

Example Paper

This example `paper.md` is adapted from *Gala: A Python package for galactic dynamics* by Adrian M. Price-Whelan <http://doi.org/10.21105/joss.00388>.

For a complete description of available options to describe author names [see here](#).

```

---
title: 'Gala: A Python package for galactic dynamics'
tags:
  - Python
  - astronomy
  - dynamics
  - galactic dynamics
  - milky way
authors:
  - name: Adrian M. Price-Whelan
    orcid: 0000-0000-0000-0000
    equal-contrib: true
    affiliation: "1, 2" # (Multiple affiliations must be quoted)
  - name: Author Without ORCID
    equal-contrib: true # (This is how you can denote equal contributions between
multiple authors)
    affiliation: 2
  - name: Author with no affiliation
    corresponding: true # (This is how to denote the corresponding author)
    affiliation: 3
  - given-names: Ludwig
    dropping-particle: van
    surname: Beethoven
    affiliation: 3
affiliations:
  - name: Lyman Spitzer, Jr. Fellow, Princeton University, United States
    index: 1
    ror: 00hx57361
  - name: Institution Name, Country
    index: 2
  - name: Independent Researcher, Country
    index: 3
date: 13 August 2017
bibliography: paper.bib

```

Optional fields if submitting to a AAS journal too, see this blog post:
<https://blog.joss.theoj.org/2018/12/a-new-collaboration-with-aas-publishing>
 aas-doi: 10.3847/xxxxx <- update this with the DOI from AAS once you know it.
aas-journal: Astrophysical Journal <- The name of the AAS journal.

```
---
```

Summary

The forces on stars, galaxies, and dark matter under external gravitational fields lead to the dynamical evolution of structures in the universe. The orbits of these bodies are therefore key to understanding the formation, history, and future state of galaxies. The field of "galactic dynamics," which aims to model the gravitating components of galaxies to study their structure and evolution, is now well-established, commonly taught, and frequently used in astronomy. Aside from toy problems and demonstrations, the majority of problems require efficient numerical tools, many of which require the same base code (e.g., for performing numerical orbit integration).

Statement of need

`Gala` is an Astropy-affiliated Python package for galactic dynamics. Python enables wrapping low-level languages (e.g., C) for speed without losing flexibility or ease-of-use in the user-interface. The API for `Gala` was designed to provide a class-based and user-friendly interface to fast (C/Cython-optimized) implementations of common operations such as gravitati



coordinate systems in the ``Astropy`` package [Astropy] (``astropy.units`` and ``astropy.coordinates``).

``Gala`` was designed to be used by both astronomical researchers and by students in courses on gravitational dynamics or astronomy. It has already been used in a number of scientific publications [Pearson:2017] and has also been used in graduate courses on Galactic dynamics to, e.g., provide interactive visualizations of textbook material [Binney:2008]. The combination of speed, design, and support for Astropy functionality in ``Gala`` will enable exciting scientific explorations of forthcoming data releases from the **Gaia** mission [Gaia] by students and experts alike.

State of the field

Several tools exist for galactic dynamics computations:

``galpy`` [Bovy:2015] is a Python package with similar goals, providing orbit integration and potential classes for galactic dynamics.

``NEMO`` [Teuben:1995] is a well-established, comprehensive stellar dynamics toolbox written primarily in C, offering extensive functionality but with a steeper learning curve and less integration with modern Python workflows.

Other tools like ``GalPot`` provide specific Milky Way potential models but lack the broader dynamical analysis capabilities.

``Gala`` was built rather than contributing to existing projects for several reasons. First, ``Gala`` was designed from the ground up to integrate seamlessly with the Astropy ecosystem, using ``astropy.units`` and ``astropy.coordinates`` as core dependencies rather than optional features. This tight integration enables natural workflows for astronomers already using Astropy. Second, ``Gala``'s object-oriented API with consistent interfaces across subpackages (potentials, integrators, dynamics) provides a more modular and extensible design than alternatives available at the time. Third, ``Gala`` fills a specific niche between simple demonstration codes and full N-body simulation packages like ``Gadget`` [Springel:2005] – it focuses on the common tasks in galactic dynamics research (orbit integration, potential evaluation, coordinate transformations) while maintaining both performance through C implementations and usability through its Python interface.

Software design

``Gala``'s design philosophy is based on three core principles: (1) to provide a user-friendly, modular, object-oriented API, (2) to use community tools and standards (e.g., Astropy for coordinates and units handling), and (3) to use low-level code (C/C++/Cython) for performance while keeping the user interface in Python. Within each of the main subpackages in ``gala`` (``gala.potential``, ``gala.dynamics``, ``gala.integrate``, etc.), we try to maintain a consistent API for classes and functions. For example, all potential classes share a common base class and implement methods for computing the potential, forces, density, and other derived quantities at given positions. This also works for compositions of potentials (i.e., multi-component potential models), which share the potential base class but also act as a dictionary-like container for different potential components. As another example, all integrators implement a common interface for numerically integrating orbits. The integrators and core potential functions are all implemented in C without support for units, but the Python layer handles unit conversions and prepares data to dispatch to the C layer appropriately. Within the coordinates subpackage, we extend Astropy's coordinate classes to add more specialized coordinate frames and transformations that are relevant for Galactic dynamics and Milky Way research.

Research impact statement

``Gala`` has demonstrated significant research impact and grown both its u



suggesting new features.

While ``Gala`` started as a tool primarily to support the core developer's research, it has expanded organically to support a range of applications across domains in astrophysics related to Milky Way and galactic dynamics. The package has been used in over 400 publications (according to Google Scholar) spanning topics in galactic dynamics such as modeling stellar streams [Pearson:2017], Milky Way mass modeling, and interpreting kinematic and stellar population trends in the Galaxy. ``Gala`` is integrated within the Astropy ecosystem as an affiliated package and has built functionality that extends the widely-used ``astropy.units`` and ``astropy.coordinates`` subpackages. ``Gala``'s impact extends beyond citations in research: Because of its focus on usability and user interface design, ``Gala`` has also been incorporated into graduate-level galactic dynamics curricula at multiple institutions.

``Gala`` has been downloaded over 100,000 times from PyPI and conda-forge yearly (or ~2,000 downloads per week) over the past few years, demonstrating a broad and active user community. Users span career stages from graduate students to faculty and other established researchers and represent institutions around the world. This broad adoption and active participation validate ``Gala``'s role as core community infrastructure for galactic dynamics research.

Mathematics

Single dollars (\$) are required for inline mathematics e.g. $f(x) = e^{\pi/x}$

Double dollars make self-standing equations:

```
$$\Theta(x) = \left\{\begin{array}{l} 0 \text{ if } x < 0 \\ 1 \text{ else} \end{array}\right.
```

You can also use plain `\LaTeX` for equations

```
\begin{equation}\label{eq:fourier}
\hat{f}(\omega) = \int_{-\infty}^{\infty} f(x) e^{i\omega x} dx
\end{equation}
```

and refer to `\autoref{eq:fourier}` from text.

Citations

Citations to entries in paper.bib should be in `[rMarkdown]` (http://rmarkdown.rstudio.com/authoring_bibliographies_and_citations.html) format.

If you want to cite a software repository URL (e.g. something on GitHub without a preferred citation) then you can do it with the example BibTeX entry below for `@fidgit`.

For a quick reference, the following citation commands can be used:

```
- '@author:2001' -> "Author et al. (2001)"
- '[@author:2001]' -> "(Author et al., 2001)"
- '[@author1:2001; @author2:2001]' -> "(Author1 et al., 2001; Author2 et al., 2002)"
```

Figures

Figures can be included like this:

```
![Caption for example figure.\label{fig:example}](figure.png)
```

and referenced from text using `\autoref{fig:example}`.

Figure sizes can be customized by adding an optional second parameter.



No generative AI tools were used in the development of this software, the writing of this manuscript, or the preparation of supporting materials.

Acknowledgements

We acknowledge contributions from Brigitta Sipocz, Syrtis Major, and Semyeong Oh, and support from Kathryn Johnston during the genesis of this project.

References

Example `paper.bib` file:

```
@article{Pearson:2017,
  url = {http://adsabs.harvard.edu/abs/2017arXiv170304627P},
  Archiveprefix = {arXiv},
  Author = {{Pearson}, S. and {Price-Whelan}, A.~M. and {Johnston}, K.~V.},
  Eprint = {1703.04627},
  Journal = {ArXiv e-prints},
  Keywords = {Astrophysics - Astrophysics of Galaxies},
  Month = mar,
  Title = {{Gaps in Globular Cluster Streams: Pal 5 and the Galactic Bar}},
  Year = 2017
}
```

```
@book{Binney:2008,
  url = {http://adsabs.harvard.edu/abs/2008gady.book....B},
  Author = {{Binney}, J. and {Tremaine}, S.},
  Booktitle = {Galactic Dynamics: Second Edition, by James Binney and Scott Tremaine.~ISBN 978-0-691-13026-2 (HB).~Published by Princeton University Press, Princeton, NJ USA, 2008.},
  Publisher = {Princeton University Press},
  Title = {{Galactic Dynamics: Second Edition}},
  Year = 2008
}
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@article{gaia,
  author = {{Gaia Collaboration}},
  title = "{The Gaia mission}",
  journal = {Astronomy and Astrophysics},
  archivePrefix = "arXiv",
  eprint = {1609.04153},
  primaryClass = "astro-ph.IM",
  keywords = {space vehicles: instruments, Galaxy: structure, astrometry, parallaxes, proper motions, telescopes},
  year = 2016,
  month = nov,
  volume = 595,
  doi = {10.1051/0004-6361/201629272},
  url = {http://adsabs.harvard.edu/abs/2016A%26A...595A...1G},
}
```

```
@article{astropy,
  author = {{Astropy Collaboration}},
  title = "{Astropy: A community Python package for astronomy}",
  journal = {Astronomy and Astrophysics},
  archivePrefix = "arXiv",
  eprint = {1307.6212},
  primaryClass = "astro-ph.IM",
  keywords = {methods: data analysis, methods: miscellaneous, virtual observatory tools},
  year = 2013,
  month = oct,
  volume = 558,
  doi = {10.1051/0004-6361/201322068},
  url = {http://adsabs.harvard.edu/abs/2013A%26A...558A..33A}
}
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```
@article{Hunt:2025,
  author = {{Hunt}, Jason A.~S. and {Vasiliev}, Eugene},
  title = {Milky Way dynamics in light of Gaia},
  journal = {New Astronomy Reviews},
  year = 2025,
```

```
}

@misc{fidgit,
  author = {A. M. Smith and K. Thaney and M. Hahnel},
  title = {Fidgit: An ungodly union of GitHub and Figshare},
  year = {2020},
  publisher = {GitHub},
  journal = {GitHub repository},
  url = {https://github.com/arfon/fidgit}
}
```

Note that the paper begins by a metadata section (the enclosing — lines are mandatory) and ends with a References heading, and the references are built automatically from the content in the `.bib` file. You should enter in-text citations in the paper body following correct [Markdown citation syntax](#). Also note that the references include full names of venues, e.g., journals and conferences, not abbreviations only understood in the context of a specific discipline.