Software

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Summary

Dyad is a Python library for studying the dynamics of binary stars considered as gravitational two-body systems. By convention, astrophysicists designate the brighter of the two components of a binary star as a reference body, which they call the 'primary star', and the dimmer of the two components as a subject body, which they call the 'secondary star'. In a frame centred on the primary star, the secondary star then moves on an elliptical orbit with one focus located at the origin. This orbit can be specified by its orbital elements, namely the semimajor axis (which specifies the size of the ellipse), eccentricity (which specifies the shape of the ellipse), and true anomaly (which specifies the secondary star's location on the ellipse) along with the longitude of its ascending node, its inclination, and its argument of pericentre (which together specify the orientation of the ellipse).

The dynamics of the system are completely determined by the two stars' masses and the secondary star's orbital elements. In a population of binary stars these eight parameters vary from member to member and can each be treated as a random variable having some probability distribution. Dyad provides a class, `dyad.TwoBody`, and a module, `dyad.stats`, for dealing with such a population of binary stars. The `dyad.TwoBody` class represents a gravitational two-body system while the `dyad.stats` module provides a suite of classes representing the probability distributions of stellar mass, mass ratio, and orbital elements. Dyad implements these probability distributions in the same way that SciPy (Virtanen et al., 2020) implements its probability distributions (see, for example, `scipy.stats.norm`, `scipy.stats.lognorm`, or `scipy.stats.expon`).

You can initialize `dyad.TwoBody` by specifying the primary and secondary bodies' masses together with the secondary body's orbital elements and then use that class's methods to compute the two bodies' angular momenta, total energies, and eccentricity vectors as well as positions, velocities, kinetic energies, and potential energies either in the primary star's frame or the centre-of-mass frame. The `dyad.stats` module includes (but is not limited to) classes representing the probability distributions of (1) stellar masses as proposed by Kroupa (2001) and Salpeter (1955), and (2) the mass ratios and orbital elements of binary stars as proposed by Duquennoy & Mayor (1991) and Moe & Di Stefano (2017). You can use it to evaluate the probability density functions, cumulative distribution functions, and inverse cumulative distribution functions of these quantities, as well as to compute their moments, i.e. their means, variances, skewnesses, *etc.* Most importantly, you can use `dyad.stats` to generate samples of these quantities. By using `dyad.TwoBody` and `dyad.stats` together you can therefore generate a custom representation of a population of binary stars.

Statement of need

I wrote Dyad to perform the work on binary-star population dynamics that my colleagues and I presented in Gration et al. (2025). Galactic dynamicists typically treat a galaxy as a population of single stars moving in the gravitational potential generated by those stars together with a halo of dark matter. They construct a model of its kinematics (say, a model of the probability density of its stars' positions and velocities) which they then fit to observations (say, those stars' on-sky positions and line-of-sight velocities) in order to infer the physical properties of that galaxy, for example its total mass. However, a large number of stars are binary, meaning that these models are misspecified since the kinematics of stars in a binary-rich galaxy are different from those in a binary-free galaxy. If observations contain binary stars then these inferences will be wrong. The error will be small for large disc galaxies but will be large for small spheroidal galaxies. For these small spheroidal galaxies the total mass is always proportional to the velocity dispersion and in our paper my colleagues and I quantified the error in the inferred galactic mass by constructing the velocity distribution using Dyad.

The modelling of binary-rich galaxies is an active area of research (see, for example, the papers by Minor et al., 2010; Rastello et al., 2020; and Arroyo-Polonio et al., 2023). However, there is no publicly available software dedicated to the field. The situation is different for the allied field of population synthesis, in which stellar physicists generate a representation of a population of binary stars by simulating the dynamical and chemical evolution of some initial population. There is a large amount of software that can perform these simulations. Amongst the available packages are COSMIC (Breivik et al., 2020), COMPAS (Riley et al., 2022), and binary_c (Hendriks & Izzard, 2023). These packages invariably allow you to generate the initial population by sampling stellar mass, mass-ratio, and orbital elements. In that respect they provide functionality similar to Dyad's. But typically they provide only the sampling routine and no further functionality, such as the ability to evaluate the probability density functions themselves. Moreover, each package provides a different library of sampling routines and these do not always allow for correlations between quantities. None of them was the laboratory that we required for our work. That laboratory was Dyad, which I hope others will find useful too.

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