Determining the Detectability of a Planet Transiting a Star of Extragalactic Origin

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Why search for extragalactic planets?

- Extrasolar planets have been discovered all of which have been relatively close to Earth.
- Independent studies has never confirmed a planet originating outside of the Milky Way.
- A population of stars has been identified in the Galaxy's inner halo with very unique kinematic properties that appear to contrast with other stellar systems = suggestive of extragalactic origin (Helmi et al., 2018).
- A combination of TESS and Gaia DR2 data make observations of these unique stars possible for the first time.

Question: Can an exoplanet be recovered via the transit method around evolved stars in the Gaia-Enceladus substructure?

Target Selection

Gaia Cuts:

- First cuts made in absolute Gaia G mag (m_G > 4.1) & Gaia B-R color 0.9 > (Bp - Rp) > 3.0.
- Additional cuts made in galactocentric velocity, removing stars with space motions consistent with the galactic thin disk (see Figure 1)

TESS:

- 8,800 targets -> 1,080 stars by filtering out targets with stellar radii < 3 R* and > 8 R* as determined by TICv8 (Stassun et al., 2019)
- Reduction made to directly compare results to previous estimates of planet occurrence around red giant stars (Grunblatt et al., 2019).

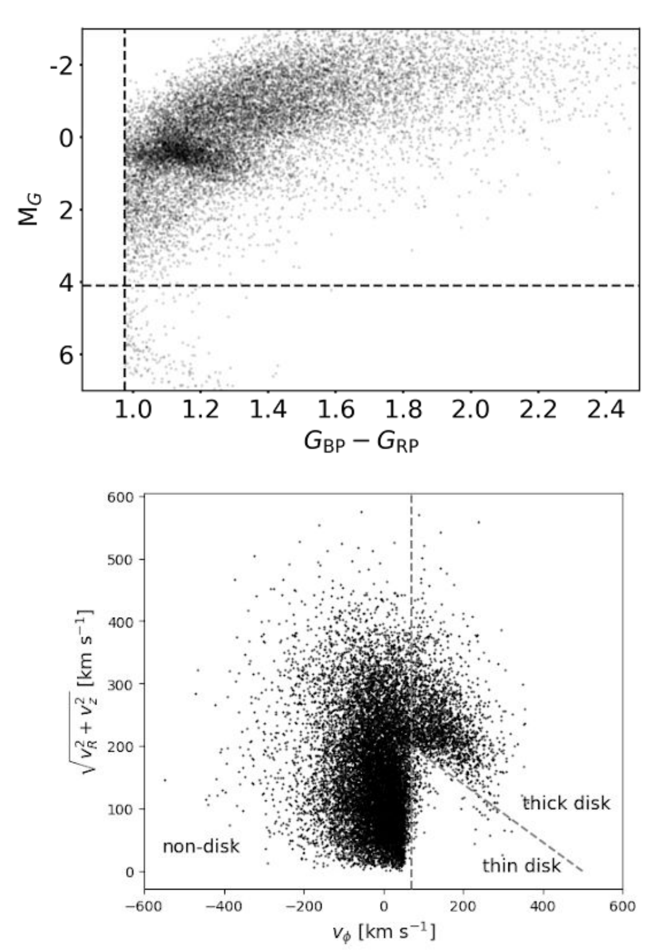


Figure 1: Top: color-magnitude diagram showing the absolute Gaia G magnitudes and Bp-Rp colors of stars in our sample. Our cuts correspond to the dashed lines. Bottom: A Toomre diagram of red giant stars in the Milky Way's halo and thick disk as a function of rotational and vertical velocity. The selection was made following the cuts in the Grunblatt et al. 2021 study, removing stars with rotational velocities exceeding ~75 km/s and low vertical velocities, leaving behind the halo star population that was studied (Grunblatt et al., 2021).

Methodology

Injection/Recovery Test: Injected artificial transits into real light curves to determine sensitivity and completeness of transit search (e.g., Howard et al. 2012, Thompson et al., 2018)

Simulated Transit Model:

- Simulated transits made with the Python package, exoplanet (Foreman et al. 2018)
- Transit periods were randomly drawn in a log-uniform distribution between 3 and 50 days & transit planet to star radius ratios were randomly drawn from a uniform distribution between 0.001 and 0.045
- The planet radii and transit depth were determined from equation 1 and equation 2, respectively:

BLS Search:

$$R_\mathrm{p} = r * R_\star \quad (1) \qquad \delta = \frac{{R_\mathrm{p}}^2}{{R_\star}^2} \quad (2)$$

- The BLS search was used to look for transits with a period between 3 and 50 days within each lightcurve.
- If the best fit period was within 10% of the input period, then the target would be considered as recovered
- To avoid noise complications from TESS' 13.7 day orbit, a mask for transits between 12.5 and 17 days was placed on the BLS search.

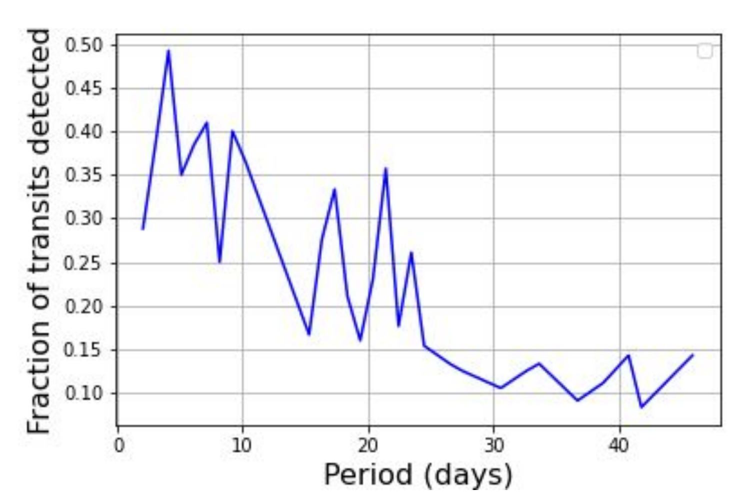
Analysis and Results

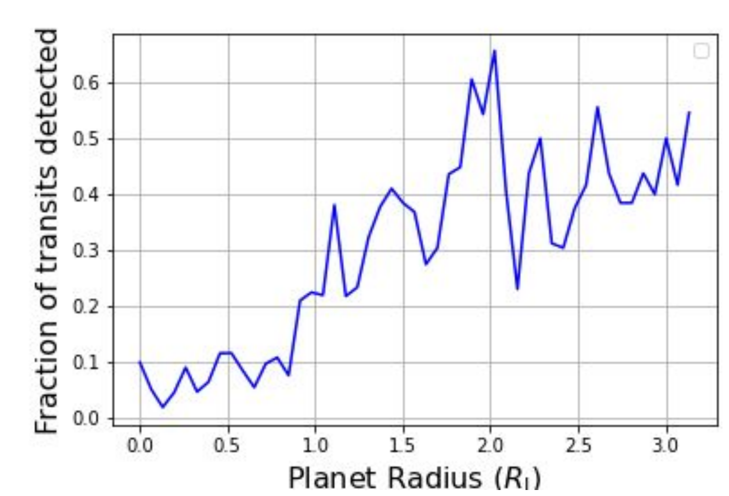
Survey Completeness: After running the injection and recovery test on all 1,080 targets, the completeness and the sensitivity of the lightcurves to planet detection were determined.

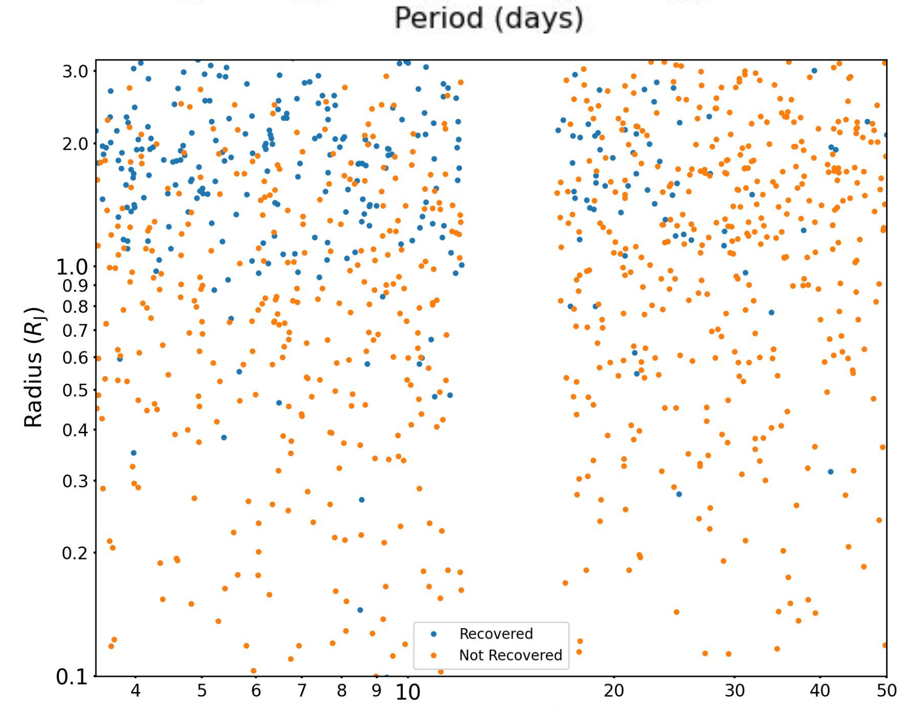
Figures 2 & 3: The recovery rate of the transits as a function of orbital period. Sensitivity to planet detection decreases as period increases. The recovery rate of the transits as a function of planet radii. Sensitivity to planet detection increases as the planet radius increases (Yoshida, 2020).

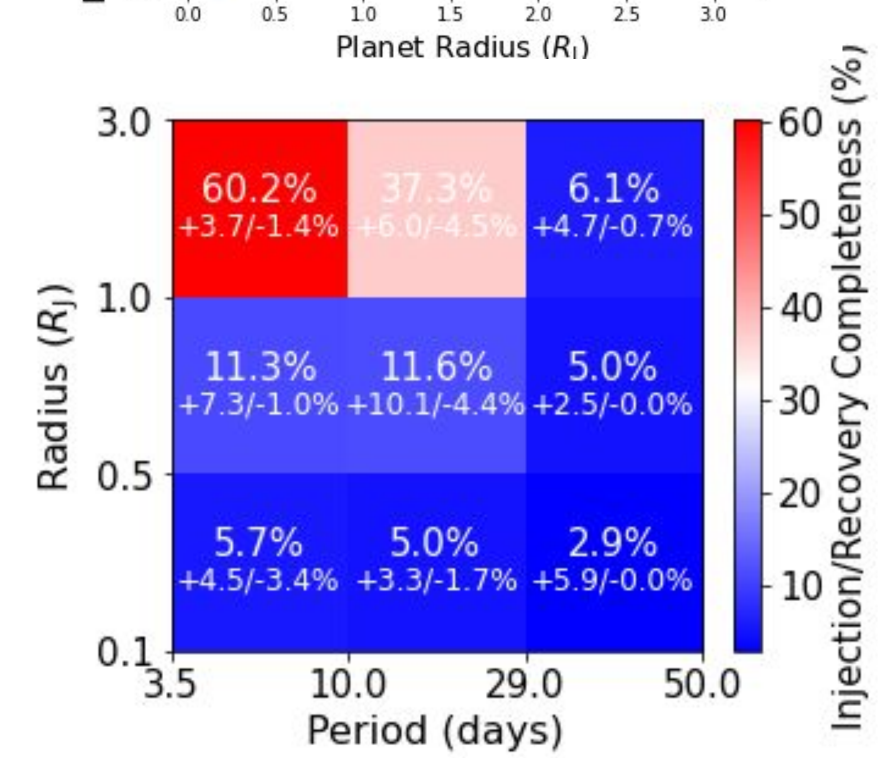
Figures 4 & 5: The transit signals injected into the observed halo stars as a period by radius plot. The blue indicates the targets recovered and the orange indicates the targets that were not successfully recovered. The gap down the middle represents the masked period range of 12.5 to 17 days during the injection and BLS search. A completeness map illustrating recovery rates estimated for nine different bins in planet radius and orbital period. This map shows that most recovered targets are clustered into the bin with a larger planet radius and lower period (Yoshida, 2020). The completeness was evaluated further after being separated into nine different bins with period precision, utilizing equation 3:

$$c_{bin} = n_{trans,det/bin} / n_{trans/bin} \quad (3)$$









What does this study suggest?

Agreement with Previous Studies: The analysis generally agrees with the recovery rate of planets orbiting low-luminosity red giant stars observed by the K2 telescope (Grunblatt et al., 2019).

Prediction: 0-2 planets found (based on Grunblatt et al., 2019)

Result: 0 planets found. Upper limit on occurrence determined.

Planet occurrence per bin:

$$f_\mathrm{bin} = \frac{n_\mathrm{pl,aug,bin}}{n_\star * c_\mathrm{bin}} \quad (4)$$

$$n_\mathrm{pl,aug,bin} = 1 \times \frac{a_\mathrm{bin,med}}{R_{\star,\mathrm{med}}} \quad (5)$$

Upper Limits of Planet Occurrence of TESS Halo Stars

Period vs. Planet Radius	*3.5 to 10 days*	*10 to 29 days*	*29 to 50 days*
1.0 to 3.0 R_j	0.38% + 0.01 / - 0.02%	1.49% + 0.20 / - 0.21%	18.2% + 2.40 / - 7.90%
0.5 to 1.0 R_j	2.04% + 0.20 / - 0.80%	4.79% + 2.93% / - 2.23%	21.8% + 7.00 / - 0.40%
0.1 to 0.5 R_j	4.06% + 6.04 / - 1.79%	11.1% + 5.70% / - 4.41%	38.3% + 0.00 / - 25.7%

- Our upper limit on occurrence for planets 1.0 Rj < planet radius < 3.0 Rj and 3.5 days < period < 10 days (0.38 +/- 0.02%) agrees well with previous studies of similar stars (0.51 +/- 0.29% for Hot Jupiters orbiting low-luminosity red giant stars in the Milky Way)

Additional factors:

- Planet metallicity correlation: $f \propto 10^{(1.2 * [Fe/H])}$ implies 10x decrease in planet occurrence for halo stars.
- Mixing of extragalactic and Milky Way stars in halo: up to 50% of stars targeted may not be extragalactic (Belokurov et al., 2020)
- ~3x larger search needed to make planet confirmation around RGB stars likely (Grunblatt et al., 2019)

*Thus, accounting for all additional factors, 1080 * 3 * 2 * 10 ~ 65,000 similar stars likely need to be searched to identify an extragalactic planet.*