Observations of the *Kepler* Field with *TESS*: Predictions for Planet Yield and Observable Features

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Abstract

We examine the ability of the *Transiting Exoplanet Survey Satellite* (*TESS*) to detect and improve our understanding of planetary systems in the *Kepler* field. By modeling the expected transits of all confirmed and candidate planets detected by *Kepler* as expected to be observed by *TESS*, we provide a probabilistic forecast of the detection of each *Kepler* planet in *TESS* data. We find that *TESS* has a greater than 50% chance of detecting 260 of these planets at the 3σ level in one sector of observations and an additional 120 planets in two sectors. Most of these are large planets in short orbits around their host stars, although a small number of rocky planets are expected to be recovered. Most of these systems have only one known transiting planet; in only ~5% of known multiply transiting systems do we anticipate more than one planet to be recovered. When these planets are recovered, we expect *TESS* to be a powerful tool to characterize transit timing variations. Using *Kepler*-88 (KOI-142) as an example, we show that *TESS* will improve measurements of planet–star mass ratios and orbital parameters, and significantly reduce the transit timing uncertainty in future years. Because *TESS* will be most sensitive to hot Jupiters, we research whether *TESS* will be able to detect tidal orbital decay in these systems. We find two confirmed planetary systems (*Kepler*-2 b and *Kepler*-13 b) and five candidate systems that will be good candidates to detect tidal decay.

*Key words:* methods: data analysis – planet–star interactions – planetary systems – planets and satellites: individual (KOI-142 b/Kepler-88 b)

*Supporting material:* machine-readable tables, tar.gz file

1. Introduction

The *Kepler* spacecraft (Borucki et al. 2010) is a ground-breaking instrument that has detected thousands of exoplanets, including several that are Earth-sized and lie in the habitable zone of their host stars (Mullally et al. 2015; Rowe et al. 2015; Coughlin et al. 2016; Thompson et al. 2018). It has also altered the way that we think about the formation and structure of planetary systems (Lissauer et al. 2011; Fang & Margot 2012). Although *Kepler* has been a valuable tool thus far in exoplanetary studies, most *Kepler* stars are too faint for detailed follow-up, such as obtaining precise RV measurements to determine the planets’ masses (Ricker et al. 2016).

Nevertheless, if a system has more than one planet, we can utilize the system’s transit timing variations (TTVs; Agol et al. 2005; Holman & Murray 2005) to teach us more about the system. TTVs occur in multiplanet systems, due to gravitational interactions between planets, and can be visible in transit timing data because they force planets off of a strictly Keplerian orbit. TTVs can be used to not only confirm planetary systems but also measure system mass ratios and orbital parameters (Fabrycky et al. 2013; Huber et al. 2013; Nespral et al. 2017). Furthermore, TTVs allow us to significantly improve our characterization of planetary systems by deriving the physical parameters of the systems, such as the star/planets’ absolute mass, eccentricity, and inclinations, especially when combined with other data (Agol et al. 2005; Montet & Johnson 2013; Almenara et al. 2018).

Because the mass measurements from TTV signals strongly depend on orbital parameters such as period ratio and eccentricity, and because for many systems we do not have enough data from *Kepler* to measure these precisely (Fabrycky et al. 2013), we have either large uncertainties or only upper limits in mass measurements (Nesvorný et al. 2012). Additionally, many TTVs are still degenerate after four years as the period of many TTV systems are comparable in length to or longer than the *Kepler* observing baseline (Mazeh et al. 2013; Holczer et al. 2016). This means that in order to obtain more precise measurements of TTVs, orbital parameters, and mass measurements, we need to increase the *Kepler* four-year baseline by continuing to observe these systems.

This is where *TESS*, the *Transiting Exoplanet Survey Satellite* (Ricker et al. 2016), comes into play. *TESS* was launched in 2018 April and will survey 80% of the sky to catalog the nearest and brightest stars in our local neighborhood (Ricker et al. 2016). This will make *TESS* planets some of the best characterized planets that exist as consistent follow-up observations will be easily performed in the future. Because *TESS* will be performing a nearly all-sky survey, it will reobserver the *Kepler* field. Thus, *TESS* will extend the amount of time we have observed these systems from four to 10 years, which will allow us to examine the long-term dynamical effects that exist in planetary systems.

This analysis will be critical in multiple ways. First, we may discover additional planets that did not transit in the *Kepler* era but will transit when *TESS* observes the system (e.g., dynamical perturbations may allow previously nontransiting planets to transit and/or the planets’ periods were longer than the *Kepler* four-year baseline). Additionally, more data on these systems will allow us to better constrain the systems’ planetary parameters.

In this paper, we discuss the procedure that utilizes previously obtained *Kepler* data together with soon to be
obtained TESS data to improve planetary parameters’ measurements. We demonstrate how we can use Kepler data in conjunction with TESS’s predicted transit times to improve our measurements of various systems and to allow us to explore other effects such as the tidal decay of hot Jupiters. We show that this will be achievable in a single sector of TESS observations, but also that with additional data, either during the primary or an extended mission, TESS’s ability to characterize the small planets originally detected by Kepler increases by a factor of several.

The rest of this paper is organized as follows. In Section 2, we discuss our method for discovering what types of planets TESS is sensitive to. In Section 3, we determine how well we can improve our measurements of masses and eccentricities with TESS data by analyzing a best-case scenario system, KOI-142. In Section 4, we examine the detectable planets from Section 2 and determine how many of these systems we have a strong chance of observing tidal orbital decay with TESS. In Section 5, we offer conclusions and look to the future.

2. TESS Sensitivity to Kepler’s Transiting Planets

2.1. Finding Probabilities of Detection

Our goal in this section is to determine how many and what types of planets TESS will detect in the Kepler field, thus increasing the observation baseline for these systems from four to 10 years. This increased baseline with TESS will improve our measurements of systems and will allow us to better and more accurately test theories on planetary formation and migration.

We use the stellar and planetary properties from Mathur et al. (2017) for systems in the NASA Exoplanet Archive to determine the types of planets TESS will be sensitive to. We consider planets labeled as “confirmed” or “candidate,” and ignore any systems identified as false positives. We contaminate the transit depths from Thompson et al. (2018) with TESS’s contamination ratios (Stassun et al. 2018) to find the transit depths that TESS is expected to observe for each system.

To find the total uncertainty expected in TESS photometry for each system, we apply the projected noise estimate given in Figure 14 of Sullivan et al. (2015) and retrieve the total noise for each observation, given a TESS apparent magnitude (Stassun et al. 2018).

Given the total noise, the calculated TESS transit depth, the Kepler transit duration, orbital period, and an exposure time of 30 minutes, we compute the expected signal-to-noise ratios (S/N) for each planet. In the above calculations, we compute the S/N for both the case where TESS will observe the Kepler field for either one or two sectors: the length of observation for any given star will depend on the exact pointing of the telescope in 2019, but much of the field may be observed for two sectors. The exact pointing of the telescope in the northern hemisphere will not be determined until 2019, due to uncertainties in the future orbit and the details of Earth–moon crossings across the detector light path, which may necessitate changes to the exact sector positioning.

To convert these S/N to probabilities of detection, we follow Christiansen et al. (2015), assuming the probability of detection is a function of the observed S/N, following a logistic function centered at a 7.1σ detection threshold. This idealized scenario was not achieved for Kepler, but may be for TESS, depending on the noise characteristics in real data from that instrument. We also consider detection at the 3σ threshold, as a lower significance might be acceptable for the characterization of known planets, rather than the discovery of new planets. We retrieve probabilities of detection for each planet, weighted by the relative likelihoods of observing N transits given the planet’s orbital period and the TESS observing baseline. We repeat this analysis under the scenario where each planet is observed for either one or two sectors. Thus, we found two probabilities of detection per planet: one probability that the star will be observed for one sector, and another that the star will be observed for two sectors. The results are shown in Table 2.

2.2. Results

Figure 1 shows the radius and period of all confirmed and candidate planets discovered by Kepler, highlighting the systems that we predict have a greater than 50% chance of
being detected by TESS. At the 7.1σ level, we find 81 (114) confirmed planets and 80 (96) candidate planets that will be detected by TESS in one (two) sector(s) of observations. At the 3σ level, there are 154 (232) confirmed and 106 (148) candidate planets that are detectable in one (two) sector(s). In total, we expect TESS is likely to recover 260 (380) of these signals originally detected by Kepler in one (two) sectors. A TESS mission that is positioned to spend two sectors of observing time covering the Kepler field rather than one will likely detect more than 120 additional planet signals from the Kepler field alone. Most of the additional detections will be planets smaller than Neptune.

Additional observations of the Kepler field during an extended mission will continue to contribute to the characterization of these small planets (Table 1). However, the timing of these additional observations does not significantly affect the future yield of these planets, as the most significant present limitation is the S/N of the individual planets in TESS data. To maximize the detections and ability to characterize known transiting planets—the number of which that can be detected are shown in Table 1—the detailed scheduling of these observations is unimportant relative to the number of sectors spent observing the Kepler field, which should be maximized. Here, the largest gain would be for the detection and possible characterization of sub-Neptune planets, which in most cases cannot be detected in one to two sectors of observations around Kepler targets. These observations will be important, however, to detect the possible long-term precession of these systems because of distant, nontransiting perturbers similar to those observed by K2 (A. Hamann et al. 2019, in preparation).

The full list of Kepler objects of interest (KOIs) and their detection probabilities with TESS is given in Table 2. A majority of the planets that are detectable at either the 3σ or 7.1σ level are large planets in short orbits around their host star: most of the Kepler planets that TESS will detect are hot Jupiters. Nevertheless, it is still important to note that smaller planets can be detected as long as their host star is bright and small in size. For example, the planet candidate KOI-06635.01 orbits a 14.353 magnitude star with a radius of 0.41 R⊙ with an orbital period of 0.5274 days. Despite being 1.5R⊕ in size, we project that this planet will be detectable.

Using the probabilities of detection for each planet, we next perform a simple analysis of how successful TESS will be at observing multiplanet systems. We compute the probabilities for different scenarios (e.g., in a one-planet system, the probability of detecting no planet or one planet), which are represented in Figure 2. Unfortunately, it is clear that for all multiplanet systems, TESS has a large probability of detecting none of the known transiting planets in a given system. In only ~5% of known multiply transiting systems do we predict more than one planet to be recovered, which agrees well with Sullivan et al.’s (2015) finding that 5%–10% of the KOIs will be recovered with TESS. The eventual launch of PLATO, projected for the mid-2020s, will provide a better opportunity to investigate these systems.

### 3. Improving Orbital Parameters of Dynamically Interacting Systems

#### 3.1. KOI-142: A Test Case

KOI-142 (Kepler-88) is a system with two known planets in near 2:1 resonance (Nesvorný et al. 2013). KOI-142b,1 is known for having one of the largest recorded TTV amplitudes, ∼12 hr, and is one of the only systems to show measurable transit duration variations (TDVs) (Nesvorný et al. 2013). With this system, we show an example of the expected improvement of planetary parameters by combining TESS and Kepler data for well-characterizable systems.

KOI-142’s parameters are already measured well due to the uniqueness of fits from successful modeling. This success led Nesvorný et al. (2013) to precisely determine the system’s mass ratios. KOI-142’s mass ratios were found to be $M_P/M_S < 5.2 \times 10^{-5}$ and $M_P/M_S = (6.32 \pm 0.13) \times 10^{-4}$. With this information, they determined that KOI-142b is a sub-Neptune-class planet with a mass upper limit of 17.6 M⊕ and that KOI-142c is a nontransiting planet with a mass of 215.9 ± 75 M⊕ (≈0.7M Jupiter). KOI-142b and KOI-142c orbit their central G-type star at periods of ≈10.95 days and ≈22.34 days, respectively.

Because we have precise values for many of this system’s parameters, teams have been able to test theories for this system’s formation and migration and have ruled out several possibilities, due to the system’s architecture (Nesvorný et al. 2013; Silburt & Rein 2015).

Nevertheless, there is still room for improvement in our understanding of this precisely characterized system and in systems that are not measured as well. We next describe our process for calculating the extent to which TESS will improve our measurements and understanding of KOI-142.

#### 3.2. Markov Chain Monte Carlo (MCMC) Analysis

Marginalized orbital parameters and uncertainties for KOI-142 from 14 quarters of Kepler data were published by Nesvorný et al. (2013). There is significant covariance between orbital parameters, as seen in Figures 2 and 3 of that work. As they did not publish detailed posterior distributions of each parameter, the detailed orbits that are consistent with Kepler data are not reproducible from their work. In addition, as three more quarters of Kepler data were collected after the publication of their paper, we choose to refit the system entirely to make use of all available data. By refitting all transit times, as provided by Holczer et al. (2016), we can develop posterior distributions consistent with all public Kepler data for KOI-142.

To find the posterior distribution and covariance between parameters, we perform an MCMC analysis for this system. We write a function that inputs potential sets of parameters into TTVFast (Deck et al. 2014) and outputs a series of transit times for all planets in the system within a specified time interval. We

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**Table 1**

| Number of Sectors | Candidate Planets | Confirmed Planets | Candidate Sub-Neptunes | Confirmed Sub-Neptunes |
|-------------------|-------------------|-------------------|------------------------|------------------------|
| 1                 | 106               | 154               | 7                      | 36                     |
| 2                 | 148               | 232               | 18                     | 89                     |
| 3                 | 181               | 302               | 29                     | 131                    |
| 4                 | 206               | 351               | 37                     | 169                    |
| 5                 | 229               | 396               | 50                     | 206                    |
| 6                 | 252               | 454               | 60                     | 252                    |

**Note.** A longer extended mission will lead to considerable growth in the number of small planets recovered.
then compare all of the transits observed by Kepler (Holczer et al. 2016) to the predicted times from TTVFast. The \( \chi^2 \) values from this comparison were outputted and used to create a likelihood function. We combine our likelihood function with flat priors on all orbital parameters to perform an MCMC analysis for KOI-142 with 13 degrees of freedom (the 13 varying planetary parameters, listed in Table 3). We use the affine invariant ensemble sampler emcee (Goodman & Weare 2010; Foreman-Mackey et al. 2013), using 150 walkers. We ran our MCMC for 20,000 steps, discarding the first 10,000 steps as burn-in, and next use the Markov chains to compute the spread in transit times and uncertainties for future years when TESS will observe this system. We provide 30,000 samples from our posterior distributions as supplemental data.

### 3.3. Spread in O–C Transits

We use all of the Markov chains after burn-in and input each set of parameters into TTVFast, with the endpoint of integration set to the beginning of the year 2020. We create an O–C (observed minus calculated) plot for the inner planet where “observed” denotes the outputted transits from TTVFast and “calculated” the transit times based on a constant-period model (Sterken 2005).

The results from this section are in Figure 3. The leftmost figure shows KOI-142.01’s TTVs in minutes from the year 2009 to 2020 using all of the Markov chains after burn-in. The rightmost figure is a portion from this O–C plot in 2019, with the green band representing the time when TESS will observe KOI-142.01 (plotted using 100 randomly selected sets of transits for clarity). The large-amplitude resonant librations generate chaos in the system, as has been noted before for Kepler-36 (Deck et al. 2012), so the future timing uncertainty grows nonlinearly and faster than the expected linear rate given the uncertainty in the orbital period and number of missed transits (see also Mardling 2008).

There is a very obvious spread in the transit times during the period that TESS will observe the system, which means that
there is certainly room for improvement in our knowledge of this system. We then proceed to calculate the uncertainty in those transit times and determine by what factor we can reduce the transit uncertainty with TESS in 2019 July.

3.4. Calculating Uncertainty in Transit Times

We use all of the Markov chains after burn-in and investigate the standard deviation of the expected time of each transit in the future, shown in green in Figure 4.

The uncertainty in the transits from 2009 until around 2013 are very small as Kepler was observing KOI-142 during that time span. After 2013, there is an underlying, upward trend in transit uncertainties because we were no longer receiving data from the system.

The behavior of the future TTVs is nonlinear and correlated with the TTVs shown in Figure 3. At some points in the TTV cycle, the spread in transit times is relatively large, and a precise observation of an observed transit at those times would be useful to provide better constraints on the orbital parameters of the system.

In order to calculate TESS’s transit uncertainty for KOI-142, we estimated the transit time uncertainty from TESS data, based on TESS’s expected performance. For this, we develop simulated light curves using the batman package of Kreidberg (2015). We initially ran batman with our best-fit parameters from Section 3.2 at a time of inferior conjunction of 0., using a

![Figure 3.](image-url) (Left) O − C plot for KOI-142.01. The data begins in 2009, when Kepler observes the system, and continues through 2013. The data from 2013 onward was obtained by running all possible sets of parameters from our Markov chains into TTVFast. (Right) A portion of the O − C plot in year 2019, when TESS will observe KOI-142. The obvious spread in transit times means that there is room for improvement in our measurements of KOI-142. The vertical green lines in both figures are representative of the time that TESS will observe KOI-142. Although the exact dates that TESS will observe this system are unknown, the width is representative of the expected performance. For this, we develop simulated light curves using the batman package of Kreidberg (2015). We initially ran batman with our best-fit parameters from Section 3.2 at a time of inferior conjunction of 0., using a

### Table 3

Mass and Orbital Parameter Values Found from Our MCMC Analysis for KOI-142

| Parameter | Data without TESS | Data with TESS | Improvement Factor (%) |
|-----------|------------------|----------------|------------------------|
| $M_b [M_\odot]$ | $(2.106_{-0.648}^{+0.600}) \times 10^{-5}$ | $(2.145_{-0.637}^{+0.600}) \times 10^{-5}$ | 6.060 |
| $M_c [M_\odot]$ | $(6.252_{-0.054}^{+0.056}) \times 10^{-4}$ | $(6.246_{-0.052}^{+0.056}) \times 10^{-4}$ | 1.472 |
| $P_b$ [days] | $10.91655_{-0.00025}^{+0.00025}$ | $10.91656_{-0.00013}^{+0.00013}$ | 42.051 |
| $P_c$ [days] | $22.2650_{-0.0017}^{+0.0017}$ | $22.2649_{-0.0014}^{+0.0014}$ | 10.737 |
| $\sigma_b$ | $0.05567_{-0.00021}^{+0.00021}$ | $0.05563_{-0.00019}^{+0.00019}$ | 9.819 |
| $\sigma_c$ | $0.05767_{-0.00061}^{+0.00061}$ | $0.05762_{-0.00041}^{+0.00041}$ | 26.489 |
| $b_\text{b}$ [$\degree$] | $88.417_{-0.155}^{+0.155}$ | $88.419_{-0.155}^{+0.157}$ | 0.714 |
| $b_\text{c}$ [$\degree$] | $86.361_{-0.707}^{+0.707}$ | $86.472_{-0.830}^{+0.559}$ | -4.936 |
| $\omega_b$ [$\degree$] | $179.178_{-1.337}^{+1.337}$ | $179.002_{-0.919}^{+0.901}$ | 32.762 |
| $\omega_c$ [$\degree$] | $1.714_{-0.048}^{+0.048}$ | $1.606_{-0.060}^{+0.060}$ | 24.314 |
| $\Omega_b$ [$\degree$] | ... | ... | ... |
| $\Omega_c$ [$\degree$] | $359.61_{-1.73}^{+1.73}$ | $359.36_{-1.31}^{+1.31}$ | 25.078 |
| $\lambda_b$ [$\degree$] | $263.85_{-1.30}^{+1.32}$ | $264.02_{-0.85}^{+0.88}$ | 33.873 |
| $\lambda_c$ [$\degree$] | $335.80_{-1.25}^{+1.20}$ | $335.96_{-1.01}^{+0.96}$ | 22.186 |
| $\sigma_{2019.5}$ [minutes] | $34.61$ | $14.73$ | $57.440$ |
| $\sigma_{2020.5}$ [minutes] | $67.34$ | $32.92$ | $51.114$ |

**Note.** The middle columns are from the 50th percentile of our posterior distribution, with 1σ errors. The rightmost column is the percentage of improvement we have when using a theoretical TESS data point in 2019 in conjunction with Kepler data. All parameters are defined at reference epoch BJD (BJD–2,454,833) = 245,675,215.
quadratic limb-darkening model and limb-darkening coefficients given by Claret’s (2017) models for a star with the physical parameters of KOI-142. We sample a flux value every 10 minutes (simulating three transits observed at 30 minute cadence) and add noise by sampling from a normal distribution with a standard deviation of 1500 ppm, TESS’s expected sensitivity for KOI-142 (Sullivan et al. 2015). We then treat those flux values with the added noise as “observed” data points. We vary the transit time for our model 3000 times on a linear grid with a width of 0.2 days and calculate the $\chi^2$ between each models’ flux values and our noisy “observed” values. We turn these $\chi^2$ values into a posterior distribution on the time of transit. The 16th and 84th percentile time values for our posterior were measured, and we obtained a standard deviation on the expected time of transit of 0.0117 days (17 minutes).

It is clear that with TESS’s predicted transit uncertainty, we will be able to improve our measurements of this system.

### 3.5. Improving Our Measurements of KOI-142

To quantify how much we can improve our measurements of the masses and eccentricities of these planets with TESS, we first went through a similar process as described in Section 3.2. The only difference is that we now include a new transit time observation in 2019 mid-July in our likelihood function. This new transit time observation is the mean of all of the transit times obtained from the Markov chains for 2019 mid-July (BKJD = 3823.01 days) with an uncertainty given by the standard deviation calculated in Section 3.3. After running MCMC again, we analyze the best-fit parameters and errors of the 16th, 50th, and 84th percentiles. Samples from this new posterior distribution are available.

Table 3 lists each of the parameter values and associated errors for both the analysis without TESS data (Section 3.2) and with TESS data (this section). The factor of improvement of our knowledge of this system with TESS data is in the last column. We expect the eccentricity measurements of both planets to be significantly improved and the mass of the inner planet to be improved by more than 5%. Even though the periods for both of these planets were well constrained with just Kepler data, we expect to obtain even more precise period measurements with TESS, with the period uncertainties improving by 42% and 11% for the inner and outer planets, respectively. Due to the considerable improvement on most orbital parameters and planet–star mass ratios, the transit timing uncertainty will be significantly reduced in the future: a single month of observations reduces the scatter in transit times expected in 2026 from 68 minutes to 33 minutes.

To illustrate this future improvement, we calculate the transit time uncertainty the same way as in Section 3.4 but now also included our data associated with the new Markov chains. In Figure 4, the green data points are transit uncertainties without any TESS data and the blue data points are transit uncertainties with our predicted TESS data in 2019 July.

There is clearly a large improvement that will be made when TESS observes this system; continued transit observations (such as through an extended TESS mission) will reduce the future uncertainties even further. The best design for a TESS extended mission with regard to improving the transit uncertainties for Kepler systems will take advantage of the oscillatory nature shown in Figure 4. As mentioned before, the behavior of the transit time uncertainty is due to the fact that at some points in the TTV cycle, the spread in the transit times is large. If we are able to observe KOI-142 at the peaks in Figure 4 where the uncertainty is largest, we will significantly improve our measurements of the system; conversely, observations where the uncertainty is small do not provide new information to distinguish possible physical models of the system. For example, the theoretical TESS data point that we used in Section 3.5 to improve our measurements of KOI-142 was in 2019 July, which is at a time very close to a large uncertainty peak in Figure 4. This concept can be applied to any Kepler system in order to get the best results out of an extended mission. The scatter in time generally follows the phase of the relative orientation of the two planets, which drives the slowly varying TTV signal. We know that the period of a TTV signal obeys the super-periodic equation from Lithwick et al. (2012):

$$P_j = \frac{1}{|j/P' - (j - 1)/P|},$$

where $P$ and $P'$ are the average orbital periods of the inner and outer planets, and their resonance is $jj' - 1$. Because most observed TTV system signals have a period ratio $P'/P$ within 1%–3% of commensurability, typical Kepler systems...
observable with TESS, with periods of 10–20 days, have super-periods of 100–500 days. Each super-period depends on the individual orbital parameters of that system. To measure any one system well, observations should be obtained at a particular phase with a cadence equal to the super-period. To maximize information about many systems, observations will need to be spaced to enable the detection of sinusoidal signals at many different periods, so the ideal observations would not be clustered, but rather aperiodically scheduled to sample many different systems at their transit time uncertainty peaks.

In this work, we only consider the effects of TTVs, not TDVs, which are observed for this system with a semiamplitude of ~5 minutes. Our orbital parameters are similar to those of Nesvorný et al. (2013) even without TDVs (but with three additional quarters of data which were not available at the time of that publication), suggesting that the TDV information does not drive the fit. However, TDVs will be important for this system on TESS timescales. The authors of that paper note they cannot discriminate between two orbital solutions: one with \( \Omega \approx 90^\circ \) and one with \( \Omega \approx 270^\circ \). These two solutions imply a mutual inclination of \( 2^\circ \) or \( 1^\circ \), respectively, as the inner planet could have an inclination either just above or just below \( 90^\circ \). However, these two models predict very different transit durations in 2019. In the case where \( \Omega \approx 90^\circ \), the inner planet will have \( b \approx 0 \) when TESS observes the system, so the transit duration will be approximately 220 minutes. In the other case, \( b \approx 0.8 \) and the transit duration will be 140 minutes. These two will be easily separable with TESS.

For many dynamically interacting systems in which TESS will be able to detect transits, the combination of TESS and Kepler data will be useful to measure system parameters better than Kepler data alone. A detailed analysis of many of these systems, originally characterized in Hadden & Lithwick (2017), is presented in Goldberg et al. (2019).

4. Tidal Decay of Hot Jupiters

Hot Jupiters have been detected in numerous ground and space-based observations, due to their large sizes and short periods, making them easy to find in both RV and transit surveys (Mayor & Queloz 1995; Bakos et al. 2004; McCullough et al. 2005, 2006; Pollacco et al. 2006; Brahic et al. 2016). Hot Jupiters are still interesting targets, with many questions about the formation and interior structure of these planets still outstanding (e.g., Guillot 2005; Guillot et al. 2006; Nelson et al. 2017; Dawson & Johnson 2018).

Birkby et al. (2014) searched for evidence of tidal decay in the population of hot Jupiters known then, finding inconclusive results from the available data. Patra et al. (2017) investigated the transit timing anomaly of WASP-12b, a hot Jupiter with an orbital period of 1.09 days, and modeled this planet’s orbital period, arguing that WASP-12b is more likely in orbital decay than in a precession cycle. Patra et al. (2017) acknowledged, however, that more observations are necessary to completely rule out the precession model. Further investigations of WASP-12b’s transit timing anomaly agree that WASP-12b is likely in orbital decay and that classifying WASP-12 as a subgiant accurately explains the observed change in period as well as its decay timescale of 3 Myr (Weinberg et al. 2017; Bailey & Goodman 2019).

Ragozzine & Wolf (2009) demonstrated how measuring apsidal precession enables one to infer properties of the interior structure of the planet and star, such as \( Q_\ast \). \( Q_\ast \) is the tidal quality parameter of a star, which is the measure of the star’s response to tidal distortion due to a perturbing body. Ragozzine & Wolf (2009) similarly mention that a longer baseline will be necessary in order to measure apsidal precession in many very hot Jupiter systems.

In Section 2.2, we showed that TESS will be able to observe many of the hot Jupiters detected by Kepler. We now investigate whether TESS will be powerful enough and will considerably extend the baseline of observations such that we can measure orbital decay or precession, and learn more about the interior structure and formation of hot Jupiter planets and their host stars.

4.1. Hot Jupiter Transit Uncertainties in 2019 July with Kepler and TESS

In the following analysis, we consider the 366 planets from Section 2.2 with radii smaller than \( 30 R_\oplus \) that were detectable in two sectors at a 3\( \sigma \) level.

We propagate the errors from the period and transit epoch (obtained from the NASA Exoplanet Archive cumulative KOI table) into 2019 July to compute the uncertainty in transit times given Kepler data alone.

To compute the TESS uncertainty, we simulate light curves using the \texttt{batman} package of Kreidberg (2015) as in Section 3.3. We create a model for each planet and add noise by sampling from a normal distribution with a standard deviation given by the expected noise from TESS calculated in Section 2.1 and listed in Table 2. We contaminate the flux values of the model depending on the TESS contamination ratio for that system and use these new flux values as “observed” data. We vary the time of inferior conjunction many times and use the same limb-darkening coefficients as in Section 3.3. This time, we sample a flux value every 2 minutes within a 30 minute interval, assuming most detectable hot Jupiters will be observed at short cadence, but we stack transits together depending on the planet’s period so the time of sampling varies for each system. We find the posterior distribution of transit times, measure the 1\( \sigma \) width of this distribution, and take that as the expected transit timing uncertainty for each system.

To find the total uncertainty in 2019 July, we combine the uncertainty in the transit times inferred from TESS data with the uncertainty from Kepler data.

4.2. Hot Jupiter Transit Times in 2019 July

We first calculate the expected transit time in 2019 July for these systems based on a constant-period model.

We next calculate the transit time in 2019 July for these systems using an orbital decay model. To do this, we first find the change in period due to orbital decay using Patra et al.’s (2017) Equation (14):

\[
\frac{dP}{dt} = \frac{27\pi}{2Q_\ast} \left( \frac{M_p}{M_\ast} \right) \left( \frac{R_p}{a} \right)^5,
\]

where \( Q_\ast \) is the tidal quality parameter of the star. Because we do not have measurements for \( M_p \) for many systems, we first assume all planets with radii larger than \( 8 R_\oplus \) to be a Jupiter-mass planet. We calculate \( M_p \) for planets with radii less than \( 8 R_\oplus \) by using the planet mass–radius relationship of Lissauer

\[
M_p \approx 1.06\left( \frac{R_p}{R_\oplus} \right)^{2.68}
\]
Table 4
List of Parameter and Critical $Q_\ast$ Values for All Detectable Systems at the $3\sigma$ Level in Two Sectors

| KOI    | Kepler Name     | Period (days) | $R_\ast$ ($R_\oplus$) | $M_\ast$ ($M_\oplus$) | $\sigma$ Kepler (minutes) | $\sigma$ TESS (minutes) | $\log_{10}(Q_{\ast,e})^a$ | $\log_{10}(Q_{\ast,c})^b$ |
|--------|-----------------|---------------|------------------------|-----------------------|---------------------------|--------------------------|---------------------------|---------------------------|
| K00001.01 | Kepler-1 b      | 2.470613      | 13.04                  | 0.97                  | 0.06                      | 0.16                     | 4.03                      | 4.03                      |
| K00002.01 | Kepler-2 b      | 2.204735      | 16.10                  | 1.45                  | 0.11                      | 0.28                     | 5.06                      | 5.06                      |
| K00003.01 | Kepler-3 b      | 4.887803      | 4.82                   | 0.83                  | 0.52                      | 0.26                     | 0.79                      | 1.88                      |
| K00004.01 | ...             | 3.849372      | 12.94                  | 1.48                  | 3.31                      | 2.68                     | 3.76                      | 3.76                      |
| K00007.01 | Kepler-4 b      | 3.213669      | 4.13                   | 1.10                  | 1.86                      | 5.75                     | 1.63                      | 2.86                      |
| K00010.01 | Kepler-8 b      | 3.522498      | 14.59                  | 1.13                  | 0.31                      | 1.37                     | 3.15                      | 3.15                      |
| K00012.01 | Kepler-444 b    | 17.855222     | 13.16                  | 1.39                  | 1.12                      | 1.86                     | –0.46                     | –0.46                     |
| K00013.01 | Kepler-13 b     | 1.763588      | 21.42                  | 2.47                  | 0.13                      | 0.30                     | 5.79                      | 5.79                      |
| K00017.01 | Kepler-6 b      | 3.234699      | 13.06                  | 1.05                  | 0.20                      | 1.06                     | 3.27                      | 3.27                      |
| K00018.01 | Kepler-5 b      | 3.548465      | 14.92                  | 1.32                  | 0.28                      | 1.51                     | 3.32                      | 3.32                      |

Notes. These systems are ordered by KOI name. This table will be published in its entirety in machine-readable format. A portion is reproduced here as a guide to the format. A version is also available in the source materials for this manuscript on arXiv.

$^a$ Calculated using planet masses obtained from the mass–radius relation for planets with radii $<8R_\oplus$. Otherwise, assumed planets with radii $\geq 8R_\oplus$ to be Jupiter-mass planets.

$^b$ Leaving planet masses as an input parameter.

(This table is available in its entirety in machine-readable form.)

Figure 5. Histogram showing the spread in $Q_{\ast,c}$ values (calculated using planet mass–radius relation) for systems that have a greater than 50% chance of detection with TESS in two sectors at the $3\sigma$ level. The seven systems with $Q_{\ast,c}$ greater than $10^5$ will be good candidates for potentially detecting orbital decay.

4.3. Candidate Decaying Systems

We compute the ratio of the transit difference between the models and the total uncertainty in Sections 4.1 and 4.2. We calculate the threshold $Q_{\ast,c}$ values that would make orbital decay detectable at $3\sigma$, which we call $Q_{\ast,c}$. For every system, $Q_{\ast,c}$ is the value at which we expect to detect tidal decay if the true $Q_\ast$ for that star is less than $Q_{\ast,c}$. Therefore, larger values of $Q_{\ast,c}$ imply a higher likelihood of detection of tidal decay for given stellar parameters.

Figure 5 shows the spread in $Q_{\ast,c}$ values that would make orbital decay detectable at $3\sigma$. A typical value of $Q_\ast$ is around $1 \times 10^5$ (Dobbs-Dixon et al. 2004) and so any planets that have $Q_{\ast,c} \geq 1 \times 10^5$ will be good candidates to potentially measure orbital decay.

We find two confirmed systems and six candidates that have $Q_{\ast,c} \geq 1 \times 10^5$ and are thus good candidates for orbital decay detection. We inspect the light curves of each candidate system by eye. We conclude that KOI-7430 is a likely false positive detection. We inspect the light curves of each candidate system leaving seven systems in total.

In Table 4, we list the $Q_{\ast,c}$ values for 10 detectable planets at the $3\sigma$ level in two sectors. We calculated $Q_{\ast,c}$ as discussed in the previous sections (using the planet mass–radius relationship to compute masses for planets smaller than $8R_\oplus$). As the planet masses are typically unknown, we also provide values for $Q/M_p$ in units of Jovian masses. As masses of these planets are measured, these updated masses can be used directly to update the expected $Q_{\ast,c}$ values.

TESS is essential for this task. For each of the seven candidate or confirmed systems with $\log(Q_{\ast,c}) > 5.0$, we repeat this exercise considering Kepler data alone, finding that in all cases TESS transits provide a significant extra constraint. For the median system, we find that $\log(Q_{\ast,c})$ increases by 0.52 when TESS observations are added to the existing Kepler data, increasing our sensitivity to $Q_\ast$ by a factor of 3.1.

4.4. Fisher Matrix Analysis

One may ask how new data from TESS can compete with the highly precise four-year Kepler data set. Or, if Kepler was not sensitive to tidal decay for the set of planets it observed, how will TESS be sensitive to it. The answer is that the phase change of a decaying planet is quadratic, so the longer one waits, the more powerful the lever arm gets for constraining this curvature. We perform a Fisher matrix analysis to determine the minimum-variance bound for each of three parameters, $a = (T_0, P, P)$, in which the model time is

$$t_m(i) = T_0 + iP + \frac{1}{2}i^2P,$$

(3)
where $i$ is the transit number with 0 at the center of the Kepler data set. The figure of merit is

$$
\chi^2 = \sum \frac{(t(i) - t_n(i))^2}{\sigma_i^2},
$$

where the measured midtime and uncertainty of a measured transit $i$ are $t(i)$ and $\sigma_i$, respectively. The curvature of the $\chi^2$ surface informs the minimum size of the uncertainties on the parameters, and this calculation is shown in the Appendix. The uncertainties on the three parameters from Kepler alone are

$$
\sigma_{\theta_0} = 3/2(\sigma/\sqrt{N}), \quad \sigma_P = 2\sqrt{3}(P/T)(\sigma/\sqrt{N}), \quad \sigma_P = 12\sqrt{3}(P/T)^2(\sigma/\sqrt{N}),
$$

where $T_0$ is the measured time of transit, $P$ the orbital period, $T$ the length of the survey, and $N$ the number of observed transits. Note that if the survey is of high duty cycle, which is true of the Kepler survey, $N \approx T/P$. Therefore, the precision on the period determination improves as the 3/2 power of survey length $T$, and the precision on period change rate improves as the 5/2 power of survey length.

We then consider a second data set augmenting the first data set, which has the centers of the two data sets offset by $D$ in time, with a certain value of $\sigma_D/\sqrt{N_2}$, and a time baseline $T_2$ (within the second data set, over which transits are uniformly spread). If the values of these survey parameters are as given in Model 2 of Table 5, for instance, with the addition of new data, the uncertainty improves by 22% for $T_0$, worsens by 1% for $P$, and improves by 48% for $P$. We suppose the formal uncertainty on $P$ can worsen because of correlations between $P$ and the other parameters when considering a heterogeneous data set. The period derivative itself, the quantity of interest for tidal decay, always improves with more data, however.

The uncertainty in the period derivative, the quantity of interest for measuring orbital tidal decay, decreases as the square of the observed time baseline and the square root of the number of observed transits as shown in Equation (6). Therefore, for the purposes of maximizing the number of detections of tidal dissipation in an extended mission, additional campaigns focused on the Kepler field should be scheduled at the end of the extended mission. This scheduling would allow for the largest possible change in period between the start of the Kepler mission and the final TESS observations.

Two real examples, to which we apply this formalism, are KOI-13 and KOI-18. The former is systematics-dominated in Kepler, and transit time uncertainties determined by TESS may be only $\sim 2.3$ times larger than Kepler. The uncertainty on the period change will decrease by a factor of about 3, with one sector of TESS observations. In the case of KOI-18, both Kepler and TESS are photon limited, and hence a more modest improvement is expected (Table 5).

### 5. Discussion and Future Prospects

#### 5.1. The Noise Properties of TESS Data

We analyzed TESS’s capabilities in detecting and improving our measurements of planetary systems in the Kepler field. By converting data from the NASA Exoplanet Archive into probabilities of detection for each planet, we found 260 (161) planets in one sector of observations and an additional 120 (18) planets in two sectors that have a strong chance of being recovered at the 3$\sigma$ (7.1$\sigma$) level. The majority of these recovered signals are hot Jupiter planets; nevertheless, there are still some smaller, rocky planets that can be recovered, such as KOI-6635.01, which orbits a small, bright star.

Although the Kepler signal detection threshold was 7.1$\sigma$, we believe that a 3$\sigma$ level will be largely sufficient for TESS in the Kepler field because the goal is to characterize planets that are already known to exist, rather than to detect new planets. Additionally, it is important to note that throughout this analysis, we made the following assumptions: (1) that Sullivan et al.’s (2015) model is correct in predicting the total noise TESS will experience while observing each system, (2) that the total noise was completely white, and (3) that the contamination ratios from Brown et al. (2011) and Stassun et al. (2018) are correct. If any of these assumptions are incorrect or too restrictive, our results will differ from what we originally predicted. With the public availability of TESS data and pipelines to produce light curves (e.g., Feinstein et al. 2019), the noise properties of stars hosting known planets can be understood (T. Daylan et al. 2019, in preparation).

The expected yield of planets in the Kepler field will provide a direct opportunity to characterize the noise properties and general performance of the TESS detector. For every confirmed planet or planet candidate in the Kepler field, we provide a probabilistic forecast of detection in TESS data. By comparing these results to the planets actually detected in late 2019, we will be able to understand specific weaknesses in the assumptions used in the development of the TESS Input Catalog (Stassun et al. 2018), which is used for target selection in the primary mission and will likely be used in the same way in an extended mission. For example, if planet yield in regions of high stellar density is higher than expected, it might suggest that the assumptions in the TIC about stellar contamination are too conservative. The precision of TESS is not higher than that of Kepler. In Kepler data, the measurement of $\eta_\sigma$ was challenging because stellar variability was higher than expected. However, given the existence of Kepler data, we already know the intrinsic variability of stars at the level of TESS precision, so any discrepancies in planet yield are, for TESS, more likely due to limitations of the instrument or the input catalog, rather than in the inherent variability of stars, which is now better understood. As the Kepler field provides the largest sample of known transiting planets available, these predictions provide the best available opportunity to understand the performance of TESS on known, characterized planetary signals.
5.2. The Future of Multitransiting Systems

Using our probabilities of detection for each planet, we organized our data such that we could determine how capable TESS will be in detecting multiplanet systems. We found that TESS will be expected to recover more than one planet in only \( \sim 5\% \) of known multiplanet systems. Future studies dealing with multiplanet systems will likely be more successful with PLATO observations of the Kepler field, perhaps in the mid-2020s.

For planets that TESS will be able to detect, we expect that TESS will be a very useful tool in improving our measurements of these systems. For KOI-142, we predict that TESS will improve a majority of the planetary parameters as well as star–planet mass ratios, which yields an improvement of over 50\% in the transit timing uncertainties in the future.

The combination of Kepler and TESS will also provide a useful test case for a possible extended TESS mission. The primary TESS mission will cover \( \approx 80\% \) of the sky. An extended mission proposal has now been submitted; additional extensions are still subject to change. With more data, smaller planets, which are more often found in multiple-planet systems, can be recovered. Some of these multiple-planet systems will exhibit TTVs and TDVs; by combining these observations together across multiple sectors with large data gaps, masses and orbital parameters will be measurable for systems without the need for any additional follow-up resources. Observations of the Kepler and TESS fields taken together will provide insights into best practices to combine these data sets to look for dynamical effects.

5.3. Characterizing Tidal Dissipation

Because we predict TESS will be most sensitive to hot Jupiters, we analyzed whether TESS will be able to detect tidal orbital decay in hot Jupiter systems. We found two confirmed and five candidate planets that will be good candidates for detecting orbital decay. If we are able to detect orbital decay in any of the systems in the Kepler field, we will be able to better understand their interiors and perhaps more accurately test theories of planetary formation and migration.

One may ask why TESS is strictly necessary for this task, as ground-based observations should be achievable for these giant planets. In this work, to measure a discrepancy in transit times in 2019 from the previous linear ephemeris, we assumed that all transits over 27 days could be observed. For the cases of Kepler-2 and Kepler-13, this is 12 and 15 transits, respectively. While 15 transits could be observed from the ground, that would require a significant investment of observing resources spread over months to collect the same amount of data for a single target. Additionally, these data may lead to a lower precision than what can be acquired from TESS, as ground-based data contain time-correlated noise, due to atmospheric variability on few-minute timescales, which can significantly inhibit precise transit time measurements (e.g., Pont et al. 2006). Therefore, TESS data provide the best opportunity to combine new observations with Kepler data to measure the tidal orbital decay of hot Jupiters, although these data could certainly be combined with additional ground- or space-based photometry once candidates are identified.

5.4. Planetary Evolution with TESS

We find, in general, that long time baseline observations of planetary systems with space-based observatories can be useful for understanding the physical parameters and long-term evolution of planetary systems. This is applicable not only to combinations of Kepler and TESS data, but also to missions like K2, where data spanning multiple years when multiple campaigns overlap can be used to confirm and measure masses of dynamically interacting planetary systems (A. Hamann et al. 2019, in preparation).

In time, as TESS continues to reobserve the Kepler field through an extended mission, each additional campaign will yield approximately 50 more planets smaller than the size of Neptune that have a good chance of being detected (Table 1). Because these smaller planets are typically found in multiplanet systems, we will be able to better characterize the systems through TTVs and TDVs. These observations will enable us to improve our understanding of transiting and nontransiting planets in these systems. In some cases, we might observe planet precession due to a nontransiting perturber through duration variations, identifying new planets in these systems that were previously missed (Ribas et al. 2008; Mills & Fabrycky 2017). Moreover, most sub-Neptunes in multiple-planet systems are confirmed planets (Morton et al. 2016), so these observations will largely probe the dynamical evolution of bona fide planets.

Although TESS may not be as sensitive to as many planets as *Kepler*, we show that TESS will be extremely effective in improving our measurements and understanding of certain systems. This improvement will only be enhanced by an extended mission that continues to include observations of the Kepler field, enabling the detection of smaller confirmed planets.

5.5. Possible TESS Extended Mission Strategies

A TESS extended mission will have many disparate goals. Here, we outline possible strategies to maximize the scientific yield of already known planets in the Kepler field. To redetect as many planets as possible, especially the small planets that are commonly found in multiple-planet systems (e.g., Fabrycky et al. 2014), maximizing the number of sectors in which the Kepler field is reobserved is the primary requirement: observations in six or more sectors is required to detect even 10\% of these systems.

Many of these systems that would be detected through additional sectors of observations have TTVs. The ideal strategy for maximizing our ability to characterize these systems would be aperiodic observations of the Kepler field. Precise transit times are needed to constrain orbital parameters like masses and eccentricities, but as shown in Section 3, the uncertainty in future transit times is a strong function of relative orbital phase for these systems. Therefore, observations at particular phases in the “super-period” are required. As every system has a different super-period, typically over the range of 100–500 days, to maximize the power of TESS to characterize these systems, we require sectors spaced in time to provide power over as much of this range as possible.

Finally, to measure tidal dissipation, as shown in Section 4, observations should be scheduled as late in the mission as possible. This is intuitive: as in this case the planet’s orbital period is monotonically decreasing, at the end of the mission
the period has the largest change from the start of the mission. This case is somewhat at odds with the previous case. However, as this one is likely to provide the largest scientific yield from the mission (at present, there is only one system with tentative tidal dissipation; Patra et al. 2017), we encourage the TESS team to consider the viability of this strategy in any and all extended mission plans to guarantee the community can get the most out of an extended mission covering the Kepler field. We are looking forward to receiving data from TESS in the Kepler field and gaining a more comprehensive understanding of planets beyond our solar system.

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Facilities: Kepler, Exoplanet Archive.
Software: numpy (Van Der Walt et al. 2011), matplotlib (Hunter 2007), TTVFast (Deck et al. 2014), emcee (Foreman-Mackey et al. 2013), batman (Kreidberg 2015), pandas (McKinney 2010), seaborn (Waskom et al. 2017).

Appendix
Derivation of the Fisher Matrix

To perform a Fisher matrix analysis, we form the array

\[
\frac{\partial^2 \chi^2}{\partial a_i \partial a_k} = \frac{N}{\sigma_i^2} \begin{bmatrix} 2 & 0 & (T/P)^2/12 \\ 0 & (T/P)^2/6 & 0 \\ (T/P)^2/12 & 0 & (T/P)^4/160 \end{bmatrix}
\]

(11)

We evaluate this array first for the Kepler data alone, assuming that \( N \) transit timings are taken uniformly spread through the time span of \( T = 4.02 \) yr, and that each transit time has an equal uncertainty of \( \sigma \). We find

\[
C_{jk} = \frac{\sigma^2}{N} \begin{bmatrix} 9/4 & 0 & -30 (P/T)^2 \\ 0 & 12 (P/T)^2 & 0 \\ -30 (P/T)^2 & 0 & 720 (P/T)^4 \end{bmatrix}
\]

(12)

To combine TESS data with Kepler data, we evaluate Equation (10) numerically, then invert, giving the values in Table 5.

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