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Abstract

We present a new transit of TRAPPIST-1 d from 2021 August 25. The measured mid-point of this transit agrees with the prediction from a recently published dynamical model for the TRAPPIST-1 system and differs significantly from a naive prediction from a simple linear ephemeris. This difference underlines the importance for using dynamical models to predict future transit times in the TRAPPIST-1 system.

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TRAPPIST-1 is an M8 dwarf star that is known to host seven Earth-sized transiting exoplanets (Gillon et al. 2016, 2017). It may be possible to characterize the atmospheres of these planets through transmission spectroscopy with upcoming space-based observing facilities like the James Webb Space Telescope, depending on the atmospheric composition of the individual planets and the number of transit events that can be observed (e.g., Barstow & Irwin 2016; Morley et al. 2017).

The TRAPPIST-1 planets exhibit transit timing variations (TTVs), introduced by gravitational interactions between the planets. Recently, Agol et al. (2021) developed a new dynamical model for the planetary system, fitting the observed TTVs from 447 transits of the TRAPPIST-1 planets and reporting high precision measurements of the planet masses. The dynamical model predicts future transit times that differ significantly from those of a simple ephemeris and orbital period, by up to several hours. This has important consequences for future transit observations of the TRAPPIST-1 planets, as an error of several hours in a predicted mid-transit time could easily result in missing a transit entirely.

Here, we present a new ground-based transit of TRAPPIST-1 d, which confirms the prediction of the dynamical model for TRAPPIST-1 from Agol et al. (2021). The measured transit time may also place stronger constraints on future transit times for planet d, as well as its companion planets. The observations were obtained on UT 2021 August 25 in *z*-band with the Perkins Re-Imaging SysteM

(PRISM) on Boston University's 1.8 m Perkins Telescope Observatory (PTO). Observing conditions were clear with an average seeing FWHM of $3\farcs5 \pm 0\farcs5$. Observations were taken with a 60 s exposure time for 8.1 hr over the course of the night.

Raw science images were bias-subtracted and flat-fielded, after which a set of suitable reference stars were identified. A total of seven reference stars were chosen, with average fluxes that ranged between 0.3 and 2.3 times the average flux of TRAPPIST-1. Centroid positions were measured for the target and references in every image, and then aperture photometry was performed, with background values estimated using circular annuli centered on the source positions. We used a weighted sum of the reference fluxes to create an artificial light curve (ALC) using the standard deviation of the reference star time series as weights, following the approach of Murray et al. (2020). We used the ALC to correct the target flux, and then performed a linear regression of the target flux to remove coeval trends with airmass and pixel position. Finally, we removed a linear trend that was present in the light curve by fitting a line to the time series.

The final light curve for TRAPPIST-1 d is presented in Figure 1, with 60 s exposures represented by gray points. We binned the data over 20 minutes intervals (black points). The error bars indicate the standard error on the mean of the points within a bin. While the transit event is clearly visible, a significant amount of time-correlated noise is present in this light curve, which could be due to changing levels of precipitable water vapor (e.g., Murray et al. 2020) or genuine photometric variability of TRAPPIST-1 itself (e.g., from a low-amplitude flare, Luger et al. 2017; Vida et al. 2017; Ducrot et al. 2020). We modeled the systematic noise using a non-periodic ($Q = 1/\sqrt{2}$) simple harmonic oscillator Gaussian process (GP) model from celerite (Foreman-Mackey et al. 2017) coupled with a quadratic limb-darkened transit model (Mandel & Agol 2002) as implemented in the batman package (Kreidberg 2015) for TRAPPIST-1 d.

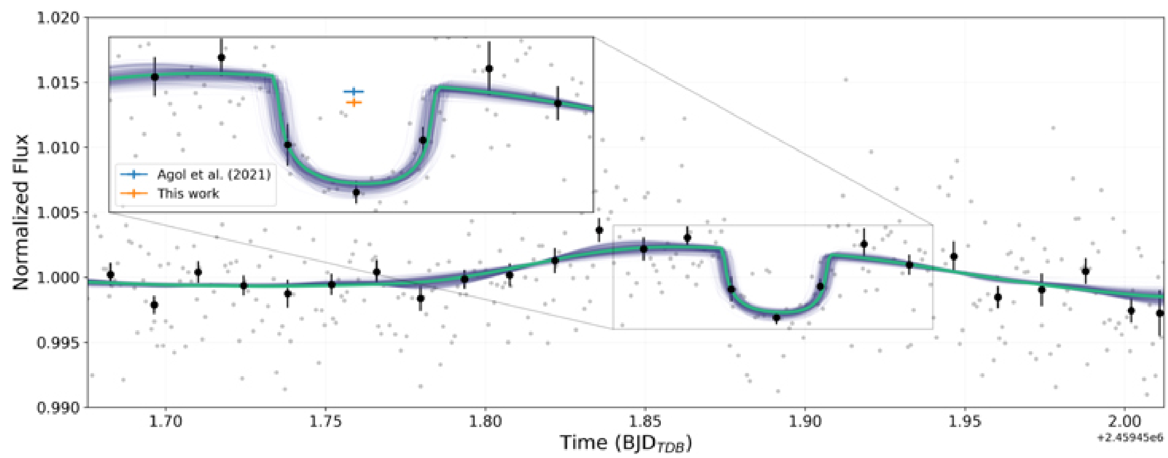

Figure 1. Transit + GP model fit to PTO/PRISM observations of TRAPPIST-1 in *z*-band on UT 2021 August 25. The raw 60 s exposures are represented with gray points, while the data binned over 20 minutes are shown as black points with error bars. The best-fit transit + GP model is shown in light blue, while 200 randomly selected models generated during the MCMC are shown in dark blue. The inset shows a zoom-in on the transit event. The predicted t_0 from Agol et al. (2021) is shown in the inset as a blue dash, with the 1σ uncertainty indicated by the horizontal error bar. The t_0 measured from our MCMC fit is shown as an orange dash for comparison, also with its 1σ uncertainty.

We fit the transit + GP model to the 60 s photometry with a Markov Chain Monte Carlo (MCMC) simulation using emcee (Foreman-Mackey et al. 2013). The mid-transit time, t_0, was allowed to vary freely, while we placed Gaussian priors on R_p/R_s (the planet radius in units of stellar radii), a/R_s (the orbital semimajor axis in units of stellar radii), and i (orbital inclination) using their measured values from Gillon et al. (2017). We fixed eccentricity e to 0, and quadratic limb darkening coefficients u_1 and u_2 to their expected z'-band values for a TRAPPIST-1-like star from Claret & Bloemen (2011). The resulting best-fit model is shown in light blue in Figure 1, while a selection of random models generated during the MCMC simulation are shown in dark blue.

The posterior distribution of t_0 gives a measured mid-transit time of $2459451.890559^{+0.001230}_{-0.001621}$. This transit time agrees with the expected time from the dynamical model of Agol et al. (2021), which predicts a mid-transit time of $2459451.890488 \pm 0.002094$ at this epoch. Additionally, the transit time measured here differs significantly from a naive prediction based on a simple linear ephemeris. Using a linear fit to the transit times for planet d reported in Agol et al. (2021), the mid-transit time would have been expected at 2459452.0466, a difference of 3.7 hr later than the measured time of transit. This discrepancy underlines the necessity for using dynamical models to predict future transit times in the TRAPPIST-1 system, as an error of almost four hours could result in missing a transit event entirely.

Transit timing monitoring of TRAPPIST-1 has continued for nearly two years since the final data in Agol et al. (2021), and so our measured time of TRAPPIST-1 d may be combined with these other measurements to better constrain the dynamical model. This in turn will allow for even greater accuracy in predicted transit times for TRAPPIST-1 d and its companion planets in the future.