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Demographics of M dwarf binary exoplanet hosts discovered by TESS

R.A. Matson[1], **R. Gore**[2], **S.B. Howell**[3] **and D.R. Ciardi**[4]

[1] *U.S. Naval Observatory, 3450 Massachusetts Avenue NW, Washington, D.C. 20392, USA (E-mail: rachel.a.matson2.civ@us.navy.mil)*

[2] *Bay Area Environmental Research Institute, Moffett Field, CA 94035, USA*

[3] *NASA Ames Research Center, Moffett Field, CA 94035, USA*

[4] *NASA Exoplanet Science Institute, Caltech/IPAC, 1200 E. California Blvd., Pasadena, CA 91125, USA*

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Abstract. M dwarfs have become increasingly important in the detection of exoplanets and the study of Earth-sized planets and their habitability. However, 20-30% of M dwarfs have companions that can impact the formation and evolution of planetary systems. We use high-resolution imaging and Gaia astrometry to detect stellar companions around M dwarf exoplanet hosts discovered by TESS and determine the separation, magnitude difference, and projected separation for each system. We find 47 companions around 216 M dwarfs and a multiplicity rate of 19.4+/-2.7% that is consistent with field M dwarfs. However, the projected separation for close binaries is shifted to larger separations, confirming the lack of close exoplanet host binaries seen in previous studies.

Key words: binary stars – planet hosting stars

1. Introduction

Nearly six thousand exoplanets have been confirmed to date[1], however, only ∼250 are known to be in binary star systems[2]. As most stars form in binaries or multiples (Duchêne & Kraus, 2013) and the presence of a stellar companion is expected to alter planet formation and evolution (e.g., Thebault & Haghighipour, 2015), the discovery and characterization of such systems provides important insight into planet formation and evolutionary processes. In particular, the architectures of planet hosting binary systems can elucidate which mechanisms are most impacted by a companion star.

Observational evidence from both radial velocity (RV) and transit planet surveys indicates planets occur less frequently in binaries with separations $\lesssim$ 100au, confirming the detrimental effect of a nearby stellar companion (e.g., Hirsch

[1] https://exoplanetarchive.ipac.caltech.edu/
[2] http://exoplanet.eu/planets_binary/

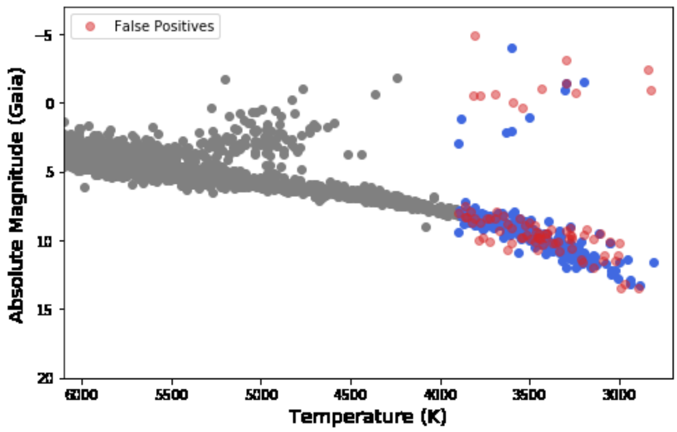

Figure 1. H-R diagram of TESS planet candidate host stars with our sample of M star TOIs shown in blue. We remove false positive and ambiguous TOIs (red dots) and the nine remaining TOIs that appear above the main sequence.

et al., 2021; Kraus et al., 2016). Such studies find fewer close companions around solar-type stars hosting giant planets (e.g., Ngo et al., 2016) and smaller short-period planets (e.g., Lester et al., 2021).

The prevalence of M dwarfs, as well as their low masses, small sizes, and cool temperatures, have made them prime targets for detecting Earth-sized planets and characterizing exoplanet atmospheres. The Transiting Exoplanet Survey Satellite (TESS) mission (Ricker et al., 2015) is focused on detecting exoplanets around nearby bright stars and includes tens of thousands of M dwarfs in its target list. Planets discovered by TESS provide the opportunity to assess the multiplicity of M dwarf exoplanet hosts, as their proximity enables follow-up observations sensitive to companions within a few astronomical units of the host star. Modest samples of TESS M dwarf host stars have shown evidence of fewer close binaries in planet hosting systems (Ziegler et al., 2020; Clark et al., 2022), similar to what has been found for solar-type stars. Here we provide an overview of our investigation of 216 M dwarf TESS Objects of Interest (TOIs) (Matson et al., 2024) to detect stellar companions and investigate the multiplicity of M dwarfs hosting short period transiting planets.

2. Sample & observations

High-resolution images of TOIs are used to detect stars that are not resolved in the TESS Input Catalog (TIC) or with seeing-limited photometry that may mimic or distort the signal of a transiting planet. These observations also allow us to assess the multiplicity of stars hosting transiting planets.

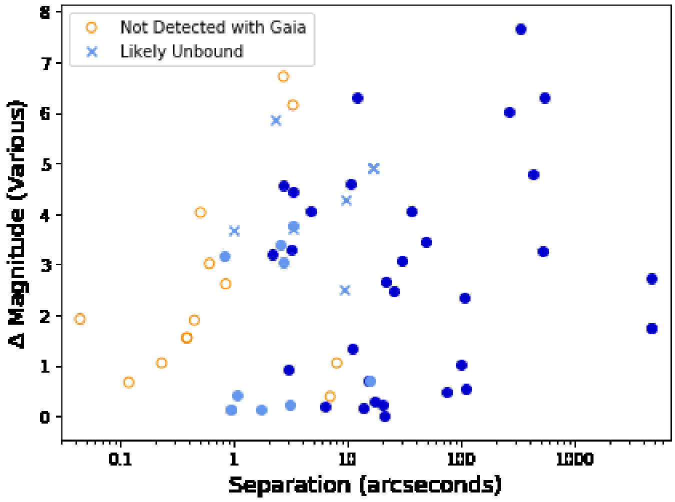

Figure 2. Magnitude difference and separation of companions to M dwarf TOIs. Companions detected with high-resolution imaging and unresolved by Gaia are shown as open circles. CPM companions detected using Gaia DR3 are plotted in blue, with companions also detected with high-resolution imaging shown in light blue. Blue ×'s indicate stars identified with high-resolution imaging that have parallax/proper motion data indicating they are unbound companions.

We selected TOIs with effective temperatures less than 3900 K from the TESS Exoplanet Follow-up Observing Program website (ExoFOP; NExScI, 2022). Targets listed as false positive or ambiguous planet candidates (as of 8 February 2024) were removed from the sample, as were stars with parameters consistent with giants (see Figure 1), resulting in a sample of 221 M dwarfs with confirmed or candidate transiting exoplanets. We then collected high-resolution imaging observations conducted as part of the TESS Follow-up Observing Program by our team and other groups available on ExoFOP.

2.1. High-resolution imaging

Speckle interferometry observations of 148 M dwarf TOIs were taken from 2019–2024 in narrow band filters centered at 562 and 832 nm. Observations were obtained with the ‘Alopeke and Zorro speckle cameras on the Gemini 8.1 m North and South telescopes, respectively, and the NESSI speckle camera at the 3.5 m WIYN telescope. Details of the instruments, observing program, and data reduction procedures can be found in Howell et al. (2021, and references therein).

We also observed 85 M dwarf TOIs with near-infrared adaptive optics (AO) imaging using NIRC2 on the Keck-II 10 m telescope and PHARO on the 200 inch

Hale telescope at Palomar Observatory from 2018 − 2022. Both narrow (e.g., Br-γ, J_{cont}) and broad-band filters (e.g., K, H_{cont}) with central wavelengths near 2.2 μm were used depending on the magnitude of the target and the observing conditions. See Schlieder et al. (2021, and references within) for more information regarding the observing program, instruments, and data reduction.

2.2. ExoFOP Observations

High-resolution imaging data for an additional 41 M dwarfs in our sample were available on ExoFOP, including companion detections from the HRCam speckle imager on the SOAR 4.1m telescope (see Ziegler et al., 2020) and the Speckle Polarimeter on the 2.5 m SAI telescope (Safonov et al., 2017). These data increase the number of detected companions and expand the parameter space searched for each TOI due to the different sensitivities of each instrument.

3. Stellar companions

3.1. High-resolution imaging

Eight stellar companions to M dwarf TOIs were detected using speckle observations and twelve companions were detected with AO observations, two of which were also detected by speckle. The high-resolution imaging data extracted from ExoFOP contained an additional ten companions, resulting in a total of 28 companions around 24 TOIs in our sample. The companions have angular resolutions ranging from $0.04 - 16''$. The TOIs and detected companions were cross-matched with Gaia DR3 (Gaia Collaboration et al., 2023), revealing six pairs with dissimilar proper motions and parallaxes indicating they are not physically bound, which we treat as single stars. Six other companions were not resolved by Gaia or had no parallax and/or proper motion measurements and were assumed to be bound. The magnitude difference as a function of angular separation for the companions detected via high-resolution imaging are shown in Figure 2. Companions also found in Gaia are shown in light blue, with unbound companions marked as $\times$'s, while those unresolved by Gaia are shown as open orange circles.

3.2. Gaia astrometry

We also searched for wide companions to the M dwarf TOIs using Gaia DR3 and code adapted from El-Badry et al. (2021) to identify common proper motion (CPM) pairs. Thirty-eight companions were identified around 35 TOIs, with angular separations of $0.8 - 540''$. Four companions were brighter than the host star, implying the TOI is the secondary component, and removed from our analysis. The magnitude difference and separation of each CPM companion is shown as a blue dot in Figure 2, with companions also detected with high-resolution imaging shown in light blue.

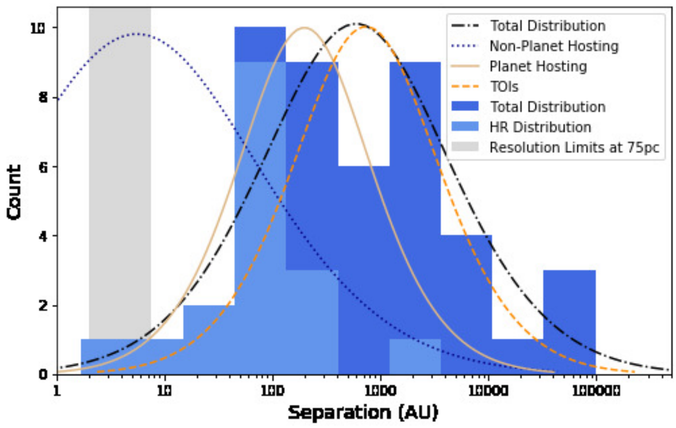

Figure 3. The projected separation distribution of companions detected around M dwarf TOI's, with the high-resolution imaging (HR) subset highlighted in light blue. A Gaussian fit to the data (dot dash line) peaks at $\mu = 596$ au ($\sigma = 11$ au). The separation distributions of non-planet hosting, planet hosting, and TOI M dwarfs from Clark et al. (2024, 2022) are shown for comparison. The gray shaded region depicts the inner angular resolution limits of the various high-resolution imaging techniques used in this study.

4. Results & discussion

Using high-resolution imaging and common proper motions we detect 47 companions around 42 M dwarf TOIs for a stellar multiplicity rate of $19.4 \pm 2.7\%$. These findings are slightly lower than the $\sim 24 \pm 2\%$ multiplicity rates observed for M dwarfs within 25pc (Winters et al., 2019) and 15pc (Clark et al., 2024), but consistent within the uncertainties. Studies of stellar companions to TOIs (e.g., Mugrauer et al., 2023) and confirmed exoplanet hosts (e.g., Michel & Mugrauer, 2024) using Gaia astrometry and close companions from the literature have found similar multiplicity rates of $\sim$19%. These results indicate short-period planet formation is a routine occurrence in binary stars, as our multiplicity rate generally agrees with field M dwarfs and other planet hosting stars.

To evaluate the separations of stellar companions to transiting exoplanet hosts, we calculate the projected physical separation of each companion from the primary star in astronomical units using the observed angular separation and Gaia distance. The separation distribution, shown in Figure 3, peaks at $\sim$600 au. This is considerably larger than the peaks in separation seen in other studies of M dwarf binaries, such as Clark et al. (2024), which shows a peak at $\sim$6 au and includes companions with separations of $0.07 - 300''$ for M dwarfs within 15pc. Although the M dwarfs in our sample are further away, with an average distance of 75 pc, high-resolution imaging allows us to probe down to $\sim$2 au for two-thirds of our sample. The inner angular resolution limits of all high-resolution imaging techniques used in this survey are highlighted in gray in Figure 3, which, at a distance of 75pc, span separations of $2 - 7.5$ au. Thus, the shifted peak in our separation distribution can be attributed to fewer close companions in our sample and not our lack of sensitivity to such companions.

Clark et al. (2024) divided their M dwarf sample by stars with and without known planets, determining statistically significant differences in the separation peaks at 198 au and 5.6 au, respectively. The distributions for the non-planet and planet hosting M dwarfs are plotted in Figure 3, as well as the separation distribution for M dwarf TOIs from Clark et al. (2022), which peaks at 735 au. Although our peak separation is larger than the planet hosting sample in Clark et al. (2024), likely due to our broader survey limits, it is generally consistent with the two planet hosting distributions and differs considerably from the non-planet hosting systems. The deficit of close companions observed in exoplanet host systems is therefore clearly seen in our sample of M dwarf TOIs.

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