LASR-Guided Variability Subtraction:
The Linear Algorithm for Significance Reduction of Stellar Seismic Activity

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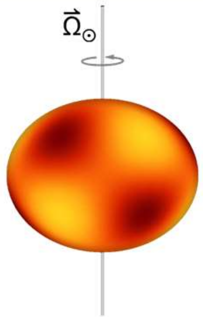
Introduction

Stellar seismic activity produces variations in brightness that introduce oscillations into transit light curves, which can create challenges for traditional fitting models. These oscillations disrupt baseline stellar flux values and potentially mask transits.[1] We develop a model that removes these oscillations from transit light curves by minimizing the significance of each oscillation in frequency space. By removing stellar variability, we prepare each light curve for traditional fitting techniques. We apply our model to δ-Scuti KOI-976 and demonstrate that our variability subtraction routine successfully allows for measuring bulk system characteristics using traditional light curve fitting. These results open a new window for characterizing planets orbiting seismically active early-type stars.

Method

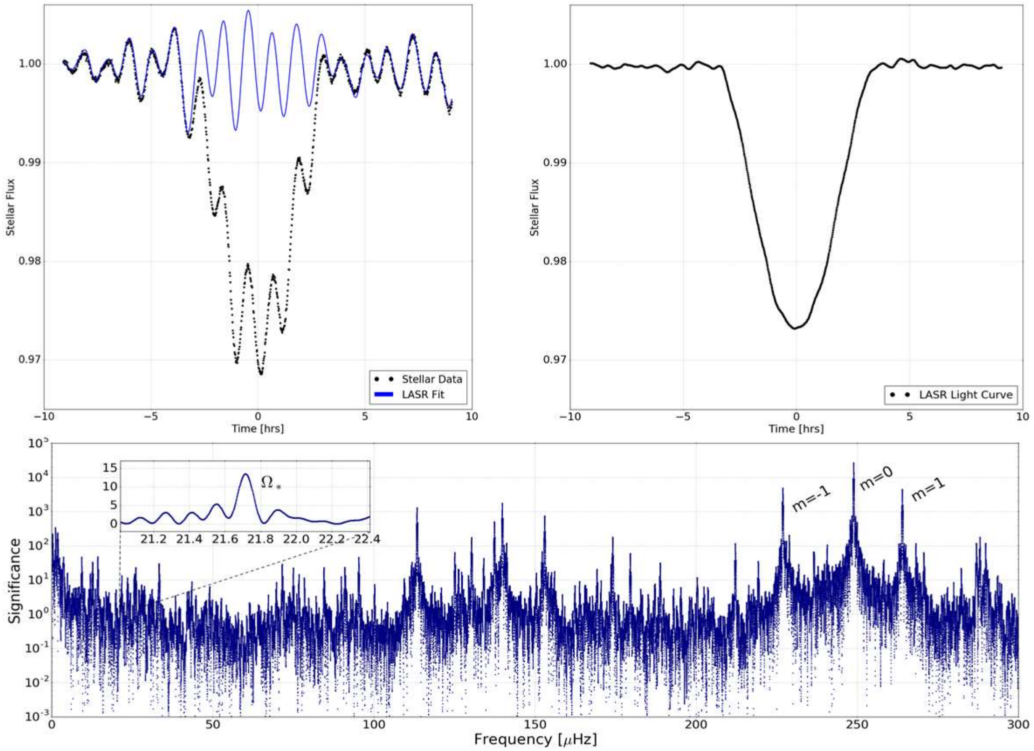


Using *Kepler* photometry for KOI-976, we mask out transit events and create an out-of-transit flux baseline. Then, to remove the stellar oscillation frequencies we:

1. Create a periodogram of the out-of-transit photometry
2. Apply the Linear Algorithm for Significance Reduction (LASR) to constrain the frequency, amplitude, and phase for individual peaks, starting with the peaks of highest significance
   a. Given an initial value for frequency (found with accuracy from the periodogram) and reasonable guesses for amplitude and phase, LASR uses a downhill simplex routine to find the best values for reduction of the given peak in frequency space[2]
   b. Given two frequencies that are either (i) close together in frequency space or (ii) integer multiples of one another, LASR reduces the pairs simultaneously to fit more accurately and account for close frequency pairs and resonant frequencies
3. Subtract the identified frequency(s) with given amplitude and phase from the current stellar baseline, to create an updated baseline with fewer oscillations
4. Repeat until all identifiable frequencies have been subtracted

We then add the transits back into the unreduced baseline and subtract all identified frequencies from the dataset. This process contrasts traditional prewhitening techniques because it operates in frequency space and removes frequencies one at a time.[2,3]

Results



Top Left: Transit light curve of KOI-976, a rapidly-rotating δ-Scuti. Black data points are normalized *Kepler* photometry. Blue data points are our best fit using frequency, amplitude, and phase values identified with LASR.
Top Right: A sample of KOI-976 baseline data, centered around the transit, after the reduction of stellar seismic activity identified by LASR. We find that the single transit available in short-cadence photometry is a grazing red dwarf companion. This transit is now prepared for traditional transit-fitting analysis.
Bottom: Periodogram showing the seismic activity of KOI-976, plotted in frequency space from 0-500μHz. The y-axis is shown in a logarithmic scale to highlight the large number of significant frequency peaks contributing to KOI-967's seismic activity. The subplot, which is also plotted in frequency space but with a linear y-axis, shows the stellar rotation frequency, Ω_*, which we identified using rotational splitting theory.[5]

KOI-976 Parameters	Values
ν_{-1} (μHz)	226.893^{+6e-5}_{-1e-4}
ν_0 (μHz)	$248.864^{+1.5e-5}_{-1.5e-5}$
ν_1 (μHz)	263.972^{+7e-5}_{-4e-5}
C_{nl}	$0.14726 \pm 3e-5$
D_1	1.82033 ± 0.00012
$\Omega_\star$ (μHz)	$21.7130 \pm 7e-4$
$v \sin(i)$ (km/s)	120 ± 5
$R_\star$ ($R_\odot$)	1.7 ± 0.3
ψ	25° ±7°

Stellar parameters of KOI-976 identified using our LASR method. We identify a frequency triplet, labeled in the periodogram. We apply second-order rotational splitting theory[5],

$$\nu_m = \nu_0 + m(1 - C_{nl})\Omega_\star + m^2 D_1 \frac{\Omega_\star^2}{\nu_0}$$

The frequencies of KOI-976's dominant multiplet are labeled m = {-1, 0. 1} in the periodogram (left). We calculate the stellar rotation rate, $\Omega_\star$, based on the frequencies of the identified multiplet mode, and the constants D_1 and C_{nl}. The second-order splitting constant and the Ledoux Constant (D_1 and C_{nl}, respectively) are dependent on stellar properties[5], and listed in the above table.

We compare $\Omega_\star$ with the spectroscopically-determined projected rotation rate, $v\sin(i)$, to determine the star's axial tilt – stellar obliquity (ψ) – in the plane of the sky.

$$\psi = \cos^{-1}\left(\frac{v\sin(i)}{2\pi\Omega_\star R_\star}\right)$$

We obtain $v\sin(i)$ from *Kepler's* Exoplanet Follow-up Observing Program[6]. We apply a nominal stellar radius $R_\star$ using the stellar mass-radius relation, and test these values against a preliminary fit of the KOI-976's grazing transit. Tighter constraints on $R_\star$ and ψ is an ongoing effort.

Applications

Technical Applications:

- Minimize the effects of stellar variability on light curve data
- Widens scope of systems which can be analyzed in terms of stellar oscillation frequencies
- Provides a path for determining stellar properties utilizing asteroseismic theory

Scientific Applications:

- Constrain spin-orbit misalignment in early-type systems
- Provide a new means of studying bulk characteristics of early-type, high-mass systems
- Test planet formation and evolution theories in traditionally under-analyzed systems[7]

References

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