OrbDot: A Python package for studying the secular evolution of exoplanet orbits

Simone R. Hagey[1] and **Aaron Boley**[1]

1 Department of Physics and Astronomy, The University of British Columbia, 6224 Agricultural Road Vancouver, BC, V6T 1Z1, Canada

DOI: 10.21105/joss.08550

Software

- Review
- Repository
- Archive

Editor: Warrick Ball

Reviewers:

- @soichiro-hattori
- @j-faria

Submitted: 06 May 2025
Published: 02 September 2025

In partnership with

AMERICAN ASTRONOMICAL SOCIETY

This article and software are linked with research article DOI 10.3847/1538-3881/aded15, published in the Astronomical Journal.

Summary

Gradual changes in exoplanet orbits, known as secular variations, can be detected through observations of transits, eclipses, and radial velocities that span multiple decades in time. Their detection and characterization enable the study of a wide range of dynamical phenomena, such as orbital decay and precession, which operate on timescales of millions of years. Under certain conditions, measurements of secular variations can even probe the interior structure of exoplanets, providing a unique tool for understanding exoplanet formation and evolution.

The necessity to search over many orbital epochs coupled with an ever-growing archive of exoplanet observations creates a need for fast and flexible open-source software that can reliably detect gradual changes in exoplanet orbits. `OrbDot` addresses this need by offering robust tools for fitting secular evolution models to exoplanet transit and eclipse mid-times, transit durations, and radial velocity data.

A key advantage of `OrbDot` is its ability to fit multiple types of data simultaneously, which can help to break parameter degeneracies. It also excels at assisting in result interpretation by generating reports on model comparisons and assessments of various physical effects in the context of the models and their corresponding theory. For example, analysis reports could determine key parameters for assessing tidal energy dissipation, apsidal precession mechanisms, variations due to systemic proper motion, and the dynamical effects of non-resonant companion objects, depending on the applied models.

`OrbDot` remains highly efficient with multiple data types and a high number of free parameters, as it utilizes powerful nested sampling algorithms of the `nestle` (Barbary, 2021; Skilling, 2006) and PyMultiNest (Buchner et al., 2014; Feroz et al., 2009) packages. The intricacies of the implementation are abstracted such that the `OrbDot` input files are simple and the method calls require only a list of free parameters, along with the desired model for fitting.

Extensive documentation, including examples, is hosted on ReadTheDocs.

The examples demonstrate that `OrbDot` can quickly reproduce literature results using only a few lines of code. Readers may be especially interested in the `OrbDot` example analysis of the transit and eclipse mid-times of Hot Jupiter WASP-12 b, which is well-known for showing strong evidence for orbital decay.

A complementary case study of TrES-1 b (Hagey et al., 2025) illustrates the full capabilities of `OrbDot`, placing it in a broader scientific context. Moreover, an early version of this code was used for the orbital analysis of the Hot Neptune LTT-9779 b, published in Edwards et al. (2023).

Statement of need

Many exoplanet systems now have transit and radial velocity data spanning over a decade, enabling studies of secular variations. While tools for analyzing short-term transit variations exist, there is a lack of open-source software dedicated to long-term orbital evolution. This does not, however, reflect a lack of interest, as the number of such studies is growing rapidly.

`OrbDot` lowers the barrier to entry for researchers at all levels, including undergraduates, by making advanced statistical methods accessible without requiring extensive computational experience. Despite its ease of use, `OrbDot` is not intended to be a black box. Rather, with extensive documentation, examples, and accessible source code, it is presented to the community with transparency that lends itself to community contributions and independent verification of results. It is designed to be easily extended, as the nested sampling framework supports custom log-likelihood models with free parameters that are part of the `OrbDot` ecosystem. This ensures that the software may evolve to meet the needs of the research community.

Similar software

Some existing tools have features that overlap with `OrbDot`'s functionality, but none provides its full suite of capabilities. The most similar codes, `Susie` (Barker et al., 2024; Barker & Kirk, 2025) and `PdotQuest` (Wang et al., 2024), which are not fully packaged software, are designed to fit secular evolution models to transit and eclipse timing data, but not to radial velocities. `OrbDot` also has greater flexibility in model fitting than `Susie` and `PdotQuest`. For example, `Susie` (Barker et al., 2024; Barker & Kirk, 2025) employs simple least-squares fitting, and while `PdotQuest` (Wang et al., 2024) uses MCMC, it currently supports only the orbital decay model, making both codes narrower in scope than `OrbDot`. Moreover, `OrbDot` includes tools for theoretical interpretation.

The well-known package `TTVFast` (Deck et al., 2014) is highly robust and capable of modeling both transit and radial velocity data, but it is focused on short-term timing variations driven by multi-planet dynamics near mean-motion resonances. `OrbDot`, in contrast, explores long-term secular models. Similarly, general-purpose frameworks such as `juliet` (Espinoza et al., 2019), `exoplanet` (Foreman-Mackey et al., 2021), `EXOFAST` (Eastman et al., 2019), `ExoStriker` (Trifonov, 2019), and `allesfitter` (Günther & Daylan, 2021) can jointly model transit and RV data, but their TTV models are also restricted to short-term variations, with an emphasis on transit light curve fitting rather than directly using transit and eclipse mid-times to constrain models.

The RV focused packages `RadVel` (Fulton et al., 2018) and `Kima` (Faria et al., 2018) provide flexible modeling of radial velocity datasets, but do not have a framework for incorporating transit and eclipse data into the modeling. The codes also have limited options for studying long-term trends. For example, `RadVel` (Fulton et al., 2018) includes linear and quadratic RV terms, which `OrbDot` also supports, but it does not model evolving orbital elements. `Kima` (Faria et al., 2018) incorporates an apsidal precession model, but only for circumbinary planets – a niche application.

In summary, `OrbDot` is a fully packaged, documented, and maintained software suite designed specifically for studies of secular orbital evolution. It unifies transit, eclipse, and RV data, bypasses light-curve fitting to focus directly on timing measurements, implements robust Bayesian inference with nested sampling, and provides a flexible framework for selecting models, priors, and parameterizations. In addition, it integrates tools for theoretical analysis, making `OrbDot` the first software to systematically support data-driven, comprehensive studies of long-term exoplanet orbital dynamics.

Acknowledgements

This work was supported, in part, by an NSERC Discovery Grant (DG-2020-04635) and the University of British Columbia. SH's contribution was further supported, in part, by an NSERC PGS-D and a Li Tze Fong Fellowship.

References

Barbary, K. (2021). *nestle: Nested sampling algorithms for evaluating Bayesian evidence*. https://ascl.net/2103.022

Barker, M., Jackson, B., Huchmala, R., Adams, E., & Kirk, A. (2024). Susie Transiting Exoplanet Ephemeris Package. *56th Annual Meeting of the Division for Planetary Sciences*, *56*, 402.02. https://doi.org/10.3847/25c2cfeb.64cecc52

Barker, M., & Kirk, A. (2025). The susie python package. In *GitHub repository*. https://github.com/BoiseStatePlanetary/susie; GitHub.

Buchner, J., Georgakakis, A., Nandra, K., Hsu, L., Rangel, C., Brightman, M., Merloni, A., Salvato, M., Donley, J., & Kocevski, D. (2014). X-ray spectral modelling of the AGN obscuring region in the CDFS: Bayesian model selection and catalogue. *Astronomy & Astrophysics*, *564*, A125. https://doi.org/10.1051/0004-6361/201322971

Deck, K. M., Agol, E., Holman, M. J., & Nesvorný, D. (2014). TTVFast: An Efficient and Accurate Code for Transit Timing Inversion Problems. *The Astrophysical Journal*, *787*(2), 132. https://doi.org/10.1088/0004-637X/787/2/132

Eastman, J. D., Rodriguez, J. E., Agol, E., Stassun, K. G., Beatty, T. G., Vanderburg, A., Gaudi, B. S., Collins, K. A., & Luger, R. (2019). EXOFASTv2: A public, generalized, publication-quality exoplanet modeling code. *arXiv e-Prints*, arXiv:1907.09480. https://doi.org/10.48550/arXiv.1907.09480

Edwards, B., Changeat, Q., Tsiaras, A., Allan, A., Behr, P., Hagey, S. R., Himes, M. D., Ma, S., Stassun, K. G., Thomas, L., Thompson, A., Boley, A., Booth, L., Bouwman, J., France, K., Lowson, N., Meech, A., Phillips, C. L., Vidotto, A. A., … Ward-Thompson, D. (2023). Characterizing a world within the hot-Neptune desert: Transit observations of LTT 9779 b with the Hubble Space Telescope/WFC3. *The Astronomical Journal*, *166*(4), 158. https://doi.org/10.3847/1538-3881/acea77

Espinoza, N., Kossakowski, D., & Brahm, R. (2019). juliet: a versatile modelling tool for transiting and non-transiting exoplanetary systems. *Monthly Notices of the Royal Astronomical Society*, *490*(2), 2262–2283. https://doi.org/10.1093/mnras/stz2688

Faria, J. P., Santos, N. C., Figueira, P., & Brewer, B. J. (2018). Kima: Exoplanet detection in radial velocities. *Journal of Open Source Software*, *3*(26), 487. https://doi.org/10.21105/joss.00487

Feroz, F., Hobson, M. P., & Bridges, M. (2009). MULTINEST: An efficient and robust Bayesian inference tool for cosmology and particle physics. *Monthly Notices of the Royal Astronomical Society*, *398*(4), 1601–1614. https://doi.org/10.1111/j.1365-2966.2009.14548.x

Foreman-Mackey, D., Luger, R., Agol, E., Barclay, T., Bouma, L., Brandt, T., Czekala, I., David, T., Dong, J., Gilbert, E., Gordon, T., Hedges, C., Hey, D., Morris, B., Price-Whelan, A., & Savel, A. (2021). exoplanet: Gradient-based probabilistic inference for exoplanet data & other astronomical time series. *The Journal of Open Source Software*, *6*(62), 3285. https://doi.org/10.21105/joss.03285

Fulton, B. J., Petigura, E. A., Blunt, S., & Sinukoff, E. (2018). RadVel: The Radial Velocity Modeling Toolkit. *Publications of the Astronomical Society of the Pacific*, *130*(986), 044504. https://doi.org/10.1088/1538-3873/aaaaa8

Günther, M. N., & Daylan, T. (2021). Allesfitter: Flexible Star and Exoplanet Inference from Photometry and Radial Velocity. *The Astrophysical Journal Supplement Series*, *254*(1), 13. https://doi.org/10.3847/1538-4365/abe70e

Hagey, S. R., Edwards, B., Tsiaras, A., Boley, A. C., Kokori, A., Narita, N., Sada, P. V., Walter, F., Zellem, R. T., A-thano, N., Alton, K. B., Álava Amat, M. Á., Benni, P., Besson, E., Brandebourg, P., Bretton, M., Caló, M., Crow, M. V., Dalouzy, J.-C., … Trnka, J. (2025). TrES-1 b: A case study in detecting secular evolution of exoplanet orbits. *The Astronomical Journal*, *170*(4), 197. https://doi.org/10.3847/1538-3881/aded15

Skilling, J. (2006). Nested sampling for general Bayesian computation. *Bayesian Analysis*, *1*(4), 833–859. https://doi.org/10.1214/06-BA127

Trifonov, T. (2019). *The Exo-Striker: Transit and radial velocity interactive fitting tool for orbital analysis and N-body simulations*. Astrophysics Source Code Library, record ascl:1906.004. http://ascl.net/1906.004

Wang, W., Zhang, Z., Chen, Z., Wang, Y., Yu, C., & Ma, B. (2024). Long-term Variations in the Orbital Period of Hot Jupiters from Transit-timing Analysis Using TESS Survey Data. *The Astrophysical Journal Supplement Series*, *270*(1), 14. https://doi.org/10.3847/1538-4365/ad0847