Predicted Yield of Transits of Known Radial Velocity Exoplanets from the TESS Primary and Extended Missions

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Abstract

Radial velocity (RV) surveys have detected hundreds of exoplanets through their gravitational interactions with their host stars. Some will be transiting, but most lack sufficient follow-up observations to confidently detect (or rule out) transits. We use published stellar, orbital, and planetary parameters to estimate the transit probabilities for nearly all exoplanets that have been discovered via the RV method. From these probabilities, we predict that 25.5±0.7% of the known RV exoplanets should transit their host stars. This prediction is more than double the amount of RV exoplanets that are currently known to transit. The Transiting Exoplanet Survey Satellite (TESS) presents a valuable opportunity to explore the transiting nature of many of the known RV exoplanet systems. Based on the anticipated pointing of TESS during its two-year primary mission, we identify the known RV exoplanets that it will observe and predict that 11.7±0.3% of them will have transits detected by TESS. However, we only expect the discovery of transits for ~3 of these exoplanets to be novel (i.e., not previously known). We predict that the TESS photometry will yield dispositive null results for the transits of ~125 RV exoplanets. This will represent a substantial increase in the effort to refine ephemerides of known RV exoplanets. We demonstrate that these results are robust to changes in the ecliptic longitudes of future TESS observing sectors. Finally, we consider how several potential TESS extended mission scenarios affect the number of transit RV exoplanets we expect TESS to observe.

Key words: planets and satellites: detection – surveys – methods: statistical

Online material: color figures, machine-readable table

1. Introduction

The vast majority of presently known exoplanets were discovered by dedicated transit surveys using space-based, e.g., Kepler (Borucki et al. 2010; Twicken et al. 2016) and ground-based observatories, e.g., KELT, HATNet, and WASP (Pepper et al. 2003; Bakos et al. 2004; Pollacco et al. 2006). The sheer number of stars that can be photometrically monitored in such surveys clearly overwhelms the probability of having the proper viewing geometry to witness a transit. However, the inverse proportionality between transit probability and orbital semimajor axis (e.g., Beatty & Gaudi 2008) has largely limited the exoplanet characteristics inferred from transit surveys to the inner regions of planetary systems, within a few tenths of an au from the host star (e.g., Howard et al. 2012).

The detection of exoplanets in radial velocity (RV) measurements of their host stars (e.g., Pepe et al. 2004; Howard et al. 2010) is less biased toward short-period exoplanets than the transit method. As a result, RV surveys have revealed exoplanet characteristics at moderate orbital distances (tenths of an au to several au from the host star), which has greatly benefited theoretical investigations of planet formation (e.g., Dawson & Murray-Clay 2013; Santerne et al. 2016).

At the intersection of the sensitivities of the transit and RV methods exists an opportunity to improve the accuracy of exoplanet demographics and properties through the validation and synthesis of independent observations. The combination of transit and RV occurrence rates better constrains the true underlying exoplanet population and identifies the biases of each method (e.g., Howard et al. 2012; Wright et al. 2012; Dawson & Murray-Clay 2013; Guo et al. 2017). Furthermore, the combination of planet mass and radius—the basic properties inferred from RV and transit observations, respectively—advances the status of
an exoplanet from merely a detected world, to one that can be characterized in depth. An exoplanet’s bulk density (derived from planet mass and radius) provides a window to its internal composition (e.g., Weiss & Marcy 2014). Furthermore, mass and radius measurements are imperative for atmospheric characterization, which may place even more precise constraints on planetary interior (e.g., Miller & Fortney 2011; Thorngren et al. 2016) and formation processes (e.g., Garaud & Lin 2007; ¨Oberg et al. 2011).

One of the following two approaches is typically employed to obtain measurements of an exoplanet’s mass and radius. Either the exoplanet is detected in a transit survey and follow-up RV observations covering the orbital phase of the planet are acquired, or the exoplanet is detected in an RV survey and follow-up photometry within the predicted transit window is acquired. Here, we consider the latter, which is potentially the riskier of the two approaches. RV exoplanet detections are biased toward edge-on orbital inclinations, but substantial photometric follow-up campaigns may nonetheless fail to measure the planet radius in the event that the exoplanet is non-transiting. In many cases, this risk factor has precluded sufficient photometric monitoring in search of transits for known RV exoplanets. This is especially true for exoplanets with relatively long orbital periods.

Substantial efforts have previously been made to improve orbital ephemerides known exoplanets. For exoplanets discovered in transit surveys, observations of subsequent transits are typically needed to constrain transit timing variations (e.g., Dalba & Muirhead 2016; Wang et al. 2018). For exoplanets discovered in RV surveys, multiple types of follow-up observations are usually required. Efforts to follow-up known RV exoplanets such as the Transit Ephemeris Refinement and Monitoring Survey (TERMS; Kane et al. 2009) acquire spectroscopic and photometric observations to search for transits and characterize host stars. TERMS and other similar efforts have successfully ruled out (e.g., Kane et al. 2011a) and discovered (e.g., Moutou et al. 2009) transits of a handful of RV exoplanets. However, there are simply not enough telescope resources to target all known RV exoplanets individually. Instead, this luxury can potentially be afforded by dedicated large-scale transit-hunting missions.

With the launch of the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) came the new opportunity to acquire light curves of known hosts of RV exoplanets. The potential yield of exoplanet discoveries from TESS has been thoroughly explored (Sullivan et al. 2015; Barclay et al. 2018; Ballard 2018; Huang et al. 2018), yet little effort has been focused on the yield of transits from known RV exoplanets. Yi et al. (2018) evaluated the detectability of RV exoplanets from the anticipated Characterizing Exoplanets Satellite (CHEOPS; Broeg et al. 2013). However, their investigation focused on making accurate predictions of RV exoplanet radii and subsequently transit signal-to-noise ratio (S/N) to maximize the efficiency of the CHEOPS observing strategy. Yi et al. (2018) calculated single point-estimates of transit probability and provided a qualitative interpretation, but their predicted yield of CHEOPS transits was set by S/N arguments (Yi et al. 2018). An extension of the transit probability calculation to the expected yield of transits for all known RV exoplanets, including those to be observed by TESS, remains to be done.

In this paper, we take a probabilistic approach to predicting the number of RV exoplanets that transit their host stars and the fraction of those that TESS may detect. In Section 2, we explain the selection criteria used to generate our sample of known RV exoplanets. In Section 3, we describe the determination of all necessary exoplanet parameters and the Monte Carlo simulation of each exoplanet’s transit probability. For each exoplanet in our sample, we report parameters describing the probability density function for its transit probability. In Section 4, we predict the total number of RV exoplanets that transit their host stars and offer comparison to the currently known sample of transiting RV exoplanets. In Section 5, we refine the predicted number of transiting RV exoplanets to only those that may be observed by TESS during its primary mission. We then extend this consideration of TESS to several potential extended mission scenarios. In Section 6, we discuss the influence of several simplifying assumptions that we employ in our analysis on our results. Finally, in Section 7, we summarize our findings.

2. Selection of RV Exoplanets

All exoplanet data used here were acquired from the NASA Exoplanet Archive\(^\text{11}\) (NEA). Of the total 3778 confirmed exoplanets, we select only the 677 exoplanets that had “Radial Velocity” as the discovery method. A small fraction of this subset of exoplanets has since been found to transit their host stars. We do not exclude these exoplanets from our analysis so that we may compare the number of RV exoplanets that are currently known to transit with the number that we predict to transit based on our statistical arguments.

3. Transit Probability

For an exoplanet on an eccentric orbit about its host star, the probability that a distant observer witnesses a transit \((p_{\text{transit}})\) can be expressed as

\[ p_{\text{transit}} = \frac{(R_p + R_\star)[1 + e \cos(\pi/2 - \omega)]}{a(1 - e^2)}, \]

where \(R_p\) is the planetary radius, \(R_\star\) is the stellar radius, \(a\) is the orbital semimajor axis, \(e\) is the orbital eccentricity, and \(\omega\) is the longitude of periastron (e.g., Kane 2007; Winn 2010). This relation assumes a uniform distribution for the cosine of the orbital inclination and ignores the prior probability distribution

\(^{10}\text{The code developed here to predict the transit probabilities of RV exoplanets will be made publicly available at https://github.com/pdalba/transit_prob.}\)

\(^{11}\text{Accessed 2018 August 28.}\)
for the exoplanet mass. Therefore, when applied to RV exoplanets, Equation (1) is the prior transit probability, not the posterior transit probability (Ho & Turner 2011, Stevens & Gaudi 2013). For Jupiter-like exoplanets, the prior and posterior transit probabilities are nearly equal (Stevens & Gaudi 2013). Given that the sample of known RV exoplanets is comprised of mostly Jupiter-like exoplanets, we continue our analysis using the relation for prior transit probability (Equation 1). The implications of this choice are considered in Section 6.3.

The NEA data have been federated from multiple sources, so some exoplanets lack one or more of the parameters needed to evaluate Equation (1). Furthermore, the vast majority of exoplanets in our sample do not have reported $R_p$ values, as they either do not transit or have not been found to transit their host stars. Before evaluating transit probabilities, we give special consideration to missing parameter values and the estimation of planet radii.

3.1. Missing Parameter Values

In some cases, the NEA lacks values of the physical parameters necessary to evaluate Equation (1). Here, we explain our decision regarding missing data.

If the NEA does not contain a value of the longitude of periastron, we assume $\omega = \pi/2$. If the NEA does not contain a value of orbital eccentricity, we assume $e = 0$ (i.e., a circular orbit). The assumption of $e = 0$ is somewhat of a simplification. The long-period nature of many of the known RV exoplanets suggests that they likely have nonzero orbital eccentricities (Kipping 2013). The assumption of $e = 0$ therefore yields a lower limit for the transit probability. The resulting effect on the full set of transit probability calculations is likely minimal, but we encourage any future extensions of this work to consider physically-motivated eccentricities, such as Beta (Kipping 2013) or Rayleigh (e.g., Fabrycky et al. 2014) distributions.

If the NEA does not contain a value of stellar radius, we estimate its value through the following methods in the following order. First, if values of stellar surface gravity (log $g$) and stellar mass ($M_*$) are available, we estimate $R_*$ from the relation (Smalley 2005)

$$\log g - \log g_\odot = \log \left( \frac{M_*}{M_\odot} \right) - 2 \log \left( \frac{R_*}{R_\odot} \right),$$

where the solar surface gravity is $\log g_\odot = 4.4374$, the solar mass is $M_\odot = 1.989 \times 10^{30}$ kg, and the solar radius is $R_\odot = 6.96 \times 10^8$ m. Second, if values of stellar B-band and V-band magnitudes are available, we estimate $R_*$ with a $B - V$ color look-up table under the assumption that the exoplanet host is a dwarf star (Cox 2000, page 388). Third, if B- or V-band magnitude is unavailable or if the $B - V$ color is outside of the range of the look-up table, we exclude this source from further analysis (four exclusions in total: HD 37124 b, HD 37124 c, HD 37124 d, and HD 41004 B b).

If the NEA does not contain a value of orbital semimajor axis, we use the stellar mass, orbital period ($P$), and planet mass ($M_p$) to estimate $a$ from Kepler’s Third Law under the assumption that the orbit has an edge-on inclination. This assumption slightly biases the value of $M_p$ used in Kepler’s Third Law. However, since $M_p \ll M_*$ in all cases, the effect of this bias on the sum of stellar and planetary mass is negligible. Only 27 exoplanets in our sample lack an $a$ value in the NEA, and each of those contain values for $P$, $M_*$, and $M_p$. Hence, none are excluded from further analysis at this step. After all exclusions, our final sample contains 673 exoplanets (of a total 677 exoplanets).

3.2. Estimation of Exoplanet Radii

Although a few of the exoplanets in our sample have measured radii, we ignore this information to maintain consistency with the vast majority of RV exoplanets. We estimate $R_p$ for all of the exoplanets in our sample using the forecaster tool (Chen & Kipping 2017). forecaster applies probabilistic mass–radius relations to an input exoplanet mass and returns an exoplanet radius along with lower and upper uncertainties based on a posterior probability distribution (Chen & Kipping 2017).

3.3. Monte Carlo Simulations of Transit Probability

Using measurements or estimates of each of the necessary stellar, planetary, and orbital parameters, we conduct a Monte Carlo simulation of the transit probabilities from Equation (1). We begin by approximating a probability density function (PDF) for each physical parameter from which parameter values can be drawn. For parameters with symmetric errors (i.e., equal upper and lower errors), we use a normal PDF peaked at the parameter value and having a standard deviation equal to the parameter uncertainty.

For parameters with asymmetric errors, we employ a skew-normal PDF (Azzalini 1985). A skew-normal PDF is defined by three functional parameters, which control location, shape, and skewness. We obtain these functional parameters through the nonlinear least-squares regression technique described by Espinoza & Jordán (2015, Appendix C). Briefly, the physical parameter value and its upper and lower uncertainties are assumed to have been derived from the 16th, 50th, and 84th percentiles of their PDF. The residuals between these percentiles and those of a skew-normal distribution defined by the location, shape, and skewness parameters are then minimized.

For parameters with no uncertainties provided by the NEA, we assume symmetric errors of 10% the parameter value. This decision primarily influences stellar radii determined through Equation (2). For our sample of exoplanets, many of those lacking values of $R_*$ also lack uncertainties on $M_*$, despite having a listed value for $M_p$. Propagating arbitrarily large errors...
on $M_*$ through Equation (2) leads to even larger errors on $R_*$, which artificially inflate the transit probability. We find that a value of 10% error does not inflate $p_{\text{transit}}$.

We evaluate the transit probability (Equation (1)) $1 \times 10^6$ times, by drawing parameter values from the aforementioned PDFs. Only probabilities in the range $0 \leq p_{\text{transit}} \leq 1$ are allowed. The result is a PDF for $p_{\text{transit}}$, an example of which is shown in Figure 1. The PDFs for $p_{\text{transit}}$ are not necessarily normal, so we describe them using percentiles instead of the mean and standard deviation. In Table 1, we describe the location and scale of the $p_{\text{transit}}$ PDFs for all exoplanets in our sample using the 16th, 50th, and 84th percentiles of the distribution.

4. Predicted Number of RV Exoplanets that Transit Their Host Stars

We use the transit probability PDFs for each exoplanet in our sample to predict the total number ($N$) of RV exoplanets that have the proper orientation to transit their host stars. First, we let $n_i$ be a random variable representing the number of transits the $i$th exoplanet contributes to the total. The value of $n_i$ can either be zero or unity. The expectation of $n_i$ is simply $\mathbb{E}[n_i] = p_{\text{transit},i}$. It follows that the total number of transiting planets in the entire sample of 673 RV exoplanets is described by

$$N = \sum_{i=1}^{673} p_{\text{transit},i}. \quad (3)$$

For each of the $1 \times 10^6$ evaluations of the transit probability, Equation (3) is also evaluated, resulting in a PDF for $N$ (Figure 2). The distribution of $N$ has a mean of 25.5 exoplanets and a standard deviation of 0.66 exoplanet. The 16th, 50th and 84th percentiles of the distribution of $N$ values are 24.8, 25.5, and 26.2 exoplanets, respectively, which (to significant figures) yields a final estimate of $N = 25.5^{+0.7}_{-0.7}$ exoplanets.

How does the predicted number of RV exoplanets that transit compare to the number of RV exoplanets that have actually been found to do so? Of our sample of 673 RV exoplanets, only 12 have been found to transit their host stars.\(^{12}\) Hence, the current number of transiting exoplanets from our sample is more than 19 standard deviations below the expectation. This suggests that additional photometric monitoring of RV exoplanets—and especially those with high transit probabilities (see Table 1)—is likely to reveal transits.

We consider whether the 12 known transiting RV exoplanets have relatively high transit probabilities compared to the rest of the sample. The 12 RV exoplanets currently known to transit have a mean transit probability of 11.6%. To compare this value to the rest of the sample, we randomly draw $1 \times 10^4$ sets of 12 RV exoplanets (not including those known to transit) and record their mean transit probability. The final distribution of mean transit probabilities has a mean of 3.6% and a standard deviation ($\sigma$) of 1.5%. The 11.6% mean transit probability of the known transiting RV exoplanets is more than 5$\sigma$ higher than the mean of the distribution. This suggests that the sample of RV exoplanets currently known to transit has significantly higher transit probabilities than the rest of the RV exoplanet sample. This result is not surprising as telescope resources that provide follow-up for RV exoplanets are limited and the exoplanets that are most likely to transit have been prioritized.

Efforts to detect or rule out transits of RV exoplanets include the Transit Ephemeris Refinement and Monitoring Survey (TERMS; Kane et al. 2009), which has been refining transit ephemerides and conducting photometric transit searches for RV exoplanets for nearly a decade. TERMS, and other similar efforts, have thoroughly ruled out transits for the exoplanet hosts GJ 581 (e.g., López-Morales et al. 2006; Dragomir et al. 2012a), GJ 876 (e.g., Shankland et al. 2006), HD 114762 (Kane et al. 2011a), HD 63454 (Kane et al. 2011b), HD 192263 (Dragomir et al. 2012b), HD 38529 (b planet, Henry et al. 2013), HD 130322 (b planet, Hinkel et al. 2015a), 70 Vir (Kane et al. 2015), HD 6434 (Hinkel et al. 2015b), and HD 20782 (Kane et al. 2016). Less confident null detections of transits have also been reported for HD 168443 b (Pilyavsky et al. 2011), HD 37605 b (Wang et al. 2012), HD 156846 b (Kane et al. 2011c), and Proxima Cen b (e.g., Kipping et al. 2017; Blank et al. 2018). However, resources for individual efforts such as those listed here are limited. Depending on observing

\(^{12}\) The RV exoplanets already known to transit are those in the NEA with values of "1" in the "pl\_transflag" column including HD 189733 b, HD 209458 b, HD 17156 b, 55 Cnc e, GJ 436 b, HD 97658 b, HD 149026 b, HD 219134 b, HD 219134 c, 30 Ari B b, HD 80606 b, and GJ 3470 b.
| Exoplanet Name          | TIC ID  | \( p_{\text{transit}} \) | \( p_{\text{transit,TESS}} \) | \( \text{Sector(s)} \) | \( \text{Camera(s)} \) | \( \text{Sector(s)} \) | \( \text{Camera(s)} \) |
|------------------------|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| NGC 2682 Sand 364 b    | 294684871 | 0.5 \( ^\pm \) 0.3 | ...             | ...             | ...             | ...             | ...             |
| BD+20 2457 b           | 99734092 | 0.4 \( ^\pm \) 0.4 | 0.03 \( ^\pm \) 0.03 | ...             | ...             | ...             | ...             |
| 55 Cnc e               | 332064670 | 0.29 \( ^\pm \) 0.05 | 0.29 \( ^\pm \) 0.004 | ...             | ...             | ...             | ...             |
| HD 240237 b            | 323919676 | 0.29 \( ^\pm \) 0.1 | 0.21 \( ^\pm \) 0.007 | ...             | ...             | 3, 4             | 3, 3             |
| HD 102956 b            | 428673146 | 0.28 \( ^\pm \) 0.03 | ...             | ...             | ...             | ...             | ...             |
| HD 86081 b             | 27073220 | 0.27 \( ^\pm \) 0.03 | 0.27 \( ^\pm \) 0.003 | 8               | 1               | ...             | ...             |
| 24 Boo b               | 441712711 | 0.26 \( ^\pm \) 0.03 | 0.26 \( ^\pm \) 0.003 | ...             | ...             | 9, 10            | 3, 3             |
| HD 96127 b             | 268634769 | 0.2 \( ^\pm \) 0.1 | 0.01 \( ^\pm \) 0.005 | ...             | ...             | 8               | 2               |
| HD 88133 b             | 54237857 | 0.23 \( ^\pm \) 0.03 | 0.23 \( ^\pm \) 0.003 | ...             | ...             | 8               | 1               |
| HD 24064 b             | 286923464 | 0.29 \( ^\pm \) 0.04 | 0.022 \( ^\pm \) 0.004 | ...             | ...             | 5, 6             | 2, 2             |
| HD 118203 b            | 120960812 | 0.21 \( ^\pm \) 0.02 | 0.21 \( ^\pm \) 0.002 | ...             | ...             | 9               | 3               |
| GJ 674 b               | 20096620 | 0.2 \( ^\pm \) 0.2 | 0.2 \( ^\pm \) 0.2 | 12              | 1               | ...             | ...             |
| HD 1690 b              | 37763102 | 0.21 \( ^\pm \) 0.07 | 0.01 \( ^\pm \) 0.003 | 3               | 1               | ...             | ...             |
| WASP-94 B b            | 68418284 | 0.21 \( ^\pm \) 0.02 | 0.21 \( ^\pm \) 0.002 | 1               | 1               | ...             | ...             |
| HD 212301 b            | 161314759 | 0.2 \( ^\pm \) 0.03 | 0.2 \( ^\pm \) 0.03 | 1, 13           | 3, 3            | ...             | ...             |
| HD 13189 b             | 63564248 | 0.2 \( ^\pm \) 0.03 | ...             | ...             | ...             | ...             | ...             |
| BD+20 2457 c           | 148563075 | 0.2 \( ^\pm \) 0.2 | 0.008 \( ^\pm \) 0.009 | ...             | ...             | 8               | 1               |

Notes.

a Unique identifier from the TESS Input Catalog (TIC, Stassun et al., 2018).

b Transit probabilities and uncertainties are approximated using the 16th, 50th, and 84th percentiles of their probability distributions.

c Cycle 2 sectors and cameras are determined using the ecliptic longitudes and latitudes of Cycle 1 mirrored to the northern ecliptic hemisphere (see the text).

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

strategy, large-scale photometric monitoring programs may be especially helpful for detecting or ruling out transits from known RV exoplanets. The ground-based transit surveys listed above (KELT, SuperWASP, and HATNet/HATSouth) have years of photometric observations of much of the sky. However, the typical magnitudes of known RV planet hosts tend to be brighter than even the bright limit of these surveys. Space-based transit surveys, as discussed in the following section, may then provide the best opportunity to follow up on known RV exoplanets.

5. Predicted Number of Transiting RV Exoplanets to be Observed by TESS

TESS was launched in 2018 April, and is actively searching bright stars for transiting exoplanets. Over the course of its two-year primary mission, TESS will search for transits across most of the sky, including in many of the currently known RV exoplanet systems. TESS has four cameras positioned in a 1 \times 4 array that provide a combined \( \sim 2300 \) deg\(^2\) field of view. TESS scans approximately half of the sky in 13 sectors, each of which receives \( \sim 27 \) days of continuous observation (at either 2- or 30-minute cadence). Depending on the ecliptic longitude and latitude of a known RV exoplanet host, it may be observed in as many as 13 consecutive sectors.

We determine the sectors and cameras in which all 673 exoplanets in our sample will be (or were) observed. We uploaded the NEA right ascension and declination for each exoplanet in our sample to the Web TESS Viewing Tool (WTV; Mukai & Barclay, 2017), which estimates the pointing of TESS’s cameras using predicted spacecraft ephemerides. At the time of writing, the WTV tool was only implemented for Cycle 1 of the TESS primary mission. We estimate the TESS pointings for Cycle 2 by assuming that the ecliptic longitudes of the sector boundaries are the same as Cycle 1, and mirroring the ecliptic latitudes from the southern to the northern ecliptic hemispheres. The output sector(s) and camera(s) (if any) for each RV exoplanet in our sample are provided in Table 1.

We explore how this assumption—and the potential alteration of TESS’s predicted pointing—affects our results by shifting the ecliptic longitudes of the Cycle 2 sector boundaries in increments of \( +5^\circ \), up to a maximum of \( +30^\circ \), and repeating our analysis. This amount of shifting is sufficient to give TESS its original total field of view. We find that specific longitude shifts cause specific stars to receive different amounts of observation or to fall outside of TESS’s field of view (e.g., in between adjacent sectors at low ecliptic latitudes). However, variation of the ecliptic longitudes of the Cycle 2 sector boundaries do not alter the results for all RV exoplanets.
12 That have previously been found to transit their host stars. Of these 12 exoplanets, 8 (HD 189733 b, HD 209458 b, HD 17156 b, 55 Cnc e, GJ 436 b, HD 149026 b, HD 219134 b, and HD 219134 c) are expected to have TESS observational baselines that are equal to or longer than their orbital periods. Hence, these 8 exoplanets are essentially guaranteed to be observed in transit by TESS. Two of the remaining four RV exoplanets already known to transit (GJ 3470 b and HD 97658 b) are not expected to be observed by TESS. GJ 3470 b has an ecliptic latitude of \( \sim -5^\circ \), placing it outside of TESS’s anticipated field of view. HD 97658 b has an ecliptic latitude of \( \sim +19^\circ \), but it falls in a field of view gap between adjacent sectors.14 The other two RV exoplanets already known to transit (30 Ari B b and HD 80606 b) have \((\tau/P)\) ratios of 0.08 and 0.24, respectively, so their respective TESS transit probabilities \( P_{\text{transit, TESS}} \) also equal 0.08 and 0.24.

The contribution of RV exoplanets that are already known to transit can be removed from the predicted value of \( N_{\text{TESS}} \) by subtracting 8 to account for the “guaranteed” transits and by subtracting an additional 0.32 to account for the \( P_{\text{transit, TESS}} \) values of 30 Ari B b and HD 80606 b. In summary, during its primary mission, we predict that TESS will discover transits of \( \sim 3 \) known RV exoplanets that were not previously known to transit.

The low value of \( N_{\text{TESS}} \) can be attributed to the long-period nature of the sample of known RV exoplanets, especially when contrasted with the relatively short observational baseline that most of the TESS fields will receive. The median and mean orbital periods of our exoplanet sample are 381 days and 867 days, respectively, demonstrating the distribution is significantly skewed toward long periods. Of the 673 known RV exoplanets in our sample, 125 have \((\tau/P) \geq 1\), meaning that the TESS baseline does not reduce the probability of observing a transit. For these exoplanets, TESS will be able to confidently refute or confirm the transiting nature of the system. This will represent a substantial contribution to ephemeris refinement efforts such as TERMS (Kane et al. 2009), and one that would

\[
P_{\text{transit, TESS}} \cdot (\tau_i/P_i) = 1
\]

14 If the actual Cycle 2 sector boundaries are defined differently than we have assumed here (in Section 5)—such that HD 97658 is in the field of view of TESS—the transit of HD 97658 b (with \( P \approx 9.5 \) days) will be observed.

exoplanets discussed below in a statistically significant manner. This outcome is expected because the distribution of RV exoplanets and their transit probabilities on the sky is essentially random (Figure 3). Nonetheless, this outcome is significant because it suggests that the search for transits of known RV exoplanets is resilient to changes in the ecliptic longitudes of TESS’s sector boundaries.

Stars at different ecliptic latitudes receive different amounts of TESS observation. If the \( i \)th exoplanet host is observed in a total of \( s \) TESS sectors, then the total duration \( (\tau_i) \) of TESS observation for that exoplanet host can be approximated by \( \tau_i = 27 \) s days. If this exoplanet’s orbital period \( (P_i) \) is greater than \( \tau_i \), then its transit probability as observed by TESS is reduced by a factor of \( (\tau_i/P_i) \). If instead \( P_i < \tau_i \), then the limited TESS baseline does not affect the probability of detecting a transit. This method of estimating transiting probabilities neglects the orbital ephemerides—except for orbital period—of our known RV exoplanets. A justification and discussion of this choice is given in Section 6.

We repeat the Monte Carlo simulation of Section 3.3, but we multiply each value of \( P_{\text{transit, i}} \) by \( (\tau_i/P_i) \) to account for TESS’s limited observational baseline. The probability \( (P_{\text{transit, TESS}, i}) \) that TESS observes a transit of the \( i \)th exoplanet in our sample becomes

where \( (\tau_i/P_i) \) is forced to unity for any exoplanet with an orbital period shorter than the duration of TESS observation.

Values of \( P_{\text{transit, TESS}} \) for each exoplanet in our sample are provided in Table 1 and are displayed in Figure 3.

Following Section 3.3, we combined the individual \( P_{\text{transit, TESS}} \) distributions to predict the total number \( (N_{\text{TESS}}) \) of known RV exoplanets that will be observed to transit their host stars by TESS (Figure 4). We find that \( N_{\text{TESS}} = 11.7^{+0.3}_{-0.3} \) exoplanets, meaning that we predict that TESS will observe transits of 11 or 12 known RV exoplanets in our sample during its primary mission.

We note that our full sample of 673 RV exoplanets includes 12 that have previously been found to transit their host stars. Of these 12 exoplanets, 8 (HD 189733 b, HD 209458 b, HD 17156 b, 55 Cnc e, GJ 436 b, HD 149026 b, HD 219134 b, and HD 219134 c) are expected to have TESS observational baselines that are equal to or longer than their orbital periods. Hence, these 8 exoplanets are essentially guaranteed to be observed in transit by TESS. Two of the remaining four RV exoplanets already known to transit (GJ 3470 b and HD 97658 b) are not expected to be observed by TESS. GJ 3470 b has an ecliptic latitude of \( \sim -5^\circ \), placing it outside of TESS’s anticipated field of view. HD 97658 b has an ecliptic latitude of \( \sim +19^\circ \), but it falls in a field of view gap between adjacent sectors.14 The other two RV exoplanets already known to transit (30 Ari B b and HD 80606 b) have \((\tau/P)\) ratios of 0.08 and 0.24, respectively, so their respective TESS transit probabilities \( P_{\text{transit, TESS}} \) also equal 0.08 and 0.24.

The contribution of RV exoplanets that are already known to transit can be removed from the predicted value of \( N_{\text{TESS}} \) by subtracting 8 to account for the “guaranteed” transits and by subtracting an additional 0.32 to account for the \( P_{\text{transit, TESS}} \) values of 30 Ari B b and HD 80606 b. In summary, during its primary mission, we predict that TESS will discover transits of \( \sim 3 \) known RV exoplanets that were not previously known to transit.

The low value of \( N_{\text{TESS}} \) can be attributed to the long-period nature of the sample of known RV exoplanets, especially when contrasted with the relatively short observational baseline that most of the TESS fields will receive. The median and mean orbital periods of our exoplanet sample are 381 days and 867 days, respectively, demonstrating the distribution is significantly skewed toward long periods. Of the 673 known RV exoplanets in our sample, 125 have \((\tau/P) \geq 1\), meaning that the TESS baseline does not reduce the probability of observing a transit. For these exoplanets, TESS will be able to confidently refute or confirm the transiting nature of the system. This will represent a substantial contribution to ephemeris refinement efforts such as TERMS (Kane et al. 2009), and one that would
otherwise necessitate a tremendous amount of ground-based resources. TESS’s contribution to ephemeris refinement will be especially valuable for exoplanets with long periods. The long-period end of 125 exoplanets with \((\tau/P) \geq 1\) includes HD 40307 g \((P \approx 198\) days, \(p_{\text{transit,TESS}} \approx 0.95\%\)), HD 65216 c \((P \approx 153\) days, \(p_{\text{transit,TESS}} \approx 0.83\%\)), and HD 156279 b \((P \approx 131\) days, \(p_{\text{transit,TESS}} \approx 3.5\%\)) among others (see Table 1).

5.1. Signal-to-noise Considerations for TESS

Our prediction for the number of known RV exoplanets for which TESS will discover transits has so far lacked any consideration of the depths of the potential transits, the brightness of the host stars, and the anticipated precision of the TESS photometry. Here, we briefly consider these factors in relation to detecting transits of RV exoplanets in TESS observations.

In Figure 5, we show the predicted distribution of transit depths for all RV exoplanets in our sample. We approximate transit depth as \(R_R R_p^2 \sum \), where \(R_p\) and \(R_s\) are determined as described in Section 3. The distribution of the predicted transit depths spans \(\sim 2-2 \times 10^5\) parts per million (ppm) and peaks near \(1 \times 10^4\) ppm, which is the equivalent of Jupiter transiting the Sun. This is expected as our sample of RV exoplanets is known to contain mostly giant planets.

It is expected that 1\% precision should be readily achievable for most TESS targets. However, we investigate the TESS detection efficiency of the known RV exoplanet sample more carefully by estimating the signal-to-noise ratio \((S/N_{\text{TESS}})\) of their potential transit signals. First, we assume circular, edge-on transits so that the transit duration \((t_{\text{dur}})\) is given by (Winn 2010)

\[
t_{\text{dur}} = \frac{P}{\pi} \arcsin \left[ \frac{R_s}{a} \left( 1 + \frac{R_p}{R_s} \right) \right].
\]

The transit duration is evaluated with the same parameters used previously to estimate transit probability. Then, for a transit signal containing \(N\) transits, we estimate \(S/N_{\text{TESS}}\) following
Barclay et al. (2018):

\[
\frac{S}{N_{\text{TESS}}} = \frac{(R_p/R_s)^2 \sqrt{N_{\text{dur}}}}{\sigma_{\text{TESS}} (1 + d)}
\]

where \(d\) is the dilution of the transit signal due to nearby sources and \(\sigma_{\text{TESS}}\) is the photometric noise model for TESS from Figure 14 of Sullivan et al. (2015). Predicted values of \(d\) are acquired from the TESS Candidate Target List (Stassun et al. 2018) in the “contratio” column. In Equation (6), \(N_{\text{dur}}\) has units of hr and \(\sigma_{\text{TESS}}\) has units of \(\text{hr}^{1/2}\). We estimate the photometric noise for our sources using their TESS-band magnitudes as a proxy for the standard Johnson–Cousins \(I_C\) band.

In calculating \(S/N_{\text{TESS}}\), we consider the total amount of observing time that a star is expected to receive by defining \(N\) as the integer value of \(\tau/P\) (rounding down). For \(0 < (\tau/P) < 1\), we ascribe \(N = 1\), as if a single transit is detected. The purpose of this calculation is not to consider the probability of such a transit detection, but instead to compare its signal to the noise assuming a transit was to occur.

Figure 6 shows the predicted distribution of \(S/N_{\text{TESS}}\) for the all of the known RV exoplanets that are expected to be observed by TESS. We compare this distribution to the nominal detection threshold of 7.3, which was derived by Sullivan et al. (2015) for TESS following a similar calculation for the original Kepler mission (Jenkins et al. 2010). Of the known RV exoplanets expected to be observed by TESS, 93\% are predicted to have \(S/N_{\text{TESS}} \geq 7.3\). Alternatively, eight exoplanets are expected to have \(S/N_{\text{TESS}} < 1\). These include the five known exoplanets orbiting GJ 667 C (which suffers from extreme flux dilution) and three others orbiting host stars with anomalously large radii values listed in the NEA (i.e., HD 208527, BD+20 2457, and HD 96127). Since the vast majority of RV exoplanets would likely produce transit signals that are significantly larger than TESS’s detection threshold, it is unlikely that the yield of transits from the RV exoplanets would be significantly reduced due to insufficient photometric precision.

5.2. Potential TESS Extended Missions

The long-term stability of TESS’s lunar resonance orbit (Gangestad et al. 2013) coupled with the anticipated use of spacecraft fuel makes an extended mission a realistic possibility. Here, we consider how the predicted number of transits of known RV exoplanets increases for three potential extended mission scenarios. The scenarios discussed here are by no means an exhaustive list of all possibilities. In this discussion, we continue to only use orbital periods and ignore the other orbital ephemerides when estimating TESS transit probabilities (see Section 6).

The first strategy for an extended mission involves obtaining a long observational baseline over a relative small portion of the sky. Scenarios such as “pole” (Bouma et al. 2017) or “C3PO” (Huang et al. 2018) achieve this by pointing TESS toward either of the ecliptic poles for timescales of a year or
longer. As displayed in Figure 3, the known RV exoplanets are distributed approximately evenly across the sky. Therefore, focusing observations on a small area would likely minimize the number of transits detected from known RV exoplanets. This strategy perhaps allows for the recovery of transits from known RV exoplanets with long orbital periods, up to the observational baseline (see Section 7). However, the transit probability for long-period exoplanets is inherently lower, meaning that a transit is less likely to occur regardless of how long the host star is observed.

On the other hand, the second strategy for an extended mission involves repeating the nominal primary mission: dividing the ecliptic hemisphere into 13 sectors, observing each sector for ~27 days, and repeating for the opposite ecliptic hemisphere (e.g., “hemi,” Bouma et al. 2017; Huang et al. 2018). For the ith known RV exoplanet, this strategy yields an extended observational baseline $\tau_{\text{ext},i}$ that satisfies

$$\tau_{\text{ext},i} = (1 + f_{\text{ext},i}) \tau_i,$$

where $f_{\text{ext},i}$ is the number of times during the extended mission that TESS surveys the ecliptic hemisphere containing the ith exoplanet. By substituting $\tau_{\text{ext},i}$ into Equation (4), we find that $P_{\text{transit},\text{TESS}}$ increases by as much as a factor of $(1 + f_{\text{ext},i}$), so long as $(\tau_{\text{ext},i}/P_i) \ll 1$. If this extended mission strategy is employed for only one year in the southern ecliptic hemisphere, then the total value of $N_{\text{TESS}}$ (including both the primary and extended missions) would increase to $12.2^{+0.3}_{-0.3}$ exoplanets. The same calculation for a one-year extended mission facing the northern ecliptic hemisphere yields $N_{\text{TESS}} = 12.6^{+0.3}_{-0.3}$ exoplanets. Following this strategy for a six-year extended mission (three years facing south, three years facing north) would yield $N_{\text{TESS}} = 15.0^{+0.3}_{-0.3}$. We find that, on average, the “hemi” extended mission scenario leads to the discovery of transits for roughly one RV exoplanet per year of the extended mission.

The third strategy for an extended mission involves observing both ecliptic hemispheres over the course of one year using the same pointing as the nominal primary mission, but reducing the sector baseline by 50%, to ~14 days each (e.g., “allsky,” Bouma et al. 2017; Huang et al. 2018). For the ith known RV exoplanet, this strategy yields an extended observational baseline $\tau_{\text{ext},i}$ that satisfies

$$\tau_{\text{ext},i} = (1 + 0.5 f_{\text{ext},i}) \tau_i,$$

which only differs from the “hemi” strategy if the extended mission lasts for an odd number of years. In the event of a single-year extended mission that follows the “allsky” strategy, we estimate that $N_{\text{TESS}}$ would increase to $12.5^{+0.3}_{-0.3}$.

In the interest of detecting transits from known RV exoplanets that are currently not known to transit, TESS extended mission scenarios that provide broad sky coverage, as opposed to long observational baselines, are preferred. For a single or multi-year extended mission, repeating the nominal primary mission pointing with the same sector durations or reduced sector durations produce similar results. Although the predicted number of transiting RV exoplanets rises slowly as a function of extended mission duration, the number of RV exoplanets for which we can rule out transits will increase more rapidly. These dispositive null results will comprise a valuable portion of the science return for known RV exoplanets from the TESS mission.

6. Discussion

In the following sections, we describe several of the simplifying assumptions we employed in our prediction of the yield of transiting RV exoplanets. We also evaluate the significance of these assumptions and any effects they may have had on the results.

6.1. Coplanarity of Multi-planet Systems

Throughout this work, the transit probability of each exoplanet is estimated independently. That is, transit probabilities of exoplanets in multi-planet systems do not take into account the coplanarity of the system or the exoplanets’ mutual inclinations. This simplifying assumption merits mention as our sample consists of 100 multi-planet systems comprising 254 total exoplanets. A more accurate approach would be to convolve the transit probabilities within a system of exoplanets with the likelihood of coplanarity (Brakensiek & Ragozzine 2016).

Depending on a particular system’s properties, considering coplanarity may either increase or decrease the transit probabilities of the members of that system. When considered for the full sample, we do not expect coplanarity to significantly alter the predicted number ($N$) of RV exoplanets that transit or the predicted number ($N_{\text{TESS}}$) that TESS is expected to observe. However, our choice to ignore coplanarity should be considered when interpreting the transit probabilities of exoplanets belonging to multi-planets systems as listed in Table 1.

6.2. Orbital Inclination Bias of the RV Method

As is true for the transit method, the detection efficiency of the RV method of exoplanet discovery increases for more edge-on orbital inclinations. This means that the sample of RV exoplanets discussed in this work is biased toward edge-on orbits. The calculation of transit probabilities according to Equations (1) and (4) ignore this bias in favor of the simplicity offered by the assumption of random inclinations. Therefore, the predictions for the number ($N$) of RV exoplanets that transit and the number ($N_{\text{TESS}}$) of RV exoplanets that TESS should see in transit are lower limits.

There is an additional subtlety to the inclination bias of the RV method. For a given RV precision, a more massive exoplanet is less affected by the inclination bias than a less massive exoplanet because the RV detection efficiency also scales with planet mass. Therefore, less massive (e.g., several $M_\oplus$) RV exoplanets are more
likely to have edge-on inclinations than more massive (e.g., several hundred $M_\oplus$) exoplanets. This subtle point further demonstrates that our predictions for $N$ and $N_{\text{TESS}}$ are lower limits. However, low mass exoplanets comprise only a minor portion of our sample of RV exoplanets, so this bias has a similarly minor effect.

6.3. Prior versus Posterior Transit Probability for RV Exoplanets

The transit probability of an exoplanet detected via the RV method depends on the prior probability density of exoplanet mass as well as prior probability density of orbital inclination (e.g., Ho & Turner 2011). Because Equation (1) does not consider the a priori mass distribution of exoplanet, it does not represent the a posteriori transit probability of an RV exoplanet. Stevens & Gaudi (2013) provided a thorough investigation of posterior transit probabilities that included the derivation of multiplicative factors useful for determining posterior transit probability from prior transit probability. The factors, however, required the assumption of upper limits for exoplanet masses, which we do not have for our sample of known RV exoplanets. Instead of introducing uncertainty through the assumption of mass upper limits, we chose to accept the approximation of Equation (1) as the RV exoplanet transit probability.

The impact of this choice can be evaluated qualitatively using Table 2 of Stevens & Gaudi (2013). Dividing our sample of RV exoplanets into mass regimes based on their measured minimum masses, we find that 12% are “Earth/Super-Earths” (0.1 $M_\oplus$–$10 M_\oplus$), 13% are “Neptunes” (10 $M_\oplus$–100 $M_\oplus$), 48% are “Jupiters” (100 $M_\oplus$–$10^3 M_\oplus$), 23% are “Super-Jupiters” ($10^3 M_\oplus$–$13 M_{\text{Jupiter}}$), and 4% are “Brown Dwarfs” ($13 M_{\text{Jupiter}}$–$0.07 M_\odot$). The posterior transit probabilities for the Earth/Super-Earth, Neptune, and Super-Jupiter regimes (i.e., 48% of our total sample) are larger than the prior transit probabilities by 12%–19% on average. The posterior transit probabilities for the Jupiter regime (i.e., 48.0% of our total sample) are only 1% smaller than the prior transit probabilities on average. The posterior transit probabilities for the Brown Dwarf regime (i.e., 4% of our total sample) are 14% smaller than the prior transit probabilities on average. Had we included the a priori distribution of exoplanet masses in the calculation of transit probability, the vast majority of transit probabilities would have either stayed nearly the same or increased. This caveat again demonstrates that our predictions for $N$ and $N_{\text{TESS}}$ are lower limits.

6.4. Ignoring RV Exoplanet Ephemerides

In determining the fraction of an exoplanet’s orbital phase sampled by TESS observation, we neglect all ephemeris information except for orbital period. This choice is motivated by the lack of precision in the current ephemerides of most RV exoplanets. Figure 2 of Kane et al. (2009) demonstrated that, for orbital periods longer than ~100 days, the size of the exoplanet’s transit window was comparable to its orbital period. Hence, the positions of those exoplanets in their orbits were essentially unknown. In the intervening 10 years since that study, most of the RV exoplanets have not received follow-up observation, so the transit windows have become even longer. Only a small handful of RV exoplanets (e.g., the TERMS targets mentioned in Section 4) have been observed sufficiently frequently and recently to have precise ephemerides that enable a meaningful comparison between the transit windows and the dates of the TESS sectors. Therefore, for consistency, we have assumed that the portions of all exoplanet orbits sampled by TESS observations are random.

7. Summary and Conclusions

We use published stellar, orbital, and planetary parameters to estimate the transit probabilities for nearly all exoplanets that have been discovered via the RV method. Monte Carlo simulations of these transit probabilities enable the prediction that 25.5$^{+0.7}_{-0.7}$ of the RV exoplanets in our sample have the proper orbital inclination to transit their host stars (Figure 2). At the time of writing, the number of exoplanets in our sample that are known to transit is only 12, which is more than 19 standard deviations below the expectation. Hence, we predict that follow-up photometric observations of known RV exoplanets are likely to yield transit discoveries.

The ability of the transit-hunting TESS mission to observe transits of known RV exoplanets is also considered. The vast majority (93%) of RV exoplanets have predicted transit signals with S/N greater than the nominal detection threshold of 7.3 (Sullivan et al. 2015), suggesting that TESS is a suitable observatory for follow-up (Figure 6). We identify the known RV exoplanets that TESS is likely to observe (Figure 3) and recalculate their transit probabilities to account for TESS’s finite observational baseline. Monte Carlo simulations of these updated transit probabilities enable the prediction that TESS will observe transits for $11.7^{+0.3}_{-0.3}$ of the known RV exoplanets in our sample (Figure 4). Of these, only ~3 exoplanets will likely not have been known to transit previously. We find that our prediction is robust to changes in the ecliptic longitudes of TESS’s sector boundaries.

We also expect TESS to be able to confidently rule out transits for ~125 known RV exoplanets that have orbital periods that are less than or equal to the anticipated baselines of TESS observations. Transit probabilities and predicted TESS observation information for each exoplanet in our sample are provided in Table 1.

We consider several possible scenarios for a TESS extended mission in regard to following up known RV exoplanets. The distribution of known RV exoplanets on the sky is essentially
even, so extended missions that emphasize all-sky coverage will maximize the number of orbital ephemerides constraints for known RV exoplanets. We find that a multi-year extended mission with an all-sky observing strategy can increase the total number of RV exoplanets that are found to transit, but only by roughly one exoplanet per year. This increase is not strongly dependent on the specific all-sky observing strategy (i.e., repeating the strategy of the primary mission or observing the full sky each year).

Alternatively, an extended mission scenario that focuses on a smaller portion of sky (e.g., an ecliptic pole) in order to acquire a longer baseline would also complement efforts to follow-up known RV exoplanets. Indeed, 23 of the known RV exoplanets in our sample have ecliptic latitudes within 13° of a pole, and 13 of these have orbital periods longer than 100 days. Detecting a transit of a known long-period RV exoplanet would be an exceptionally valuable, albeit rare, discovery. Having a measured mass and radius, this exoplanet could extend relations of planet density versus stellar insolation and potentially serve as a solar system analog. During a subsequent transit, its transmission spectrum could also be observed, an endeavor that would likely prove fruitful for terrestrial (e.g., Robinson & Reinhard 2018) or giant (e.g., Dalba et al. 2015) long-period exoplanets alike. The observational strategy employed by the TESS primary mission is largely geared toward short-period exoplanets. This is evident by the relatively small number of known RV exoplanets that we predict TESS will observe in transit. An extended mission that focuses on longer period exoplanets, both new and previously known, would likely yield a valuable and complementary science return.

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