Photometric Analysis & Transit Times of TRAPPIST-1 b, c

Brett M. Morris,¹ Eric Agol,¹ and Suzanne L. Hawley¹

¹ Astronomy Department, University of Washington, Seattle, WA 98195, USA

(Accepted RNAAS, January 10, 2018)

TRAPPIST-1 hosts seven Earth-sized planets transiting an M8 star (Gillon et al. 2016, 2017). We observed mid-transit times of each of the inner two planets with the Astrophysical Research Consortium (ARC) 3.5 m Telescope at Apache Point Observatory (APO) to help constrain the planet masses with transit timing variations (Agol et al. 2005; Holman & Murray 2005), and we outline a procedure for analyzing transit observations with APO.

We observed one transit each of TRAPPIST-1 b and c with the ARCTIC imager using 4×4 binning and 10 second exposures in SDSS z′ (Huehnerhoff et al. 2016). Since the star is dim (R = 16.6) and the transit depths are small (∆F/F ∼ 1%), we develop a technique for removing background fringing, and for computing the transit light curve.

We collected ten night sky flats, rotating and slewing the telescope between exposures, to correct for background fringing in the SDSS z′-band (Howell 2006). Typically, flat fields are created by taking the median of a number of exposures of a constant, evenly illuminated field. The sky emission that produces the fringe pattern is variable and non-monotonic, so we developed a technique for flats.

In the series of i = 1, ..., N flats, the flux of the jth pixel, p_{j,i}, changes significantly between frames. Occasionally a star falls on a pixel, making one or two fluxes orders of magnitude brighter than the others. The median of all pixels in the ith frame, m_i, produces a light curve, which tracks the variations in flux from the sky emission. We regress p_{j,i} against m_i to match each individual pixel’s light curve, masking 3σ outliers when a star landed within a pixel. We normalize the matrix of linear regression coefficients by its median to create the flat field.

We correct for the local background measured in circular annuli centered on the stellar centroids using annuli with radii 10 and 20× larger than each source aperture radius. We normalize the TRAPPIST-1 light curve by a mean comparison star, which is computed from a linear combination of the following regressors: the fluxes of each comparison star, the target centroid pixel x and y coordinates, median sky background, air humidity, air pressure, and airmass. We regress the light curve of TRAPPIST-1 against these time series, and normalize the light curve by the combination of regressors that minimizes the out-of-transit scatter in the light curve. To avoid overfitting, we used the principle component analysis (PCA) cross-validation technique of Luger et al. (2016), which reduces the large number of available regressors to the smallest number of significant principle components necessary to detrend the light curve. We train the regression on a fraction of the out-of-transit observations while excluding a number of test fluxes. We choose the number principle components and aperture radius that produce a mean comparison star light curve with minimal test flux scatter.

We fit the light curve in Figure 1 for the depth and mid-transit time, and fix other parameters to the values of Gillon et al. (2016), with quadratic limb-darkening (Mandel & Agol 2002). We compute N posterior samples with Markov Chain Monte Carlo (Foreman-Mackey et al. 2013), and model correlated noise with a Matern 3/2 gaussian process (Ambikasaran et al. 2014). Chains are “converged” when N > 150τ_{int}, where τ_{int} is the integrated autocorrelation length. Analysis software and posterior samples are available online (Morris 2017).

The transit times of TRAPPIST-1 b and c are BJD_{TDB} = 2457580.87634^{+0.00034}_{-0.00033} and 2457558.89477^{+0.00080}_{-0.00085}, respectively, which will help constrain the planet masses.

We gratefully acknowledge help from Rodrigo Luger and Dan Foreman-Mackey. Based on observations obtained with the APO 3.5-meter telescope, which is owned and operated by ARC.

bmmorris@uw.edu
Figure 1. Transits of TRAPPIST-1.

Software: trappist1_arctic_2016 (Morris 2017), astropy (Astropy Collaboration et al. 2013), photutils (Bradley et al. 2016), george (Foreman-Mackey 2015), emcee (Foreman-Mackey et al. 2013), astroplan (Morris et al. 2017)

Facility: APO/ARC 3.5m

REFERENCES

Agol, E., Steffen, J., Sari, R., & Clarkson, W. 2005, MNRAS, 359, 567
Ambikasaran, S., Foreman-Mackey, D., Greengard, L., Hogg, D. W., & O’Neil, M. 2014, ArXiv e-prints, arXiv:1403.6015
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Bradley, L., Sipocz, B., Robitaille, T., et al. 2016, Photutils: Photometry tools, Astrophysics Source Code Library, , , ascl:1609.011
Foreman-Mackey, D. 2015, George: Gaussian Process regression, Astrophysics Source Code Library, , , ascl:1511.015
Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306
Gillon, M., Jehin, E., Lederer, S. M., et al. 2016, Nature, 533, 221
Gillon, M., Triaud, A. H. M. J., Demory, B.-O., et al. 2017, Nature, 542, 456
Holman, M. J., & Murray, N. W. 2005, Science, 307, 1288
Howell, S. B. 2006, Handbook of CCD Astronomy, ed. R. Ellis, J. Huchra, S. Kahn, G. Rieke, & P. B. Stetson
Huehnerhoff, J., Ketzeback, W., Bradley, A., et al. 2016, in Proc. SPIE, Vol. 9908, Ground-based and Airborne Instrumentation for Astronomy VI, 99085H
Luger, R., Agol, E., Kruse, E., et al. 2016, AJ, 152, 100
Mandel, K., & Agol, E. 2002, ApJL, 580, L171
Morris, B. M. 2017, doi:10.5281/zenodo.1064302
Morris, B. M., Tollerud, E., Sipocz, B., et al. 2017, ArXiv e-prints, arXiv:1712.09631