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Updated forecast for TRAPPIST-1 times of transit for all seven exoplanets incorporating JWST data

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ABSTRACT

The TRAPPIST-1 system has been extensively observed with JWST in the near-infrared with the goal of measuring atmospheric transit transmission spectra of these temperate, Earth-sized exoplanets. A byproduct of these observations has been much more precise times of transit compared with prior available data from Spitzer, HST, or ground-based telescopes. In this note we use 23 new timing measurements of all seven planets in the near-infrared from five JWST observing programs to better forecast and constrain the future times of transit in this system. In particular, we note that the transit times of TRAPPIST-1h have drifted significantly from a prior published analysis by up to tens of minutes. Our newer forecast has a higher precision, with median statistical uncertainties ranging from 7-105 seconds during JWST Cycles 4 and 5. Our expectation is that this forecast will help to improve planning of future observations of the TRAPPIST-1 planets, whereas we postpone a full dynamical analysis to future work.

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1. INTRODUCTION

During Cycles 1-3 of JWST, transits of all seven planets in the TRAPPIST-1 system (Gillon et al. 2017) have been observed in the near-infrared with NIRISS-SOSS (Albert et al. 2023) and NIRSPEC-BOTS (Jakobsen et al. 2022), as well as four additional transits observed with MIRI F1500W during a phase-curve observation of the system (Gillon et al. 2023). In this note we focus on touching-up the timing forecast for this system; hence, we only utilize near-IR transits thanks to their higher precision. From July 2022 - December 2023, using JWST NIRISS or NIRSPEC, there have been three transits observed of planet b (NIRISS-SOSS, JWST GO-2589, PI: Lim et al. 2023; JWST GO-1981, PI: Stevenson/Lustig-Yaeger), five of planet c (NIRISS-SOSS, JWST GO-2589, PI: Lim; NIRspec-BOTS, JWST GO-2420, PI: Rathcke), two of planet d (NIRSpec-BOTS, JWST GO-1201, PI: Lafrenière), four of planet e (NIRSpec-BOTS, JWST GTO-1331, PI: Lewis), five of planet f (NIRISS-SOSS, JWST GO-1201, PI: Lafrenière), two of planet g (NIRSpec-BOTS, JWST GO-2589, PI: Lim), and two of planet h (NIRSpec-BOTS, JWST GO-1981, PI: Steveson/Lustig-Yaeger).

For the unpublished times of transit, the light curves were analyzed using standard pipelines with quadratic limb-darkened transit models (Mandel & Agol 2002). The first two transit times of planet b were published in Lim et al. (2023), while the third was simultaneous with a transit of planet h, described below. For planet c, NIRISS/SOSS light curves were produced using the `exoTEDRF` code (Feinstein et al. 2023; Radica et al. 2023; Radica 2024), and fitted using `juliet` (Espinoza et al. 2019), following the same procedure as Radica et al. (2024) for each of the two visits. Planet c NIRSpec PRISM light curves were generated using the `transitspectroscopy` pipeline (Espinoza 2022) and fitted with the `juliet` python package (Espinoza et al. 2019) to provide best-fit transit timings and their uncertainties. For planets d, f and g, the light curves were fitted with the same framework as in Lim et al. (2023). For planet h (and one simultaneous transit of planet b) the transit timings were derived using the Eureka pipeline, which was run to produce the light curves, and then the `trafit` (Gillon et al. 2010, 2012) code was used to fit the transits and provide the best fit timings and their uncertainties. When timing uncertainties are two-sided, we used the greater of the uncertainties to provide a symmetric error bar for utilizing a chi-square statistic. When multiple timing analyses were carried out, we checked that the measured times were consistent across analyses, and we used the larger of the timing uncertainties for each transit to make our forecast conservative.

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The measured times are for planet b: 9779.210475 ± 0.000025, $9780.72134581 \pm 0.000025$, $10289.8849446 \pm 0.0000098$; planet c: 9772.420388 ± 0.000012, 9881.401521 ± 0.000032, $10247.0939505 \pm 0.0000125$, $10249.515096 \pm 0.000034$, $10256.7810661 \pm 0.0000185$; planet d: 9889.264477 ± 0.000024, 9893.313946 ± 0.000060; planet e: $10118.459836 \pm 0.000032$, $10124.558969 \pm 0.000022$, $10148.956261 \pm 0.000043$, $10246.539286 \pm 0.000030$; planet f: 9881.035336 ± 0.000064, $10111.185753 \pm 0.000043$, $10120.387970 \pm 0.000045$, $10129.593868 \pm 0.000096$, $10148.005153 \pm 0.000042$; planet g: $9777.8353589 \pm 0.0000105$, 9926.053178 ± 0.000017; and planet h: $10139.74928085 \pm 0.0000809$ and $10289.88762392 \pm 0.000299$. Each time is given as $BJD_{TDB} - 2,450,000$ in days.

2. TIMING ANALYSIS

We carried out a transit-timing analysis using the timing data published in Agol et al. (2021a) as well as the 23 new JWST times listed above. The `NbodyGradient.jl` (Agol et al. 2021b) code was used to compute the transit times and their derivatives with respect to the initial conditions, using the same integrator, initial conditions, time step, and parameter set described in Agol et al. (2021a). The computation is Newtonian and plane-parallel. We minimized the chi-square of the fit using the `LsqFit.jl` package which implements a Levenberg-Marquardt optimization algorithm.

With the optimization completed, we integrated the model to July 2027 to cover the end of JWST Cycle 5. Using the Laplace approximation, we propagated the uncertainties using the covariance matrix of the optimum model parameters dotted with the Jacobian of the transit times with respect to the initial model parameters, yielding the uncertainties on the forecast times. Yet, these forecast uncertainties almost certainly underestimate the true uncertainty.

Notably, some of the JWST transits were affected by flares, and they may also be impacted by instrumental and/or stellar variability noise. Moreover, using the Laplace approximation may not fully represent the probability distribution. To address these issues we did the following: 1). we successively dropped a single transit of the 23 new JWST times, and re-optimized the timing model using the remaining data; 2). we used each optimized model to forecast the dropped time and its uncertainty; 3). we computed the normalized residuals of these 23 JWST times with respect to the forecast time and uncertainty based on the remaining data. We found that the cumulative distribution of the normalized residuals is consistent with a Gaussian distribution, but with the uncertainties inflated by a factor of 3.14. Consequently, for our forecast times based on the entire dataset, we inflate the forecast uncertainties by a factor of 3.14; this approach is analogous to leave-one-out cross-validation. We leave a more detailed analysis, including a markov-chain monte carlo analysis with a more robust likelihood function, to future work.

Figure 1 shows the resulting transit-timing variations as a function of time. The deviation of the new timing solution relative to the best-fit timing solution presented in Agol et al. (2021a) is shown with dashed lines in each panel. In all cases the agreement is excellent through the end of 2019, while the timing solutions diverge slightly over the next few years. The most extreme case of divergence is for planet h, which is already arriving $\gtrsim$0.5 hr later than the forecast from Agol et al. (2021a). The other planets have forecasts accurate to ≈minutes through July 2027.

The values of the forecast times can be found in the data behind the figure. A Jupyter notebook used to produce this code is available from the first author. As a check on the forecast times, we compared with five unpublished transit times from July 2024 for planets b, d and e under JWST program GO-6456 (PI: Natalie Allen and Néstor Espinoza), and all five lie within 1-σ of our forecast.

Several questions arise: Can we better constrain the masses and orbital parameters when including the JWST data? Is there evidence for an 8th planet, a moon, or other non-Keplerian effects? How much better can we constrain the bulk densities of these planets using JWST data? To address these questions in detail may require more data for redundancy, as well as a careful analysis of the JWST data in light of the impact of frequent flares found in TRAPPIST-1 with JWST (Howard et al. 2023) and the possible presence of correlated noise. Hundreds of unpublished transit measurements from ground-based telescopes (Ducrot, private communication), as well as observations of the secondary eclipses of planets b and c with MIRI (Greene et al. 2023; Zieba et al. 2023), could be included to further improve a dynamical analysis. For now, though, our forecast transit times may be used for future planning purposes to attempt spectroscopic measurements with JWST in the presence of stellar inhomogeneities (Lim et al. 2023; de Wit et al. 2024), while in turn these measurements will help to further constrain the dynamics of this system. For planning purposes for secondary eclipses, it should suffice to take the half-way point between adjacent transits (this ignores the light travel time and eccentricity offset, but both should be insignificant).

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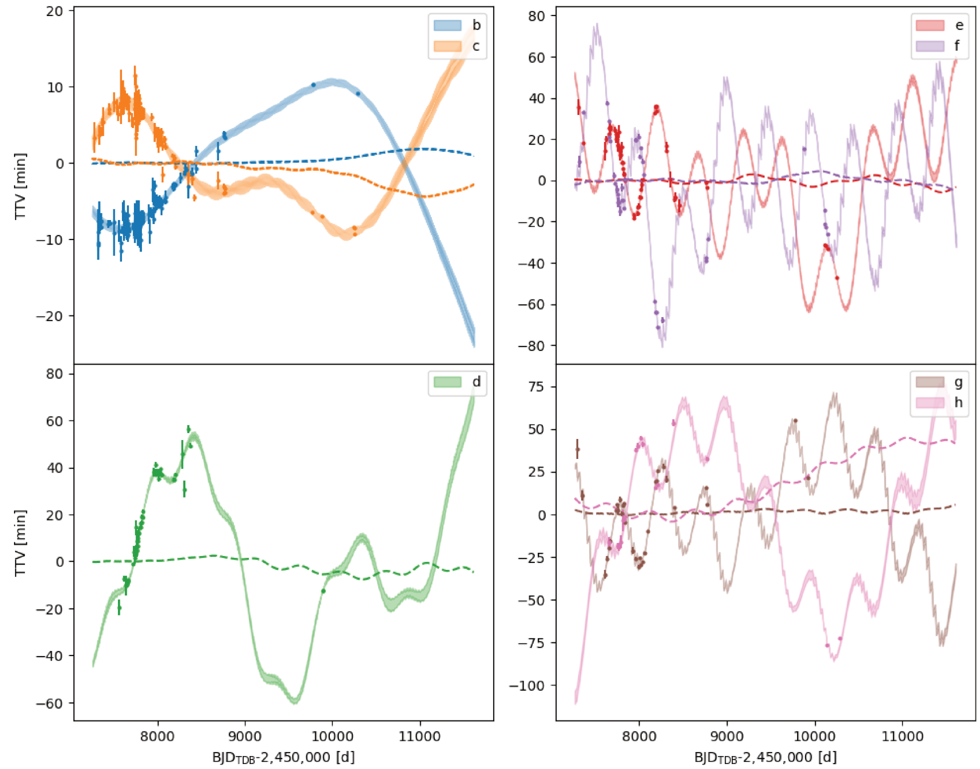

Figure 1. Transit-timing variations of the seven TRAPPIST-1 planets. Error bars are measurements from Agol et al. (2021), and the JWST times from this paper. Dashed curves show the difference between the new timing solution minus that from Agol et al. (2021). The data behind the figure are available for quantitative forecasting purposes.

Facilities: JWST (NIRISS, NIRSpec).

Software: `NbodyGradient.jl` (Agol et al. 2021b), `juliet` (Espinoza et al. 2019), `exoTEDRF` (Feinstein et al. 2023; Radica et al. 2023, 2024), `transitspectroscopy` (Espinoza 2022), `trafit` (Gillon et al. 2010, 2012), `LsqFit.jl` (https://github.com/JuliaNLSolvers/LsqFit.jl

REFERENCES

Agol, E., Hernandez, D. M., & Langford, Z. 2021b, MNRAS, 507, 1582, doi: 10.1093/mnras/stab2044

Agol, E., Dorn, C., Grimm, S. L., et al. 2021a, The Planetary Science Journal, 2, 1, doi: 10.3847/psj/abd022

Albert, L., Lafrenière, D., Doyon, R., et al. 2023, Publications of the Astronomical Society of the Pacific, 135, 075001, doi: 10.1088/1538-3873/acd7a3

de Wit, J., Doyon, R., Rackham, B. V., et al. 2024, Nature Astronomy, 8, 810–818, doi: 10.1038/s41550-024-02298-5

Espinoza, N. 2022, doi: 10.5281/zenodo.6960924

Espinoza, N., Kossakowski, D., & Brahm, R. 2019, MNRAS, 490, 2262, doi: 10.1093/mnras/stz2688

Feinstein, A. D., Radica, M., Welbanks, L., et al. 2023, Nature, 614, 670, doi: 10.1038/s41586-022-05674-1

Gillon, M., Deming, D., Demory, B. O., et al. 2010, A&A, 518, A25, doi: 10.1051/0004-6361/201014144

Gillon, M., Triaud, A. H. M. J., Fortney, J. J., et al. 2012, A&A, 542, A4, doi: 10.1051/0004-6361/201218817

Gillon, M., Triaud, A. H. M. J., Demory, B.-O., et al. 2017, Nature, 542, 456–460, doi: 10.1038/nature21360

Gillon, M., Ducrot, E., Agol, E., et al. 2023, TRAPPIST-1 Planets: Atmospheres Or Not?, JWST Proposal. Cycle 2, ID. #3077

Greene, T. P., Bell, T. J., Ducrot, E., et al. 2023, Nature, 618, 39–42, doi: 10.1038/s41586-023-05951-7

Howard, W. S., Kowalski, A. F., Flagg, L., et al. 2023, The Astrophysical Journal, 959, 64, doi: 10.3847/1538-4357/acfe75

Jakobsen, P., Ferruit, P., Alves de Oliveira, C., et al. 2022, Astronomy & Astrophysics, 661, A80, doi: 10.1051/0004-6361/202142663

Lim, O., Benneke, B., Doyon, R., et al. 2023, The Astrophysical Journal Letters, 955, L22, doi: 10.3847/2041-8213/acf7c4

Mandel, K., & Agol, E. 2002, The Astrophysical Journal, 580, L171–L175, doi: 10.1086/345520

Radica, M. 2024, arXiv e-prints, arXiv:2407.17541, doi: 10.48550/arXiv.2407.17541

Radica, M., Welbanks, L., Espinoza, N., et al. 2023, MNRAS, 524, 835, doi: 10.1093/mnras/stad1762

Radica, M., Coulombe, L.-P., Taylor, J., et al. 2024, ApJL, 962, L20, doi: 10.3847/2041-8213/ad20e4

Zieba, S., Kreidberg, L., Ducrot, E., et al. 2023, Nature, 620, 746–749, doi: 10.1038/s41586-023-06232-z