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pySYD: Automated measurements of global asteroseismic parameters

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Summary

Asteroseismology, 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 penetrate into different depths within the star and therefore provide powerful constraints on stellar interiors that would otherwise be inaccessible. Asteroseismology is well-established in astronomy as the gold standard for characterizing 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 archeology). 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.

Statement of Need

The NASA space telescopes *Kepler*, K2 and TESS have recently provided very large databases of high-precision light curves of stars. By detecting brightness variations due to stellar 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), 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.

`pySYD` is adapted from the framework of the IDL-based `SYD` pipeline (Huber et al., 2009), which has been used frequently to measure asteroseismic parameters for *Kepler* stars and has been extensively tested against closed-source tools on *Kepler* data (Hekker et al., 2011; Verner et al., 2011). Papers based on asteroseismic parameters measured using the `SYD` pipeline include Huber et al. (2011), Bastien et al. (2013), Chaplin et al. (2014), Serenelli et al. (2017), and Yu et al. (2018). `pySYD` was developed using the same well-tested methodology, but has improved functionality including automated background model selection and parallel processing as well as improved flexibility through a user-friendly interface, while still maintaining its speed and efficiency. 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. The combination of well-tested methodology, improved flexibility and parallel processing capabilities will also make pySYD a promising tool for the broader community to analyze current and forthcoming data from the NASA TESS mission.

The pySYD library

The excitation mechanism for solar-like oscillations is stochastic and modes are observed over a range of frequencies. Oscillation modes are separated by the so-called large frequency spacing ($\Delta\nu$), with an approximately Gaussian-shaped power excess centered on ν_{max}, the frequency of maximum power. The observables ν_{max} and $\Delta\nu$ are directly related to fundamental properties such as surface gravity, density, mass and radius (Kjeldsen & Bedding, 1995).

pySYD is a Python package for detecting solar-like oscillations and measuring global asteroseismic parameters. Derived parameters include ν_{max} and $\Delta\nu$, as well as characteristic amplitudes and timescales of correlated red-noise signals due to stellar granulation.

A pySYD pipeline Target class object has two main methods:

- Target.find_excess() searches for the power excess due to solar-like oscillations by implementing a frequency-resolved collapsed autocorrelation method. The output from this routine provides an estimate for ν_{max}.
- Target.fit_background() starts by optimizing and determining the best-fit stellar background model. The results from the first module are translated into a frequency range in the power spectrum centered on the estimated ν_{max}, which is masked out to determine the stellar background contribution. After subtracting the best-fit model from the power spectrum, the peak of the smoothed power spectrum is used to estimate ν_{max}. An autocorrelation function is computed using the region centered on ν_{max}, and used to calculate an estimate for $\Delta\nu$.

The pySYD software depends on a number of powerful libraries, including Astropy (Astropy Collaboration et al., 2018, 2013), Matplotlib (Hunter, 2007), Numpy (Harris et al., 2020), and SciPy (Virtanen et al., 2020). pySYD has been tested against IDL-SYD using results from the *Kepler* sample for differing time series lengths (Figure 1). The comparisons show no significant systematic differences, with a median offset and scatter of 0.2% and 0.5% for ν_{max} as well as 0.01% and 0.2% for $\Delta\nu$, which is smaller or comparable to the typical random uncertainties (Huber et al., 2011).

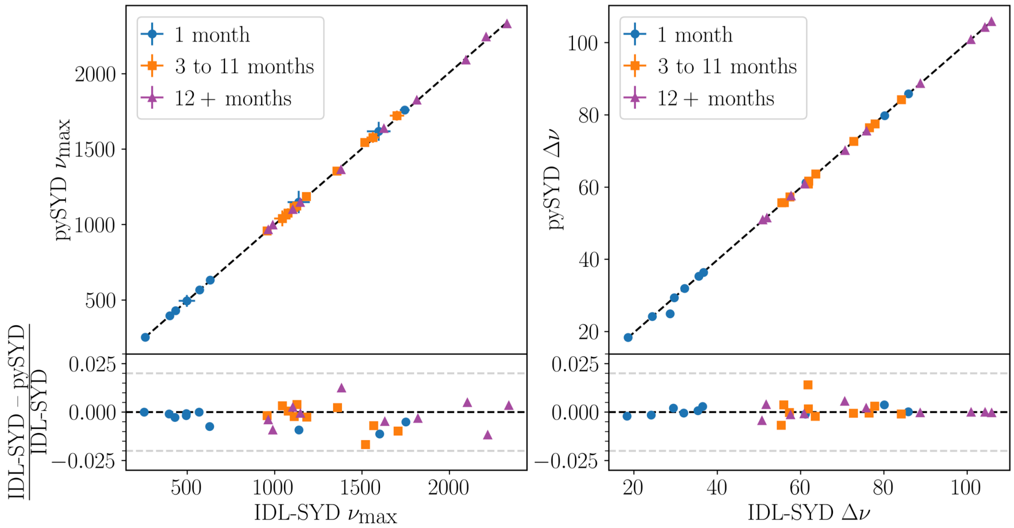

Figure 1: Comparison of `pySYD` and `IDL-SYD` results for global parameters ν_{max} (left) and $\Delta\nu$ (right) for 30 *Kepler* stars, which are colored by the time series baseline. The bottom panels show the fractional residuals.

Documentation & Examples

The main documentation for the `pySYD` software is hosted at pysyd.readthedocs.io. `pySYD` provides a convenient setup feature that will download data for three example stars and automatically create the recommended files for an easy quickstart. The features of the `pySYD` output results are described in detail in the documentation.

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