National Aeronautics and Space Administration

The Hunt for Hidden Planets

Principal Investigator: Kyle Pearson (398)

Program: FY21 R&TD Innovative Spontaneous Concepts

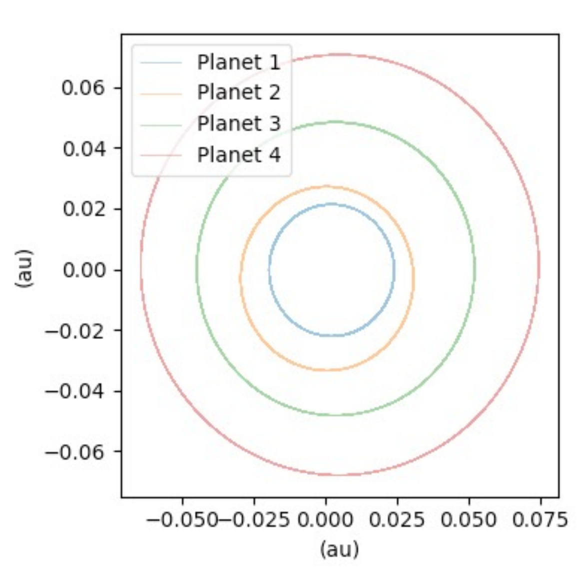
Objectives and Background

This work conducts a systematic search for transit timing variations in “single” planet systems and in planet candidates with data from the Transiting Exoplanet Survey Satellite (TESS). TESS is conducting an all-sky photometric survey to discover hundreds of transiting planets around bright stars. 748 exoplanet systems are analyzed in order to constrain their orbital properties such as inclination, period, and time of mid-transit. The new orbital periods of the planets are used to forecast an ephemeris which is then compared to the observed mid-transit measurements. Significant deviations from the calculated ephemeris may be indicative of gravitational perturbations originating from a "hidden" companion that does not transit the star.

The formation and evolution of single vs. multiplanet systems are subject to debate due to discrepancies between the observed population from Kepler and the predicted occurrence rate for a respective formation model (Hansen & Murray 2013; Mariarty & Ballard 2015; Volk & Gladman 15; Pu & Wu 2015; Ballard & Johnson 2016; Mulders et al. 2019). Typically, the planetary formation model underestimates the distribution of single planet systems despite the mechanism (e.g. in-situ assembly, dynamical instability, etc.) being tested. Thus identifying multi-planet systems is key for understanding planet formation. A portion of the "single" transiting planet systems are suspected to be multi-planet systems but with slightly larger (~1 deg) mutual inclinations than the observed multi-population. Larger mutual inclinations are the result of planetary disks with more mass and suggest larger stars support more non-transiting companions than lower mass stars (Mariarty & Ballard 2015; Mulders+ 2019). Transiting exoplanets in multi-planet systems exhibit non-Keplerian orbits as a result of the gravitational influence from companions which can cause the times and durations of transits to vary (TTV/ TDV). The amplitude and periodicity of the TTV/TDVs are characteristic of the perturbing planet's mass and orbit (Nesvorný & Morbidelli 2008).

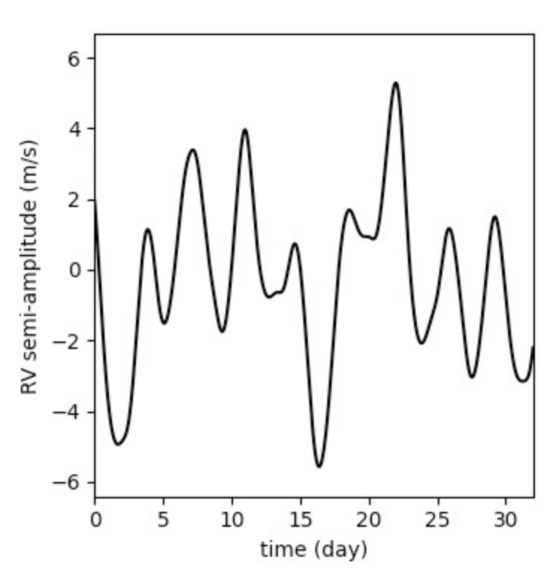
Significance/Benefits to JPL and NASA

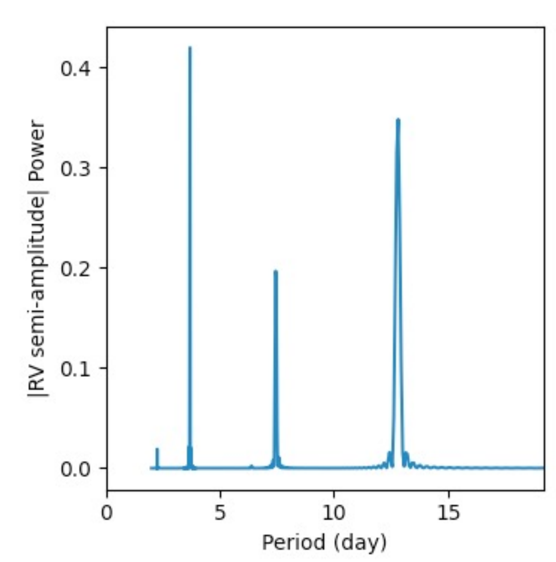
This project contains a repository of new planetary parameters for over 700 exoplanets and planet candidates. These parameters include orbital period and inclination which is necessary for measuring an accurate planetary radius from transits. The light curve fitting code from this project is already included in the Exoplanet Watch project, a JPL lead citizen science project for conducting transit measurements of exoplanets for orbital maintenance. The analysis of over 19,000 light curves will provide valuable constraints when computing a planet’s ephemeris which is necessary for planning future observations e.g. with CASE/ARIEL or James Webb. The uncertainty on planning a transit measurement is proportional to time and can quickly grow to be on the order of a few hours in as little as a year which is comparable to the duration of a transit and thus a liability when planning future observations using a small window around the estimated transit time.

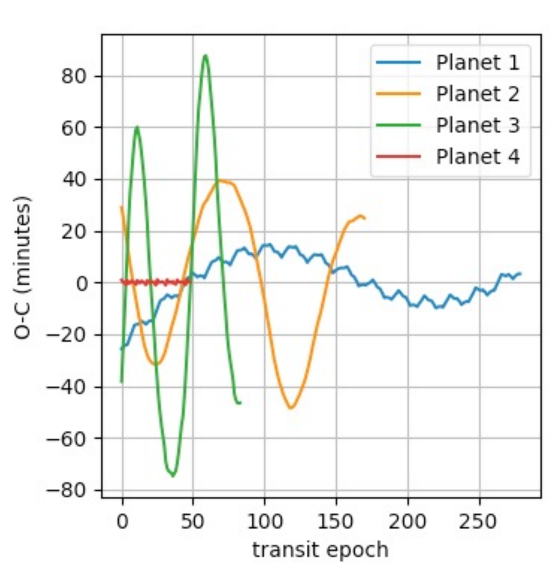


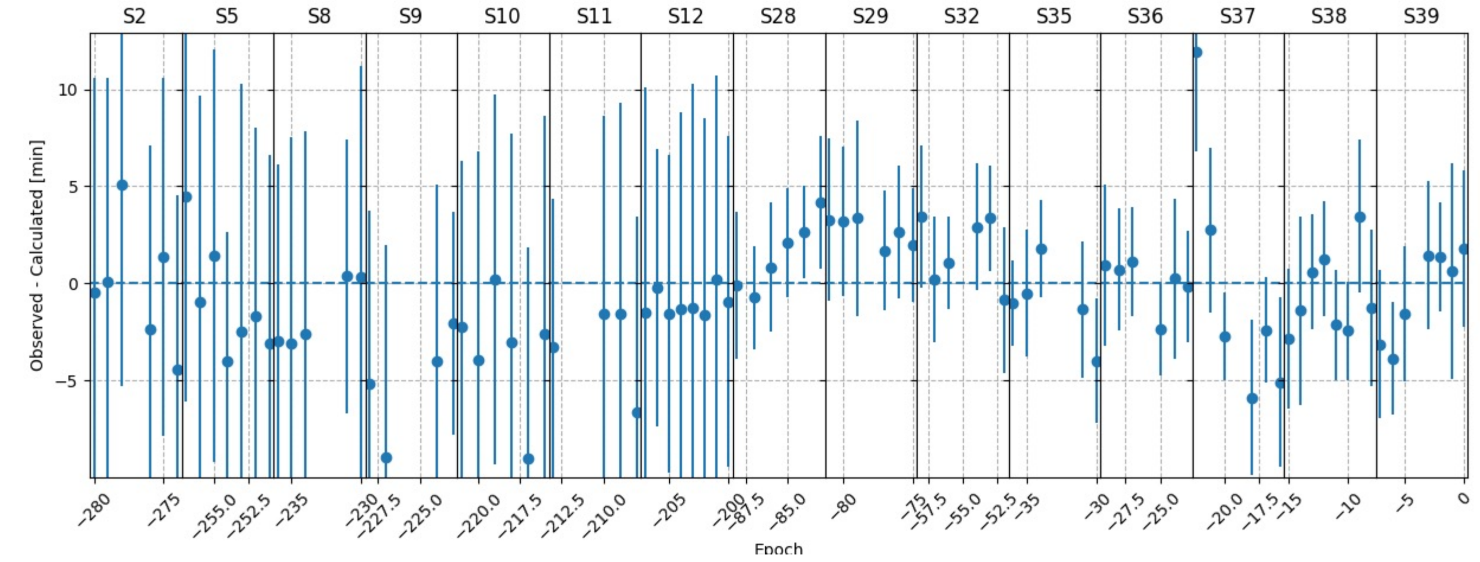
Stellar mass: 0.27 Msun

	P 1	P 2	P 3	P 4
Mass (Mearth)	0.4	2.22	1.94	3.06
Semi-major Axis (au)	0.022	0.03	0.048	0.069
Period (day)	2.25	3.69	7.46	12.8
Inclination (deg)	90.0	90.0	90.0	90.0
Eccentricity	0.1	0.106	0.073	0.074
TTV Max Avg (min)	18.1	41.0	75.3	1.0







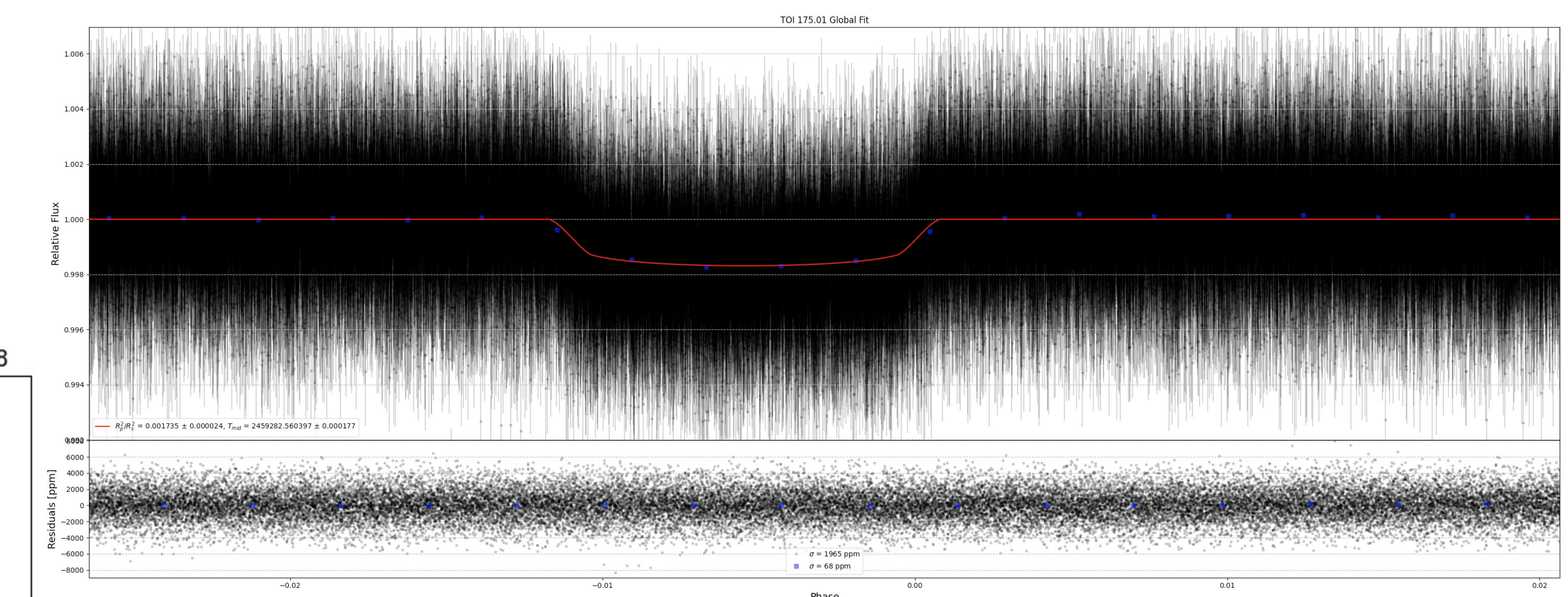


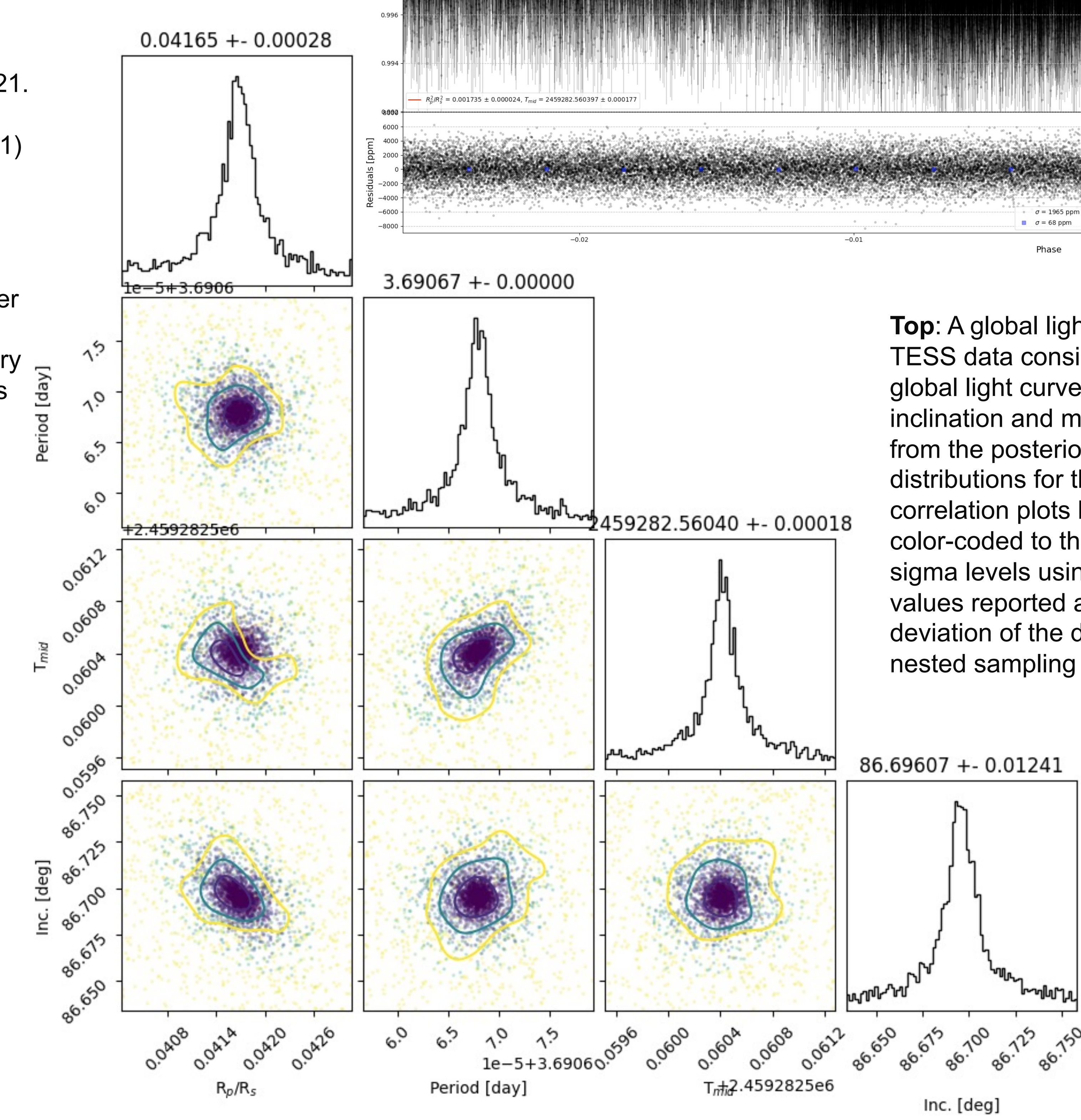
An N-body simulation using the orbit parameters of the TOI 175 system (L 98-59) as measured in Demangeon et al. 2021. The observed minus calculated mid-transit plot (middle bottom) is for the simulation and shows Planet 2 (TOI 175.01) as having a perturbation on the order of ~30 minutes. However, the results presented here only measure an O-C deviation of ~5 minutes in the TESS data (Right bottom figure). This difference suggests either the mass of the neighboring planets is overestimated and is something closer to that of Earth and/or the eccentricity of TOI 175.01 is overestimated. More work is needed to rederive the planetary parameters by simultaneously fitting the TTV measurements of every planet in the system using an N-body retrieval.

Approach and Results

The work here uses data from all sectors of the TESS spacecraft. Data in TESS’s prime mission is taken at a cadence of 2- and 30-minutes and in the extended mission, it is 10-minutes, which is faster than the average cadence in the Kepler mission. The high cadence data from TESS are necessary to characterize transit mid-points to within a few minutes enabling TTV detections of planets as small as a few Earth-masses (Zellem et al. 2020). The photometric data are first calibrated using the Science Processing Operations Center (SPOC) pipeline which is based on the predecessor Kepler mission pipeline. The flux is extracted from the target using a range of apertures from 2-5 times the FWHM with the aperture yielding the lowest out of transit scatter being used in the final reported light curve. The target pixel files include quality flags that indicate when the photometric measurements may have been compromised due to non-optimal conditions on the spacecraft and are thus removed from the analysis. The time series is detrended with a quadratic spline using a biweight loss function and a window size comparable to 2 times the transit duration in order to ensure the transit signal remains intact during the detrending process however multiplanet systems with longer orbital periods may be subject to removal and are handled using a separate detrending step involving a longer window. Before the individual light curves are fit a global solution is derived using the entire time series concatenated from every TESS sector. The orbital inclination and period are estimated from the global fit and left as fixed parameters when fitting the individual light curves for transit depth and mid-point. The individual light curves are fit using an efficient Monte Carlo sampling method called nested sampling and the derived mid-transit times are compared against a calculated time using the global solution. Differences in the calculated versus observed mid-transit time can indicate the presence of additional companions in the system.

Major milestones of this project include developing a Bayesian light curve fitting code using a new nested sampling package in python called "UltraNest". The new code improves the efficiency of fitting light curves by +75% compared to past techniques like Markov Chain Monte Carlo and has enabled one of the largest TTV searches to date with 19,751 light curves (18,229,384 images) being fit using a statistically robust method. 748 exoplanet systems had more than two light curve measurements and were able to have a new orbital period derived. The new orbital periods are used to calculate mid-transit measurements in the past which are compared to the observed values and 17 targets show significant perturbations between their calculated and observed mid-transit times. The source code and results are available on the JPL GitHub: https://github.jpl.nasa.gov/kpearson





Top: A global light curve for the target TOI 175.01 from 15 sectors of TESS data consisting of 79,319 images and 96 light curves. The global light curve model is fit for transit depth, orbital period, inclination and mid-transit time. The final parameters are derived from the posterior distributions on the right. **Right**: Posterior distributions for the global light curve fit of TOI 175.01 and correlation plots between the free parameters. The data points are color-coded to the chi-squared and the contours represent different sigma levels using a standard deviation from the histograms. The values reported above each histogram are the median and standard deviation of the distribution. These posteriors were derived using a nested sampling algorithm.

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Clearance Number:
RPC/JPL Task Number: R21236