Speckle Observations of TESS Exoplanet Host Stars. II. Stellar Companions at 1–1000 au and Implications for Small Planet Detection

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Abstract

We present high-angular-resolution imaging observations of 517 host stars of TESS exoplanet candidates using the ‘Alopeke and Zorro speckle cameras at Gemini North and South. The sample consists mainly of bright F, G, K stars at distances of less than 500 pc. Our speckle observations span angular resolutions of ~ 20 mas out to $1''.2$, yielding spatial resolutions of < 10 –500 au for most stars, and our contrast limits can detect companion stars 5–9 mag fainter than the primary at optical wavelengths. We detect 102 close stellar companions and determine the separation, magnitude difference, mass ratio, and estimated orbital period for each system. Our observations of exoplanet host star binaries reveal that they have wider separations than field binaries, with a mean orbital semimajor axis near 100 au. Other imaging studies have suggested this dearth of very closely separated binaries in systems which host exoplanets, but incompleteness at small separations makes it difficult to disentangle unobserved companions from a true lack of companions. With our improved angular resolution and sensitivity, we confirm that this lack of close exoplanet host binaries is indeed real. We also search for a correlation between planetary orbital radii versus binary star separation; but, given the very short orbital periods of the TESS planets, we do not find any clear trend. We do note that in exoplanet systems containing binary host stars, there is an observational bias against detecting Earth-size planet transits due to transit depth dilution caused by the companion star.

Unified Astronomy Thesaurus concepts: [Speckle interferometry \(1552\)](#); [High angular resolution \(2167\)](#); [Exoplanets \(498\)](#); [Binary stars \(154\)](#)

Supporting material: machine-readable tables

1. Introduction

The Kepler, K2, and TESS missions have provided precise, light-curve photometry for millions of stars and contributed breakthrough advancements in many fields of stellar astrophysics (Borucki et al. 2010; Howell et al. 2014; Ricker et al. 2015). This includes the discovery of thousands of extra-solar planets through the transit method, where a planet passing in front of a star causes a periodic dip in brightness. Due to the large pixel sizes of $4''$ for Kepler/K2 and $21''$ for TESS, nearby stars or unresolved stellar companions within the aperture dilute the transit depth and bias the measured planet radius (Ciardi et al. 2015). About 50% of solar-type exoplanet hosts have companions (e.g., Horch et al. 2014; Matson et al. 2018), so follow-up high-resolution imaging is needed to search for unresolved companions and aid exoplanet validation and characterization.

Understanding how binary companions affect the formation, evolution, and survival of exoplanets is also an important component to understanding planet formation overall. Theoretical studies show that a companion can truncate the protoplanetary disk, leaving less material for planets to form (Martin et al. 2014; Jang-Condell 2015), cause the migration of gas giant planets (Dawson & Johnson 2018), or disperse the disk before planets are able to form (Cieza et al. 2009; Kraus et al. 2012). Observational studies using high-resolution imaging (Kraus et al. 2016; Fontanive et al. 2019; Ziegler et al. 2020, 2021; Howell et al. 2021) and radial

velocities (Wang et al. 2014; Hirsch et al. 2021) have found fewer companions within 100 au around exoplanet hosts than around field stars, supporting the idea that close stellar companions do suppress planet formation.

However, it is difficult to disentangle unobserved companions from a true lack of companions without sufficient angular resolution. The angular separations of the closest companions (< 50 au) around Kepler exoplanet hosts are near or below the diffraction limit of most telescopes, but TESS observed brighter, nearby stars for which we can resolve companions at smaller physical separations from the host star. We present the highest angular resolution speckle images of TESS exoplanet host stars in search of companions at 1–100 au where planet formation would be greatly hindered. We describe our observations and companion detections in Section 2, then create a simulated sample of binary stars to investigate the separation distribution of exoplanet host binaries in Section 3. Our results and conclusions are presented in Sections 4 and 5, respectively.

2. Observations

2.1. Speckle Imaging

We observed 517 stars from the TESS Objects of Interest (TOI) catalog using the ‘Alopeke and Zorro speckle cameras (Scott et al. 2018; N. J. Scott et al. 2021, in preparation) on the

Table 1
Gemini Observing Log

TOI	TIC	TESS Mag.	Distance (pc)	T_{eff} (K)	Tel	UT Date (MM/DD/YY)	ΔMag (562 nm)		ΔMag (832 nm)		Notes
							0"2	1"0	0"2	1"0	
101	231663901	12.4	372.0	5600	S	6/20/19	4.45	4.79	4.85	5.68	WASP-46
104	231670397	9.9	317.5	6036	S	6/20/19	4.84	5.20	5.32	7.09	WASP-73
107	92352620	9.6	210.5	6153	S	5/21/19	5.36	5.64	5.60	6.71	WASP-94 A
109	29344935	13.2	515.6	5346	S	7/16/19	4.23	5.16	4.99	6.66	HATS-14
112	388104525	11.6	302.4	5650	S	11/26/20	4.28	4.67	5.44	6.82	WASP-119
116	238176110	11.0	151.2	4920	S	7/20/19	4.11	4.43	5.24	6.57	WASP-91
130	263003176	7.4	56.9	6296	S	7/17/19	4.77	5.92	4.65	7.13	
134	234994474	9.2	25.2	3794	S	7/14/19	4.49	4.70	5.29	7.29	L 168-9
					S	9/12/19	4.73	5.19	5.49	7.66	
138	277683130	9.6	191.9	5722	S	6/20/19	4.55	5.00	5.22	6.78	False positive
139	62483237	9.4	42.4	4356	S	7/20/19	5.72	7.05	5.40	7.72	
					N	10/12/19	4.00	4.45	5.02	7.35	
140	140068425	9.8	350.2	6174	S	6/20/19	4.71	5.44	4.71	6.68	APC
141	403224672	7.4	47.8	5795	S	6/20/19	5.25	5.99	5.20	7.74	
					S	6/21/19	5.51	6.11	5.46	7.78	
					S	7/15/19	5.40	6.05	5.28	7.90	
143	25375553	9.8	288.4	6371	N	6/9/19	4.48	5.30	5.30	8.74	WASP-111
145	265612438	11.7	453.7	5431	S	6/22/19	4.67	5.30	5.32	6.66	
146	355636844	10.2	499.3	5620	S	7/20/19	4.54	4.99	4.99	6.81	False positive

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

Gemini 8.1 m North and South telescopes, respectively, from 2019 May–2020 December. Before each observing season, targets were selected from the latest version of the TOI catalog of likely planet candidates. All of our observations are listed in Table 1, with the TOI and TIC numbers, TESS magnitude, UT date, the inverse of the parallax from Gaia EDR3 (Gaia Collaboration et al. 2016, 2021) for the distance, effective temperature of the host star from the TESS Input Catalog (TIC v8.1, Stassun et al. 2019), and notes for each target. The Julian date of each observation can be found in the headers of the archival data hosted on the Gemini Observatory Archive.⁸ At least three image sets were obtained for each target, where one set consists of 1000 60 ms exposures taken in a 562 nm and an 832 nm filter simultaneously. Additional image sets were taken for fainter targets ($V > 9$ mag), and a point-source standard star was observed immediately before or after each target for calibration.

The data were reduced using the pipeline developed by the speckle team (Horch et al. 2011; Howell et al. 2011) to calculate and average the power spectrum of each image, then correct for the speckle transfer function by dividing the mean power spectrum of the target by that of the standard star. The pipeline also produces a reconstructed image of each target with a field of view of $1\frac{1}{3}$ in radius around the target. The contrast limits for each target were determined with the method described in Horch et al. (2011), which uses the background flux levels to determine the faintest companions one could reliably detect at each separation. These 5σ contrast limits at 0'2 and 1'0 in the blue and red filters are also listed in Table 1.

Due to the large TESS pixels, some transit detections were identified to be false positives through follow-up photometry. If the light curve shows chromaticity or v-shaped dips of alternating depth, the event must be a binary eclipse rather

than a planet transit, then confirmed with follow-up observations to identify the eclipsing source within the TESS aperture. The transits for 105 of the TOIs in our sample have been identified as false positives (or false alarms) on the Exoplanet Follow-up Observing Program (ExoFOP)⁹ website, noted in Table 1. We have eliminated these host stars from further consideration here, leaving us with 412 stars. A few additional systems were classified as ambiguous planetary candidates (APC), for example, if only a single transit was observed. Because these systems have not yet been confirmed as false positives, we kept them in our sample and discuss their impact in Section 4.1.

Figure 1 shows the distributions in effective temperature, distance, and TESS magnitude for our 412 exoplanet host TOI's. Our sample contains primarily bright, Solar-type stars with smaller distances from Earth compared to Kepler host stars, allowing Gemini speckle observations to detect companions quite close to the target star. For distances of 100–500 pc, our inner angular resolution of 0'017 at 562 nm corresponds to separations of 1.7–8.5 au, while our inner angular resolution of 0'026 at 832 nm corresponds to separations of 2.6–13.0 au. Therefore, we can successfully detect stellar companions in the 1–100 au regime and determine their properties.

2.2. Detected Companions

Binary stars produce a characteristic interference fringe pattern in the power spectrum from which the companion's angular separation (ρ), position angle (θ , measured East of North), and magnitude difference (Δm) can be determined from a weighted least squares fit. Figure 2 shows an example contrast curve and reconstructed image for the binary star TOI 1343. We detected a total of 102 stellar companions around 99

⁸ <https://archive.gemini.edu/searchform>

⁹ <https://exofop.ipac.caltech.edu/teess>

Figure 1. Stellar parameter distributions for the 412 exoplanet host TOI’s in our sample, including stellar effective temperature (top), Gaia EDR3 distance (middle), and TESS magnitude (bottom).

TOI’s in our sample: 73 companions around exoplanet host stars and 29 companions around transit false-positive stars. Our results are listed in Table 2 for both the exoplanet candidate host stars and the false-positive stars, with the TOI number, observation date, and companion parameters (ρ , θ , Δm) determined from both the 562 nm and 832 nm images. We detected some companions only in the 832 nm filter, and could not constrain the magnitude difference for three of these systems. Results from multiple nights were averaged together because no orbital motion could be seen, so any TOI’s with duplicate entries in Table 2 were found to be triple systems. The typical uncertainties in the separation, position angle, and magnitude difference are $0''.01$, $0^\circ.5$, and 0.5 mag, respectively.

Several of these companions were previously detected by the NESSI speckle camera on the WIYN 3.5 m telescope (Howell et al. 2021) or HRCam on the SOAR 4.1 m telescope (Ziegler et al. 2020). Most separations and position angles from Gemini agree with those from WIYN and SOAR at the 1σ level. One exception was TOI 1191, for which a companion was found at $\rho = 0''.68$ with $\Delta m = 5$ mag by ‘Alopec but at $\rho = 0''.046$ with $\Delta m = 1.54$ mag by NESSI. Palomar adaptive optics observations also found a companion at $0''.5$, consistent with the

‘Alopec results. This TOI could be a triple system, but future observations at higher signal to noise are needed to confirm these companions.

Due to speckles becoming decorrelated at $1''.2$, companions beyond this limit have larger uncertainties, especially in Δm . These wide companions are also more likely to be line-of-sight companions, rather than gravitationally bound systems (Horch et al. 2014; Matson et al. 2018), but this can be confirmed with Gaia proper motion and parallaxes (e.g., Mugrauer & Michel 2020). We do not consider these wide companions nor the companions around transit false-positive TOI’s in the rest of our analysis. Figure 3 shows the magnitude difference versus angular separation for the remaining 58 companions with $\rho < 1''.2$ as well as our typical detection limit. We also chose to include the companions detected at WIYN in our analysis to increase our sample size; Howell et al. (2021) observed an additional 130 solar-type TOIs and detected 18 companions with separations less than $1''.2$ that are included in our comparison of exoplanet host binaries and field binaries in Section 4.1. This final sample only includes binaries, as no triple systems with separations less than $1''.2$ were detected.

Figure 2. Example detection limit as a function of radius from the center for a binary star (TOI 1343). The black points represent the local maxima (crosses) and minima (dots). The blue squares mark the 5σ background sensitivity limit within $0''.05$ bins, and the red line corresponds to a spline fit. A companion is detected if any maxima points lie below the detection limit, such as the point near $0''.5$ in this example. The inset plot shows the reconstructed image where the companion is visible in the top right (northwest) corner.

2.3. Binary Properties

We estimated the mass ratio (M_2/M_1) of each detected binary system using the method in Matson et al. (2019) and Howell et al. (2021). For each primary star, we found the nearest value in the Modern Mean Dwarf Stellar Color and Effective Temperature Sequence¹⁰ (Pecaut & Mamajek 2013) based on the effective temperature, then calculated the V -band magnitude differences (Δm_V) of all possible companions (stars with cooler effective temperatures). For companions detected in our 562 nm filter, we fit a polynomial to the mass ratio as a function of Δm_V then calculated the mass ratio corresponding to the observed magnitude difference. For companions detected in the 832 nm filter, we converted the magnitude differences from the V -band to the TESS band (Δm_{TESS}) using the relations in Stassun et al. (2018), then interpolated the mass ratio from the polynomial fit. We took the average if a companion was detected in both filters, then estimated a typical uncertainty of 0.02 from the difference in the mass ratio across filters. Our results are listed in Table 2, and Figure 4 shows the mass ratio as a function of magnitude difference for select binaries and a histogram of the mass ratios. Our sample of exoplanet host binaries does not show the peak toward $M_2/M_1 = 1$ seen in field binaries, possibly because our binaries have long orbital periods that do not show a preference for equal mass components (Raghavan et al. 2010).

Next, we calculated the separation in astronomical units from the angular separation and the Gaia distance for each system, shown in the right panel of Figure 3. We then estimated the binary orbital period using Kepler’s Third Law, the primary component’s mass estimated from the effective temperature, the secondary component’s mass calculated from the mass ratio, and the semimajor axis equal to the instantaneous separation measured with our speckle observations. This last assumption is discussed further in Section 3.3. The estimated

semimajor axes and orbital periods are listed in the last columns of Table 2. Figure 5 shows the logarithmic distribution of companion separation broken down by spectral type of the primary star. The distributions look similar for all spectral types, except the M stars for which we only detected two companions. This is likely due to their decreased multiplicity rate (27%) and the smaller peak separation (20 au) of M-type field binaries (Winters et al. 2019), so most close companions could not be resolved by speckle interferometry. These stars are also quite faint, so our observations may not have achieved sufficiently deep contrast limits to detect fainter companions. For our comparison with different model predictions, we only consider binaries with an F-, G-, or K-type primary (47 systems), which make up the majority of our sample.

3. Simulated Binaries

3.1. Field Binary Model

We simulated a series of binary stars following the methods in Matson et al. (2018) and Ziegler et al. (2020) in order to compare our results to the predictions for field binaries and investigate the suppression of close companions around exoplanet hosts. We began by selecting only F-, G-, and K-type exoplanet candidate hosts from our Gemini TOI sample (337 stars) and the sample observed with WIYN by (Howell et al. 2021; 130 stars), then used these masses and distances as the inputs for our simulations. For each of a thousand iterations, we randomly chose 46% of these stars to be the primary components of our simulated binaries following the multiplicity rate of solar-type field stars found by Raghavan et al. (2010). Masses for the secondary components were then drawn randomly from the distribution in Raghavan et al. (2010): uniform probability for $M_2/M_1 = 0.4 - 0.9$ then a higher probability for 0.9–1.0. The absolute I -band magnitude of each component was interpolated based on mass using the Modern Mean Dwarf Sequence (Pecaut & Mamajek 2013) in order to calculate a magnitude difference for each system.

Next, orbital parameters were randomly assigned to each system from the log-normal period distribution of Raghavan et al. (2010, $\log P = 5.03$ days, $\sigma = 2.28$), the eccentricity distribution of Duquennoy & Mayor (1991), and uniform distributions for the inclination, angular semimajor axis (α), longitude of periastron, and longitude of the ascending node. Finally, we calculated the projected angular separation (ρ) of each companion at a random orbital phase to mimic our speckle observations, then identified “detectable” companions that lie within the Gemini angular resolution (inner) limit of $0''.025$ and the speckle correlation (outer) limit of $1''.2$ and have a magnitude difference within the mean 832 nm Gemini contrast limit.

The results of our simulated binary sample are shown in Figure 6. The left panel shows the companion magnitude difference versus separation for several iterations of our simulation, with detectable companions plotted in purple and the undetectable companions plotted in gray. The middle panel shows a histogram of the physical separation on a logarithmic scale for all simulated companions. We averaged the results from each iteration to predict the number of companions detectable with speckle imaging in each 0.5 dex bin and estimated the uncertainty from the standard deviation across all iterations. This expected number of companions is compared to the observed number in the next section (Section 4.1). We note

¹⁰ http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt

Table 2
Companions Detected

Target	ρ (") (562 nm)	θ (deg) (562 nm)	Δm (mag) (562 nm)	ρ (") (832 nm)	θ (deg) (832 nm)	Δm (mag) (832 nm)	M_2/M_1	a (au)	Binary Period (yr)
Exoplanet Host Stars									
TOI 140	0.044	336.2	0.76	0.048	337.0	0.48	0.88	16.8	46
TOI 141 ^a	...	...	...	0.494	240.6	4.63	0.47	23.6	93
	...	...	...	1.333	306.8	5.60	0.38	63.7	430
TOI 172	1.175	319.3	5.20	1.262	321.9	5.36	0.43	452.9	7900
TOI 224	0.100	224.8	2.07	0.099	226.6	1.00	0.72	6.9	20
TOI 235	0.850	289.2	1.78	0.854	291.4	1.50	0.75	117.8	1000
TOI 245	0.990	109.1	3.54	1.206	109.6	2.39	0.59	148.3	1300
TOI 252	0.436	307.8	2.16	0.436	309.9	1.54	0.79	112.7	1000
TOI 264	0.655	329.5	5.38	0.654	331.7	4.46	0.45	273.8	3400
TOI 271	...	...	...	0.146	231.1	4.98	0.43	14.6	44
TOI 287	...	...	...	0.152	125.9	3.96	0.52	79.8	570
TOI 291	0.035	146.2	0.65	0.029	145.2	1.38	0.82	16.0	46
TOI 309	0.330	77.6	1.27	0.344	77.7	1.03	0.81	165.6	1700
TOI 325	...	...	...	0.616	221.8	4.05	0.49	112.3	1200
TOI 354	0.054	87.1	1.08	0.056	87.8	1.03	0.82	21.5	73
TOI 364	0.384	95.2	0.36	0.405	96.6	0.35	0.93	107.8	730
TOI 380	...	...	...	0.201	6.1	1.96	0.73	80.4	590
TOI 402	...	...	...	1.467	234.2	9.33	0.14	65.8	540
TOI 457	...	...	...	1.122	223.8	0.69	0.83	141.2	3000
TOI 487	0.515	198.7	1.53	0.515	200.8	1.25	0.77	81.2	570
TOI 492	...	...	...	0.668	321.1	3.89	0.49	327.7	4400
TOI 564	...	...	...	0.671	73.9	4.95	0.44	133.4	1300
TOI 568	0.310	189.8	0.90	0.332	192.0	0.81	0.85	101.5	740
TOI 573	1.442	227.6	1.30	1.600	234.3	1.25	0.69	142.0	2200
TOI 676	...	...	...	1.331	103.8	2.20	0.68	944.1	23300
TOI 680	...	...	...	0.806	331.4	...	...	129.0	1400
TOI 697 ^a	...	...	...	1.199	137.9	5.17	0.41	111.4	1000
	...	...	...	1.269	139.4	5.46	0.38	117.9	1100
TOI 722	0.224	114.1	2.46	0.221	115.8	1.47	0.72	25.7	120
TOI 791	...	...	...	0.709	25.6	5.60	0.37	238.6	2700
TOI 798	0.289	179.4	0.64	0.289	181.5	0.32	0.93	35.0	180
TOI 854	0.023	204.6	1.35	0.022	211.1	1.21	0.79	6.1	11
TOI 906	1.294	49.0	3.67	1.375	50.7	2.98	0.57	186.2	1900
TOI 926	0.192	156.9	2.53	0.192	158.8	2.18	0.68	59.1	350
TOI 931	0.113	234.9	0.65	0.120	237.6	0.50	0.90	76.1	460
TOI 952 ^a	...	...	...	0.169	72.1	3.52	0.48	70.7	390
	...	...	...	1.262	135.4	4.91	0.39	526.3	8300
TOI 1032	1.161	81.6	2.16	1.329	83.0	1.61	0.59	796.0	11300
TOI 1035	0.101	100.2	1.96	0.107	112.1	1.77	0.71	39.1	180
TOI 1037	...	...	...	0.250	242.1	4.98	0.32	68.7	340
TOI 1039	0.708	285.6	4.02	0.736	286.3	2.41	0.38	1121.6	15500
TOI 1131	0.095	214.4	1.45	0.111	214.0	1.66	0.75	27.5	110
TOI 1133	0.550	102.1	3.05	0.571	102.4	2.77	0.59	149.9	1300
TOI 1152	1.074	22.6	0.93	1.284	22.7	0.85	0.83	133.9	1200
TOI 1189	0.984	318.5	1.36	1.005	319.1	1.60	0.78	279.5	3700
TOI 1191	...	...	...	0.677	85.8	4.94	0.40	240.1	2600
TOI 1192	0.187	200.6	3.37	0.196	201.4	2.91	0.55	73.5	440
TOI 1204	...	...	...	0.375	38.8	5.02	0.39	39.9	180
TOI 1217	1.088	242.7	5.02	1.169	242.7	5.02	0.44	552.3	9700
TOI 1261	...	...	...	1.722	316.9	2.87	0.59	344.2	4900
TOI 1293	...	...	...	1.016	120.4	4.76	0.45	240.4	3000
TOI 1335	0.057	303.1	0.01	0.061	304.1	0.01	0.99	42.4	150
TOI 1343	...	...	...	0.517	333.6	5.17	0.30	204.9	1700
TOI 1440	...	...	...	1.536	324.9	...	...	363.2	6800
TOI 1447	0.150	67.7	0.22	0.157	67.7	0.21	0.96	48.8	200
TOI 1491	...	...	...	0.754	269.5	4.48	0.47	157.0	1600
TOI 1531	0.565	199.2	1.11	0.567	199.6	1.69	0.82	307.1	4500
TOI 1544	0.624	129.3	3.35	0.652	129.9	3.62	0.58	641.6	15200
TOI 1559	0.039	122.6	2.08	0.043	123.0	2.04	0.61	29.9	92
TOI 1560	1.246	62.7	4.03	1.366	68.4	3.08	0.44	731.2	11400
TOI 1565	0.233	207.3	0.85	0.235	207.7	0.82	0.81	77.2	360
TOI 1598	...	...	...	1.076	304.3	4.86	0.44	151.6	1500

Table 2
(Continued)

Target	ρ (") (562 nm)	θ (deg) (562 nm)	Δm (mag) (562 nm)	ρ (") (832 nm)	θ (deg) (832 nm)	Δm (mag) (832 nm)	M_2/M_1	a (au)	Binary Period (yr)
TOI 1636	...	...	...	0.183	356.3	2.34	0.72	27.7	130
TOI 1641	0.194	296.1	3.53	0.195	296.4	2.80	0.46	121.3	730
TOI 1677	...	...	...	0.183	142.0	4.54	0.47	40.9	210
TOI 1678	0.336	307.1	4.01	0.397	307.5	2.80	0.49	280.2	2800
TOI 1719	0.116	193.3	1.78	0.117	193.8	1.99	0.70	27.7	100
TOI 1740	...	...	...	0.241	258.6	3.60	0.56	28.1	130
TOI 2010	...	...	...	1.578	138.0	...	...	171.1	2200
TOI 2035	0.415	245.9	0.45	0.418	246.2	0.41	0.87	150.2	900
TOI 2220	...	...	...	1.128	251.2	2.83	0.61	400.3	6200
TOI 2305	...	...	...	0.237	203.1	3.98	0.52	138.6	1300
TOI 2310	0.708	332.5	2.81	0.705	334.8	1.80	0.71	650.9	13600
Transit False-positive Stars									
TOI 138	0.099	258.9	1.38	0.108	260.5	1.33	0.78	20.7	94
TOI 146	0.302	75.0	1.15	0.324	77.0	1.15	0.80	161.8	2100
TOI 154	...	...	...	0.154	202.8	1.28	0.77	61.8	470
TOI 311	0.039	130.6	0.91	0.028	148.8	0.96	0.85	6.5	21
TOI 372	...	...	...	0.267	262.3	2.45	0.64	137.8	1600
TOI 378	0.098	167.9	1.29	0.137	182.0	1.49	0.77	316.2	5400
TOI 379	0.053	19.5	0.07	0.052	21.3	0.41	0.95	12.0	41
TOI 463	...	...	...	0.816	214.4	3.78	0.48	150.3	1600
TOI 593	...	...	...	0.664	170.1	3.81	0.49	255.5	3700
TOI 884	0.049	323.2	1.79	0.052	324.1	1.69	0.56	52.7	210
TOI 894	0.619	329.5	3.32	0.649	331.0	2.41	0.49	233.1	2300
TOI 896	...	...	...	0.062	126.2	3.48	0.49	9.6	25
TOI 898	1.306	34.9	2.11	1.358	35.4	2.07	0.70	651.2	16800
TOI 919	0.088	83.7	0.71	0.095	85.9	0.48	0.89	31.4	170
TOI 935	...	...	...	0.785	146.5	2.19	0.74	296.7	5900
TOI 995	0.116	137.9	2.22	0.121	139.5	2.54	0.73	151.1	2100
TOI 996	0.143	228.7	1.99	0.153	230.9	1.87	0.64	79.1	520
TOI 1038	0.443	99.9	1.84	0.474	102.1	1.42	0.66	119.5	910
TOI 1047	0.826	246.4	2.83	0.883	248.7	2.31	0.66	119.5	1300
TOI 1051	0.368	241.0	1.12	0.368	243.1	1.00	0.81	23.2	110
TOI 1093	0.102	108.2	2.21	0.109	110.7	2.04	0.70	64.6	680
TOI 1147	...	...	...	0.377	346.0	3.62	0.51	77.9	620
TOI 1193	0.087	255.3	0.62	0.090	255.4	0.59	0.88	77.9	550
TOI 1417	0.031	307.0	2.71	0.027	307.2	2.63	0.57	4.1	6
TOI 1487	0.097	45.6	4.20	...	...	...	0.55	10.6	39
TOI 1543	...	...	...	0.320	178.5	5.02	0.32	194.4	1800
TOI 1557	...	...	...	1.406	135.7	5.59	0.38	407.3	8200
TOI 1662	0.226	347.4	2.52	0.227	347.5	2.11	0.61	79.3	560
TOI 1673	0.274	50.5	1.61	0.276	50.9	1.50	0.75	58.2	450

Note.^a Found to be a triple system, so the parameters for each companion are listed separately.

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

that WIYN has a slightly larger angular resolution limit and shallower contrast limit than Gemini and therefore is less sensitive to close companions, but this difference between telescopes is within the simulation’s uncertainties. Lastly, the right panel of Figure 6 shows the ratio between the instantaneous separation and the modeled semimajor axis of the detectable companions, which we discuss in Section 3.3.

3.2. Additional Period Distributions

Recent work has found that exoplanet host binaries have larger separations than field binaries; for example, Howell et al. (2021) suggests a peak at $\log P = 5.5$ days. We used a grid search to test several different log-normal period distributions against the distribution of companions seen by Gemini and WIYN. We

found that a log-normal distribution with a peak at $\log P = 6.2$ days and width of $\sigma = 1.2$ minimized the χ^2 between the simulated and observed companion separations. The simulation results using this “longer period” model are shown in Figure 7. This distribution agrees with that found by Howell et al. (2021).

Lastly, we created simulated binaries based on the model of Moe & Kratter (2019) representing the lack of close binaries as planet hosting systems. They calculated the ratio between the number of exoplanet host binaries and the number of field binaries as a function of the binary separation. For this model, we started with the Raghavan et al. (2010) period distribution, then removed a fraction of close companions within each separation range used by Moe & Kratter (2019). Within 1 au, all companions are removed. From 1–200 au, the survival fraction increases linearly

Figure 3. Properties of the 58 companions with separations less than $1''/2$ around exoplanet host stars. Left: the magnitude difference as a function of the angular separation. The detected companions are shown as the solid blue points. The average 5σ detection limit is shown as the solid red line, and the shading corresponds to the typical spread in this limit. The few companions below the contrast limit correspond to observations taken during better seeing or at higher signal to noise. The Gemini angular resolution limit in the 832 nm filter is shown as the vertical red line. Right: comparison of the observed angular separation of our detected companions and the derived spatial separation determined using Gaia distances. The color corresponds to the system distance.

Figure 4. Left: mass ratio as a function of magnitude difference for example exoplanet host binaries. The Pecaute & Mamajek (2013) model values are shown as the colored dots and the polynomial fit for each binary is shown as the solid line; both are color coded by spectral type of the possible companions and primary star, respectively. The values of the observed companions are shown as the solid black dots. Right: histogram of the mass ratio for exoplanet host stars. The light-gray histograms represent all detected companions, while the blue histograms represent companions with separations $< 1''/2$.

in log-space. All companions outside 200 au are kept. These simulation results are shown in Figure 8 and have a median period of $\log P = 6.4$ days similar to the longer period model, but include more stars at large separations (typically past $1''/2$ where speckle interferometry is not sensitive).

3.3. Testing Binary Separations

When we observe a binary at a random orbital phase, are we more likely to underestimate or overestimate the separation compared to the true semimajor axis? To answer this question, we compared the projected angular separation to the assigned semimajor axis for all detectable companions. The right panels of Figures 6–8 show a histogram of the ratio between these two parameters (ρ/α). We then fit a Gaussian to this distribution and found that the mean ratio is 0.97 ± 0.41 for the Raghavan et al. (2010) model, 0.90 ± 0.42 for the longer period model, and

0.91 ± 0.42 for the Moe & Kratter (2019) model. These ratio distributions are statistically consistent based on p values of 0.05 found from comparing each distribution to the others using a Kolmogorov–Smirnov test. Therefore, our observed separation distribution is only slightly underestimated and the projected separation measured in one observation is likely a reasonable estimate until the true semimajor axis can be found by resolving the full visual orbit.

4. Results

4.1. Binary Exoplanet Host Orbital Period Distribution

Figure 9 shows the logarithmic separation distribution for the 65 companions of solar-type exoplanet hosts found by speckle imaging at Gemini (this work) and WIYN (Howell et al. 2021), compared to the predictions of three different binary period distributions. All predictions use a companion frequency of 46%.

Figure 5. Histograms of the projected physical separation (i.e., semimajor axis) of the exoplanet host binaries in our sample on a logarithmic scale and broken down by the spectral type of the primary star.

Figure 6. Results of our simulated binary sample based on orbital demographics of field binaries from Raghavan et al. (2010). Left: magnitude difference as a function of the angular separation for a subset of the simulated companions. The detectable companions are shown as purple diamonds, while the undetectable companions are shown as gray circles. The mean Gemini detection limit is shown as the solid red line and the angular resolution limits are shown as the dashed red lines. Middle: logarithmic distribution of the projected physical separation for the full simulated binary sample. The filled, purple histograms represent the detectable companions; while the gray, hatched histograms represent the full sample. Right: histogram of the ratio between the instantaneous separation and the modeled semimajor axis of the detectable companions. The Gaussian fit is shown in solid black and a dashed line at unity is shown for reference.

The observed companions peak at larger separations (~ 100 au) than predicted by the field binary model (50 au; Raghavan et al. 2010). The field binary model has a reduced χ^2 value of 4.5 and predicted a total of 56 companions, indicating that this period distribution is also too wide. Next, the “longer period model” ($\log P = 6.2$ days, $\sigma = 1.2$) is based on the observed distribution, so naturally peaks at larger separations. This model has the lowest reduced χ^2 value of 1.1 and predicts 67 companions. Lastly, the Moe & Kratter (2019) model matches the observed distribution well with a reduced χ^2 value of 1.3. It also best matches the total number of companions by predicting 65 would be detected.

Overall, both the longer period model and the Moe & Kratter (2019) model provide good fits to the observed companion distribution, but we cannot statistically distinguish between the two. Future work to include common proper motion binaries from Gaia could help differentiate between these models at larger orbital separations (e.g., Ziegler et al. 2021). Lastly, excluding the APC systems from our sample would remove up to two companions from each histogram bin, but the overall shape would remain intact. The observed companions would still peak at 100 au, supporting our conclusion that binary exoplanet hosts have larger separations than field binaries.

Figure 7. Same as Figure 6, but for simulated binaries created using a log-normal period distribution with the peak at $\log P = 6.2$ days and width of $\sigma = 1.2$.

Figure 8. Same as Figure 6, but for simulated binaries created using the Moe & Kratter (2019) model.

Figure 9. Histograms for the projected physical separation in logarithmic bins. The solid bars correspond to the companions with separations less than $1''/2$ around solar-type exoplanet host stars detected by Gemini (blue) and WIYN (Howell et al. 2021; green). The purple unfilled histograms correspond to the expected number of companions based on the field binary period distribution (left), on a distribution peaking at longer periods (middle), and on the Moe & Kratter (2019) model (right).

4.2. Exoplanet Candidate Properties

We investigated if any correlations existed between the exoplanet candidate properties (such as radius or orbital period), the presence of a stellar companion, and the orbital properties of that companion. The planet parameters were taken from ExoFOP¹¹ and the radii of planets in binary systems have been corrected for “third-light” contamination from the companion star that

dilutes the transits (Ciardi et al. 2015). Table 3 lists the radius correction factor, apparent radius from ExoFOP (when available), and the corrected radius for each planet found in a binary system with $\rho < 1''/2$, assuming the planet orbits the brighter, primary component. Our sample includes some planet candidates with radii larger than $20R_{\oplus}$, which are likely red dwarf companions.

The left panel of Figure 10 shows the planet radius as a function of the planet’s period, color coded by whether the host star is single or part of a binary system. Giant planet candidates are seen at all periods independent of host binarity. However,

¹¹ The planet radii were estimated using the stellar radii from the TESS Input Catalog, which does not account for the multiplicity of the host stars and therefore could underestimate the radii of stars with bright, unresolved companions.

Figure 10. Left: planet radius as a function of orbital period for planet candidate hosts in single star systems (light blue) and in close binary systems (purple). For the planets in binaries, we show the increase in radius (tail to plotted point) when correcting for dilution by the companion. Right: normalized cumulative distribution function for the radii of planets in single and binary systems. The two subsamples appear similar, except for the clear observational bias against detecting Earth-sized, transiting planets in binary systems.

Table 3
Corrected Radii of Planet Candidates in Close Binary Systems

Planet Candidate	Correction Factor	Apparent R_{pl} ($R_{\oplus}$)	Corrected R_{pl} ($R_{\oplus}$)	Planet Candidate	Correction Factor	Apparent R_{pl} ($R_{\oplus}$)	Corrected R_{pl} ($R_{\oplus}$)
TOI 140.01	1.282	12.74	16.33	TOI 1037.01	1.005	3.29	3.31
TOI 141.01	1.007	1.66	1.67	TOI 1039.01	1.053	...	...
TOI 224.01	1.182	14.75	17.44	TOI 1131.01	1.103	5.56	6.13
TOI 235.01	1.119	...	...	TOI 1133.01	1.038	4.86	5.05
TOI 252.01	1.114	3.90	4.35	TOI 1189.01	1.109	10.76	11.93
TOI 264.01	1.008	18.25	18.40	TOI 1191.01	1.005	25.36	25.50
TOI 271.01	1.005	2.66	2.68	TOI 1192.01	1.034	11.65	12.04
TOI 287.01	1.013	20.41	20.68	TOI 1204.01	1.005	2.12	2.13
TOI 291.01	1.132	20.52	23.23	TOI 1217.01	1.005	4.34	4.36
TOI 309.01	1.178	...	...	TOI 1293.01 ^a	1.000	3.86	3.86
TOI 325.01	1.012	5.95	6.02	TOI 1335.01	1.411	28.83	40.67
TOI 354.01	1.178	25.20	29.68	TOI 1343.01	1.004	4.06	4.08
TOI 364.01	1.312	3.13	4.11	TOI 1447.01	1.351	4.43	5.99
TOI 380.01	1.079	20.57	22.19	TOI 1491.01	1.008	6.24	6.29
TOI 457.01 ^a	1.000	9.12	9.12	TOI 1531.01	1.100	9.44	10.38
TOI 487.01	1.147	2.73	3.13	TOI 1544.01	1.018	...	...
TOI 487.02	1.147	...	...	TOI 1559.01	1.074	9.20	9.88
TOI 492.01	1.014	14.29	14.49	TOI 1565.01	1.212	23.87	28.93
TOI 564.01	1.005	9.36	9.41	TOI 1598.01	1.006	3.78	3.80
TOI 568.01	1.214	3.55	4.31	TOI 1636.01	1.056	18.98	20.05
TOI 680.01	...	5.74	...	TOI 1641.01	1.037	12.54	13.00
TOI 697.01	1.004	2.03	2.04	TOI 1677.01	1.008	5.09	5.13
TOI 722.01	1.122	2.38	2.67	TOI 1678.01	1.037	20.34	21.10
TOI 791.01	1.003	10.68	10.71	TOI 1719.01	1.077	7.83	8.43
TOI 798.01	1.321	...	...	TOI 1740.01	1.018	2.46	2.51
TOI 854.01	1.152	4.80	5.53	TOI 2035.01	1.298	5.90	7.66
TOI 926.01	1.065	21.00	22.37	TOI 2220.01	1.036	17.85	18.49
TOI 931.01	1.277	20.69	26.42	TOI 2305.01	1.013	15.21	15.40
TOI 952.01	1.019	7.84	7.99	TOI 2310.01	1.091	13.68	14.93
TOI 1035.01	1.094	31.50	34.45				

Note.

^a The companion for this TOI is listed as a nearby star in ExoFOP, so its flux has already been accounted for when calculating the planet radius.

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

Figure 11. Planet and stellar companion separations for the binary exoplanet host systems observed with Gemini. The planets are plotted as red circles (size scaled with the cube root of the planet radius) and the stellar companions are plotted as blue circles (size scaled with the binary mass ratio). The systems are sorted by the stellar companion separation. We see no obvious trends between the two populations, perhaps not unexpected for the very short orbital period planet detections common for TESS.

we see an observational bias against the detection of Earth-sized ($R_{\text{pl}} < 2 R_{\oplus}$), transiting planet candidates in binary star systems. Using the Kolmogorov–Smirnov test to compare the

radius distribution of planets in binaries to those around single stars, we found a p value of 0.001 indicating that these subsamples are statistically different. This is also evident in the

right panel of Figure 10 that shows the cumulative distribution function for these two subsamples and the lack of Earth-sized, transiting planets in binary systems. Savel et al. (2020) investigated this observational bias and found that the occurrence rates for super-Earths and sub-Neptunes are underestimated by roughly 26% if transit dilution from stellar companions is not taken into account. In addition, this effect will manifest itself more strongly as the planet orbital period becomes longer (fewer measured transits, lower signal-to-noise ratio) making planets approaching or in the Habitable Zone particularly susceptible to this bias.

Figure 11 shows the separations of the planet candidates and stellar companions for the 58 host binaries in our sample with $\rho < 1''.2$ and sorted by companion separation. No corresponding trend with the planet separation is seen, likely because the companions are at least $100\times$ farther from the host stars than the planets and well beyond the limit for dynamically stable circumstellar systems (roughly $5\text{--}10\times$, Holman & Wiegert 1999). However, TESS cannot detect longer period planets due to its short observation window, so revisits to these systems during the extended mission will be highly valuable to search for longer period planets and investigate whether their separations are influenced by the stellar companions.

5. Conclusions

We observed 517 TOI stars using speckle interferometry at Gemini in search of stellar companions to validate and characterize the exoplanets and their stellar environments. We detected 73 companions around exoplanet candidate host TOI's and 29 companions around false-positive TOI's and present the binary parameters for each system. The magnitude differences of exoplanet host binaries can be used to correct for transit dilution when calculating the exoplanet radii and density (Ciardi et al. 2015), but additional observations may be needed to determine around which stellar component the planet is actually orbiting (e.g., Howell et al. 2019).

We then combined our sample of exoplanet host binaries with those found with speckle interferometry at WIYN (Howell et al. 2021) in order to test the predictions of several different binary period distributions. Our results are consistent with past studies (Kraus et al. 2016; Fontanive et al. 2019; Ziegler et al. 2020, 2021; Howell et al. 2021) in showing that the binary exoplanet host period distribution is narrower and peaks at a larger value than that of field binaries, but our lack of very close companions (<100 au) is less dramatic than found by these previous studies due to our improved angular resolution and sensitivity to faint companions. Furthermore, our sample clearly shows the observational bias against detecting small planets in transit surveys like TESS due to the third light from a stellar companion. Both the host star multiplicity and this observational bias must be taken into account when calculating the occurrence rates of Earth-sized planets (Ciardi et al. 2015; Furlan et al. 2017; Savel et al. 2020). We did not find any additional correlations in the properties of the planets or companions in our sample.

Finally, understanding how binary companions affect the formation, evolution, and survival of exoplanets is an important component to understanding planet formation overall. This work focused on the impact of the binary separation; but the relative inclination between the planet and companion, the eccentricity of the binary orbit, and the mass ratio are other important factors (e.g., Holman & Wiegert 1999; Quintana et al. 2002; Jang-Condell 2015).

We are currently monitoring exoplanet host binaries with shorter periods to resolve the visual and spectroscopic orbits and determine each system's orbital parameters (e.g., Colton et al. 2021). We plan to test each system's dynamical stability and potential for habitable planets in order to investigate how these other binary properties affect planet formation and survival.

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Facilities: Gemini North ('Alopeke), Gemini South (Zorro).

Software: astropy (Astropy Collaboration et al. 2013, 2018), Matplotlib (Hunter 2007), NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020).

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