The Journal of Open Source Software

pySYD: Automated measurements of global asteroseismic parameters

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DOI: 10.21105/joss.03331

Software

- Review
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Editor: Monica Bobra

Reviewers:

- @danhey
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Submitted: 08 May 2021
Published: 07 November 2022

Summary

Asteroseismology is well-established in astronomy as the gold standard for determining precise and accurate fundamental stellar properties like masses, radii, and ages. Several tools have been developed for asteroseismic analyses but many of them are closed-source and therefore not accessible to the general astronomy community. Here we present pySYD, a Python package for detecting solar-like oscillations and measuring global asteroseismic parameters. pySYD was adapted from the IDL-based SYD pipeline, which was extensively used to measure asteroseismic parameters for *Kepler* stars. pySYD was developed using the same well-tested methodology and comes with several new improvements to provide accessible and reproducible results. Well-documented, open-source asteroseismology software that has been benchmarked against closed-source tools are critical to ensure the reproducibility of legacy results from the *Kepler* mission. Moreover, pySYD will also be a promising tool for the broader astronomy community to analyze current and forthcoming data from the NASA TESS mission.

Introduction

The study of stellar oscillations is a powerful tool for studying the interiors of stars and determining their fundamental properties (Aerts, 2021). For stars with temperatures that are similar to the Sun, turbulent near-surface convection excites sound waves that propagate within the stellar cavity (Bedding, 2014). These waves probe different depths within the star and therefore, provide critical constraints for stellar interiors that would otherwise be inaccessible by other means.

Asteroseismology of such "solar-like" oscillators provide precise fundamental properties like masses, radii, densities, and ages for single stars, which has broad impacts on several fields in astronomy. For example, ages of stars are important to reconstruct the formation history of the Milky Way (so-called galactic archaeology). For exoplanets that are discovered indirectly through changes in stellar observables, precise and accurate stellar masses and radii are critical for learning about the planets that orbit them.

The NASA space telescopes *Kepler* (Borucki et al., 2010) and TESS (Ricker et al., 2015) have recently provided very large databases of high-precision light curves of stars. By detecting brightness variations due to oscillations, these light curves allow the application of asteroseismology to large numbers of stars, which requires automated software tools to efficiently extract observables.

Several tools have been developed for asteroseismic analyses (e.g., A2Z, Mathur et al., 2010; COR, Mosser & Appourchaux, 2009; `OCT`, Hekker et al., 2010; `SYD`, Huber et al., 2009), but many of them are closed-source and therefore inaccessible to the general astronomy community. Some open-source tools exist (e.g., `DIAMONDS` and `FAMED`, Corsaro & De Ridder, 2014; `PBjam`, Nielsen et al., 2021; `lightkurve`, Lightkurve Collaboration et al., 2018), but they are either optimized for smaller samples of stars or have not yet been extensively tested against closed-source tools.

Statement of need

There is a strong need within the astronomy community for an open-source asteroseismology tool that is 1) accessible, 2) reproducible, and 3) scalable, which will only grow with the continued success of the NASA TESS mission. In this paper we present a Python tool that automatically detects solar-like oscillations and characterizes their properties, called `pySYD`, which prioritizes these three key aspects:

- **Accessible.** The `pySYD` library and source directory are both publicly available, hosted on the Python Package Index (PyPI) and GitHub. The `pySYD` GitHub Page also serves as a multifaceted platform to promote community engagement through discussion forums to communicate and share science, laying out instructions to contribute and encourage inclusivity, and providing a clear path for issue tracking. To facilitate future use and adaptations, the documentation includes a broad spectrum of examples that showcase the versatility of the software. Additionally, Python usage has become standard practice within the community, which will promote integrations with complementary tools like `lightkurve` and `echelle`.
- **Reproducible.** `pySYD` implements a similar framework to the closed-source IDL-based `SYD` pipeline (Huber et al., 2009), which has been used frequently to measure global asteroseismic parameters for many *Kepler* stars (Chaplin et al., 2014; Huber et al., 2011; Serenelli et al., 2017; Yu et al., 2018) and has been extensively tested against other closed-source tools (Hekker et al., 2011; Verner et al., 2011). Figure 1 compares global parameter results from the `pySYD` and `SYD` pipelines for ~ 100 *Kepler* legacy stars, showing excellent agreement with no significant offsets. In fact, the small amount of scatter is likely because `pySYD` is *not* a direct 1:1 translation, incorporating many new custom features and software enhancements. In addition to the important benchmark sample, `pySYD` ensures reproducible results for *every* locally-processed star by saving and setting seeds for any randomly occurring analyses.
- **Scalable.** `pySYD` was developed for speed and efficiency. `pySYD` has more than 50 optional commands that enable a customized analysis at the individual star level and on average, takes less than a minute to complete a single star (with sampling). The software also features parallel processing capabilities and is therefore suitable for large samples of stars.

Well-documented, open-source asteroseismology software that has been benchmarked against closed-source tools are critical to ensure the reproducibility of legacy results from the *Kepler* mission. `pySYD` will also be a promising tool for the broader community to analyze current and forthcoming data from the NASA TESS mission.

Software package overview

`pySYD` depends on a number of powerful libraries, including `astropy` (Astropy Collaboration et al., 2018, 2013), `matplotlib` (Hunter, 2007), `numpy` (Harris et al., 2020), `pandas` (The pandas development team, 2020) and `scipy` (Virtanen et al., 2020). The software package is structured around the following main modules, details of which are described in the online package documentation:

- `target` includes the `Target` class object, which is instantiated for every processed star and roughly operates in the following steps:

- checks for and loads in data for a given star and applies any relevant time- and/or frequency-domain tools e.g., computing spectra, mitigating *Kepler* artefacts, etc.
- searches for localized power excess due to solar-like oscillations and then estimates its initial properties
- uses estimates to mask out that region in the power spectrum and implements an automated background fitting routine that characterizes amplitudes (σ) and characteristic time scales (τ) of various granulation processes
- derives global asteroseismic quantities $_{\mathrm{max}}$ and $\Delta\nu$ from the background-corrected power spectrum
- performs Monte-Carlo simulations by drawing from a chi-squared distribution (with 2 dof) to estimate uncertainties

- `plots` includes all plotting routines
- `models` comprises different frequency distributions used to fit and model properties in a given power spectrum
- `cli` & `pipeline` are the main entry points for terminal and command prompt usage
- `utils` includes a suite of utilities such as the container class `Parameters`, which contains all default parameters, or utility functions like binning data or finding peaks in a series of data

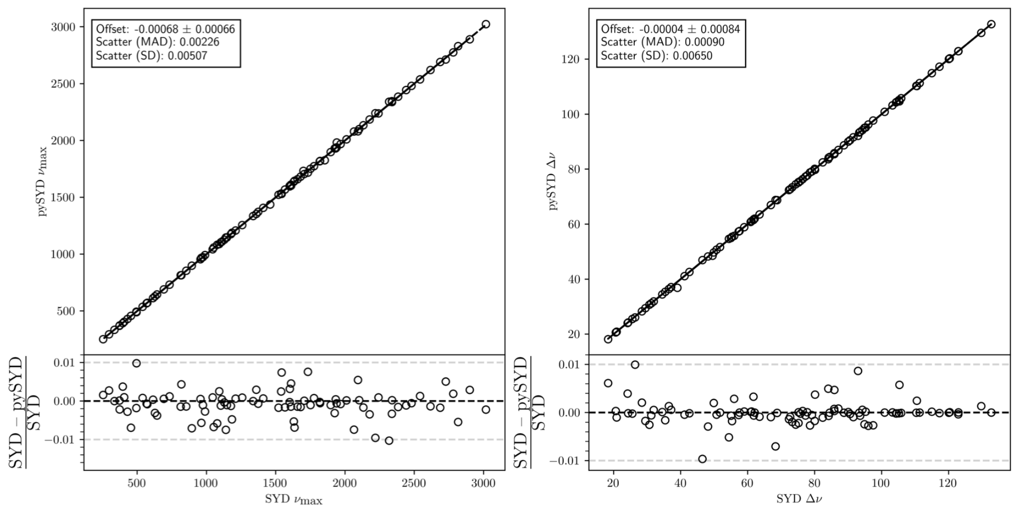

Figure 1: Comparison of global parameters $_{\mathrm{max}}$ (left) and $\Delta\nu$ (right) measured by `pySYD` and `SYD` for ~ 100 *Kepler* stars (Serenelli et al., 2017), with fractional residuals shown in the bottom panels. The comparison shows excellent agreement, with median offsets of $0.07 \pm 0.07\%$ for $_{\mathrm{max}}$ and $0.004 \pm 0.008\%$ for $\Delta\nu$. Typical random errors for such measurements are 1-2 orders of magnitude larger.

Documentation

For installation instructions and package information, the main documentation for the `pySYD` software is hosted at ReadTheDocs. `pySYD` comes with a setup feature which will download information and data for three example stars and then establish the recommended, local directory structure. The documentation comprises a diverse range of applications and examples to make the software more accessible and adaptable. Tutorials include:

- basic command-line examples for stars of varying signal-to-noise detections
- customized command-line examples to showcase some of the new, optional features
- different ways to run a large number of stars

- a notebook tutorial walkthrough of a single star from data to results
- other notebook tutorials demonstrating the use of some optional commands and/or software hacks

The documentation also contains a complete list of all parameters, which includes everything from their object type, default value(s), and how it is stored within the package, as well as relevant links or similar keyword arguments.

Acknowledgements

We thank Dennis Stello, Tim Bedding, Marc Hon, Yifan Chen, Yaguang Li, and other pySYD users for discussion and suggestions which helped with the development of this software. We acknowledge support from the National Aeronautics and Space Administration (80NSSC19K0597, 80NSSC21K0652) as well the Alfred P. Sloan Foundation.

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