14 New Light Curves and an Updated Ephemeris for the Hot Jupiter HAT-P-54 b

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Abstract

Here we present an analysis of 14 transit light curves of the hot Jupiter HAT-P-54 b. Thirteen of our datasets were obtained with the 6” MicroObservatory telescope, Cecilia, and one was measured with the 61” Kuiper Telescope. We used the EXOplanet Transit Interpretation Code (EXOTIC) to reduce 49 datasets in order to update the planet’s ephemeris to a mid-transit time of 2460216.95257 ± 0.00022 BJD_TBD and an updated orbital period of 3.79985363 ± 0.00000037 days. These results improve the mid-transit uncertainty by 70.27% from the most recent ephemeris update. The updated mid-transit time can help to ensure the efficient use of expensive large, ground- and space-based telescope missions in the future. This result demonstrates that amateur astronomers and citizen scientists can provide meaningful, cost-efficient, crowd-sourcing observations using ground-based telescopes to further refine current mid-transit times and orbital periods.

1. Introduction

To date, there have been over 5,000 confirmed exoplanets discovered with over 7,000 candidates yet to be validated[1]. While it is impractical to perform follow up using solely space or large ground-based telescopes, which are generally expensive to operate and under strict observing schedules, large-scale citizen science projects, such as Exoplanet Watch[2] (Zellem et al., 2020), use crowd-sourced data to improve upon results from expensive space-based missions (e.g. Mizrachi et al., 2021; Hewitt et al., 2023a). Exoplanet Watch solicits the help of the public by utilizing small, (oftentimes privately owned), telescopes to validate findings or improve the ephemerides of exoplanets for potential follow-up observation with large ground-based or space-based telescopes.

Over time, a planet's mid-transit time can become "stale" in which the uncertainty of orbital times grows, causing the uncertainty of future transit times to require additional observing time in order to capture the entire transit (Zellem et al., 2020). This can become problematic, as valuable time and money can be lost if a transit time is miscalculated and missed. Small instruments can be used to collect data and amateur astronomers can analyze these observations to produce light curves and update orbital parameters of the planet. Studies using large amounts of observations taken by small telescopes prove to be invaluable to further refine the published knowledge. Small robotic telescopes, used by groups like Exoplanet Watch, can measure the orbital parameters of 195 known exoplanets to 3σ, and the number of exoplanets that can be viewed by ground-based telescopes will expand as the number of discovered exoplanets from JWST, TESS, or ARIEL increases (Zellem et al., 2020). Undergraduate students in the Spring 2023 offering of an online research course (discussed below) partnered with Exoplanet Watch to update the mid-transit time and orbital period of HAT-P-54 b, a hot Jupiter exoplanet (a = 0.04 AU; P = 3.8 days; M = 0.760 ± 0.032 M_{Jup}; Bakos et al. 2015) orbiting a K-type star 442.93-ly from the Earth.

This study was accomplished at Arizona State University (ASU) in one of the first course-based undergraduate research experiences (CUREs) for online astronomy majors. This 15-week course, titled *Exoplanet Research Experience*, was developed to offer non-traditional, online learners the opportunity to participate in authentic research experiences. CUREs help to make research accessible to a more diverse learning population, including people with full-time jobs, parents, veterans, and persons with disabilities (Auchincloss et al., 2014; Hewitt et al., 2023b).

2. Observatory and Observing Conditions

Forty-eight observations were collected using MicroObservatory's Cecilia telescope. Operated by the Harvard-Smithsonian Center for Astrophysics, MicroObservatory is a network of five automated 6-inch telescopes that provides an accessible avenue for students to make astronomy a

[1] NASA Exoplanet Archive
[2] https://exoplanets.nasa.gov/exoplanet-watch/about-exoplanet-watch/overview/

more hands-on and interactive laboratory in an online environment. Most of our observations were taken with MicroObservatory's Cecilia telescope which is located at the Fred Lawrence Whipple Observatory on Mt. Hopkins in Arizona.

Cecilia is a custom-built Maksutov-Newtonian with a 6-inch diameter mirror and a focal length of 560 mm. Its imaging sensor is a custom Kodak KAF1400 CCD with pixels 6.9 µm per side producing an image 0.94 x 0.72 degrees, using 2x2 pixel binning, giving an overall resolution of 5.0 arc-second/pixel (Sadler et al., 2001). All image series used from MicroObservatory had exposure times of 60 seconds using a clear filter.

The MicroObservatory telescope network's weather ratings rely on data provided by NOAA IR Satellite images (Observing with NASA, n.d.). MicroObservatory's weather rating ranges from 000 to 100, with 000 indicating a complete overcast, and 100 indicating a clear night sky. Weather ratings are determined through an automated process wherein software encircles the location of where the telescope is on the satellite image, then places the pixels within the circle on a scale from 000 to 100 (Sienkiewicz, 2021). Although weather ratings provide a guide, the NOAA weather ratings are not always entirely accurate. Therefore, a more in-depth analysis of each night of data is required to determine the quality of the dataset. All nights of data used to determine the mid-transit timings had recorded weather scores greater than 90, with the exception of several dates in 2018 and 2019 when MicroObservatory weather rating parameters were unavailable.

An additional dataset was obtained using the Steward Observatory 61" Kuiper Telescope atop Mt. Bigelow, Arizona. The telescope uses the cryo-cooled Mont4K camera which features 15 µm pixels per side resulting in an image 580 arcsec x 580 arcsec (9.7 arcmin x 9.7 arcmin) at a resolution of 0.14 arcsec/pixel (University of Arizona, n.d.). The image series obtained from Kuiper were 10 seconds while using the clear filter and there was no evidence of imprecise tracking.

Weather data is not recorded in the same manner for the 61" Kuiper Telescope observation as it is for MicroObservatory, but it should be noted that on 2023-09-29 skies were clear, with a moon at 100% illumination and 94° degrees from target.

3. Data reduction

For the photometric evaluation of our data, we used Exoplanet Watch's software, the EXOplanet Transit Interpretation Code (EXOTIC; Zellem et al., 2020). EXOTIC is a Python 3 pipeline designed for the analysis and interpretation of exoplanet transit observations. It processes data in the form of '.fits' image files to locate and track the host star over the course of a night in order to derive information such as the light curve and the planet's orbital parameters. EXOTIC can be run locally or on the Google Colaboratory (Colab). For our purposes, we chose to run EXOTIC on the

Google Colab to enable all our CURE student members to avoid installing Python and its various libraries on their local machines.

After an initial run of the data, we identified a list of the strongest candidates for significant detections. To determine which light curves should be included in this study, we determined that a light curve with a detection significance equal to or greater than 3σ would be considered a significant detection.

We re-ran significant and borderline significant (> 2.8σ; < 3σ) detections through EXOTIC using a standardized method similar to that used in Hewitt et al. (2023a): we first identified and manually removed any 'bad' images which we defined as images with deficient telescope tracking or weather-related incidents (i.e., cloud cover) that significantly obstructed our view of the host or comparison star. Next, with no recommended comparison stars available from the American Association of Variable Star Observers (AAVSO) in the field of view, we chose comparison stars close to HAT-P-54 to ensure that they were affected similarly by systematic errors, such as air mass variations. To identify the set of the best comparison stars, we input multiple potential comparison stars and let EXOTIC select the one that best reduced the scatter of the residuals from each of the individual datasets. We then identified the top 5 best comparison stars from all of the analyses and re-analyzed each significant and borderline dataset with EXOTIC with these top 5 comparison stars (Figure 1).

With this standardized analysis method, we found that 14 of the original 48 MicroObservatory datasets and the single Kuiper telescope observation had statistically-significant detections, which we present here.

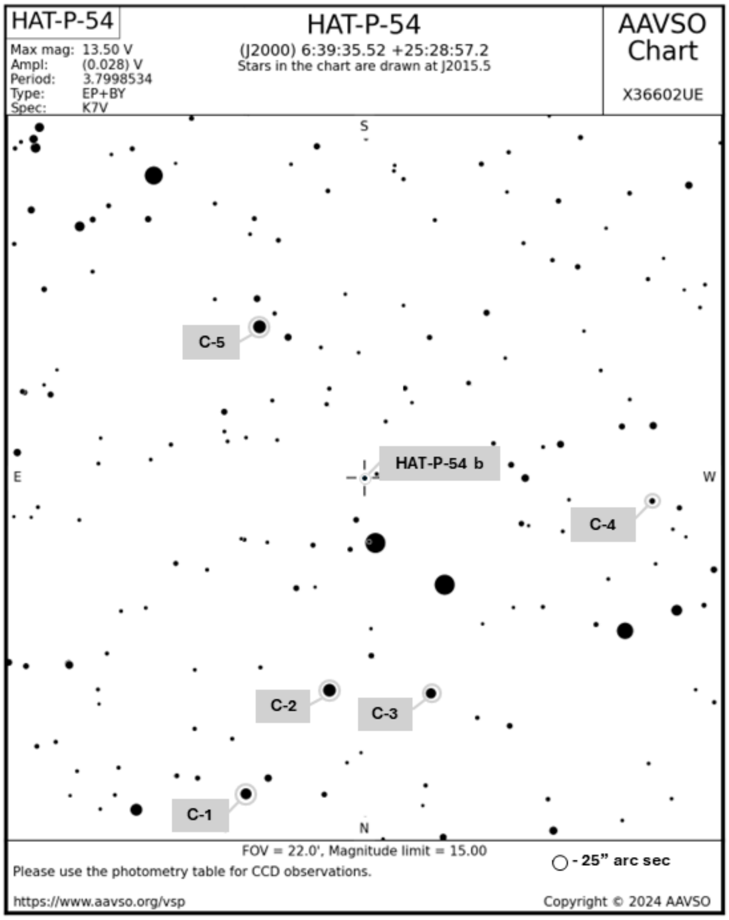

Figure 1. AAVSO VSP star chart for HAT-P-54. The field of view is 22’ and the largest aperture used was 49.61”. The comparison stars used in this study are labeled C-1 through C-5.

4. Data

We reduced 14 statistically significant light curves of HAT-P-54 b from our original 49 nights of data from MicroObservatory and the Kuiper telescope (Table 1; Figure 2). All 14 of the light curves used in this study are provided in Appendix A.

Table 1. Mid-transit times and transit depths for the 14 significant detections calculated by EXOTIC.

Date	*Mid-Transit (BJD_TDB) (+2450000)*	*Mid-Transit Uncertainty (days)*	*Transit Depth (Rp^2/Rs^2) (%)*	*Transit Depth Uncertainty*
2016-01-24	7412.6674	0.0032	0.0326	0.0059
2016-03-22	7469.6525	0.0029	0.0397	0.0034
2016-12-08	7731.8468	0.0014	0.0301	0.0039
2017-11-15	8073.8332	0.0013	0.0317	0.0060
2018-02-22	8172.6313	0.0016	0.0320	0.0044
2018-10-23	8415.8145	0.0030	0.0365	0.0099
2019-01-07	8491.8167	0.0032	0.0398	0.0066
2019-11-27	8814.8065	0.0034	0.0279	0.0049
2020-01-27	8875.6101	0.0036	0.0366	0.0053
2021-01-17	9232.7838	0.0062	0.0213	0.0060
2021-02-24	9270.8065	0.0058	0.0400	0.0100
2021-12-03	9551.9896	0.0030	0.0400	0.0037
2022-03-30	9669.7897	0.0061	0.0398	0.0088
2023-09-29*	10216.9531	0.00046	0.02003	0.0005

* Denotes the 61” Kuiper observation

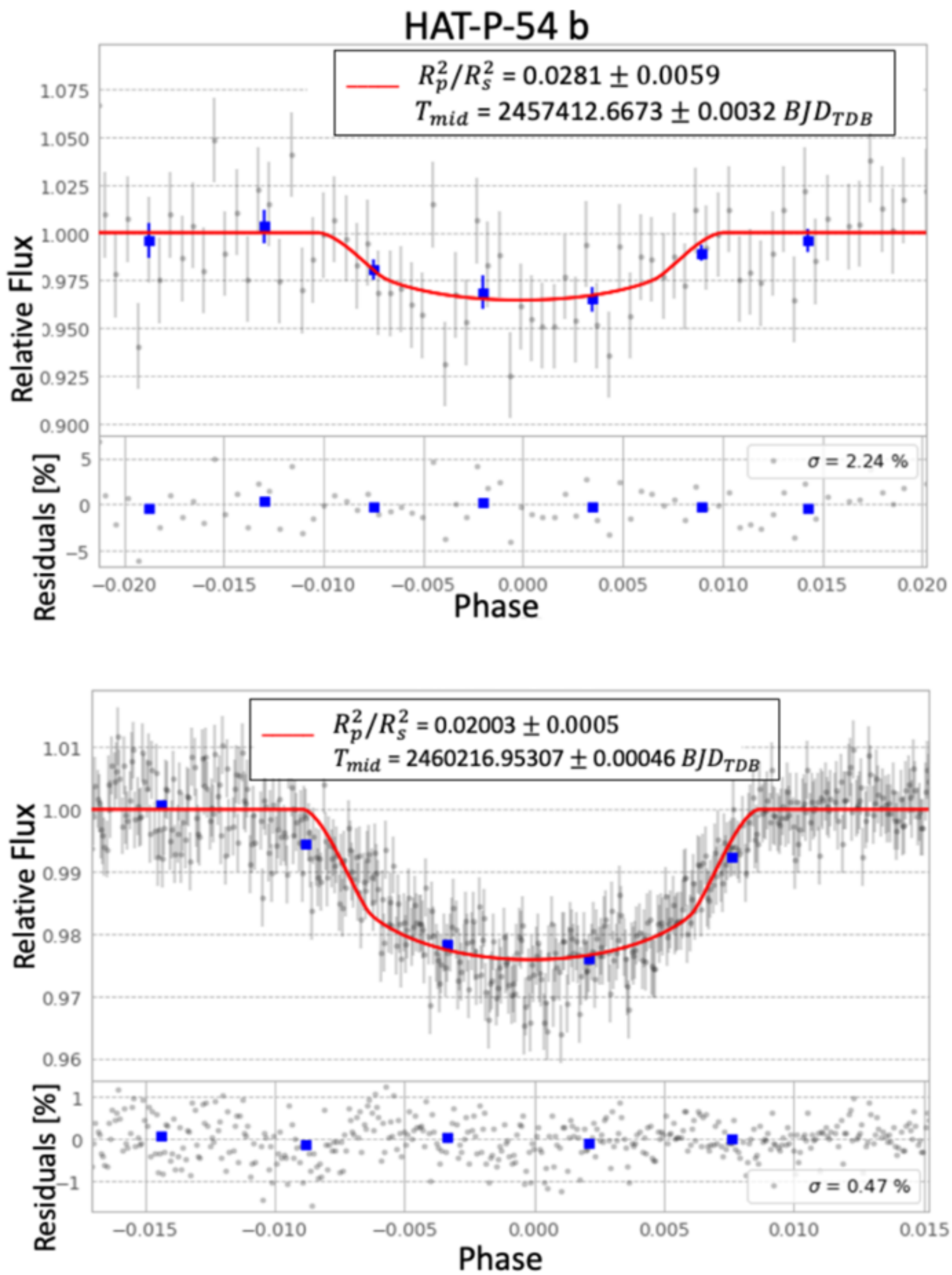

Figure 2. An example of a significant light curve from MicroObservatory on 2016-01-24 (top) and the light curve from the Kuiper telescope on 2023-09-29 (bottom). The gray data points represent data collected from each image of the data set. The blue data points represent an average from a set of binned data points and were used to fit the light curve.

In order to calculate an updated mid-transit time and orbital period, we created an Observed - Calculated (O-C) plot, presented in Figure 3. The 14 mid-transit times analyzed in this study were included in the plot as well as the reported mid-transit time from the initial discovery paper (Bakos et al., 2015), 4 mid-transit times from Saha et al. (2021) that were fit by Ivshina and Winn (2022), and 6 additional mid-transit times from Ivshina and Winn (2022). Other studies on the NASA Exoplanet Archive (Bonomo et al., 2017 and Kokori et al., 2022) were excluded from the creation of the O-C plot in an effort to keep the data consistent and only include those studies that derived the mid-transit time from a light curve. The values used from Bakos et al. (2015), Saha et al. (2021), and Ivshina & Winn (2022) are shown in Table 2 and the 14 values used from this study are shown in Table 1. For the creation of the O-C plot, we used an Exoplanet Watch notebook, "Exoplanet Ephemeris Fitting Tutorial,"[3] which allows for the generation of the O-C plot and posterior plot distribution and to calculate the mid-transit time and orbital period. The mid-transit time from the most recent observation, that from the Kuiper telescope on 2023-09-29, and the most recently published period (3.7998529 ± 0.0000017 days; Ivshina & Winn, 2022) were used as priors. We updated the mid-transit time to be 2460216.95257 ± 0.00022 BJD_TDB and the orbital period to be 3.79985363 ± 0.00000037 days. The O-C plot and the posterior plot distribution are presented in Figures 3 and 4, respectively.

Given that the point spread function (PSF) of our target star had an average full-width half-max of ~26", the light from nearby stars (located 24" and 32" away) could enter the aperture and dilute the transit signal (e.g., Crossfield et al., 2012; Bergfors et al., 2013; Stevenson et al., 2014; Ciardi et al., 2015; Collins et al., 2018; Zellem et al. 2020). However, this effect does not impact our measured mid-transit time and is therefore inconsequential for this work to update the ephemeris of HAT-P-54 b. Despite this potential dilution, we still see a 2-sigma agreement between our derived transit depths (Table 1) and those previously reported in the literature (Bakos et al., 2015) and, as we discuss in detail in the Results section, we can improve upon the reported mid-transit ephemeris. Similarly, MicroObservatory's imprecise tracking during its 60-sec exposures (which manifests as oblate PSFs) can be tolerated as the extraction and accurate measurement of the total amount of photons measured during this time is the most important facet.

[3] The ephemeris fitter can be found at https://colab.research.google.com/drive/1T5VT2gZ-ip6K6T9IXqMzQdSiEaf-UbJn?usp=sharing

Table 2. Prior solutions included in our combined O–C plot (Figure 4).

Citation	*Mid-Transit (BJD_TDB) (+2450000)*	*Mid-Transit Uncertainty (days)*
Bakos et al. (2015)	6299.30370	0.00024
Ivshina & Winn (2022) fit of Saha et al. (2021)	8864.20126	0.00041
Ivshina & Winn (2022) fit of Saha et al. (2021)	8883.20451	0.000427
Ivshina & Winn (2022) fit of Saha et al. (2021)	8883.20456	0.000437
Ivshina & Winn (2022) fit of Saha et al. (2021)	8902.20360	0.000308
Ivshina & Winn (2022)	9475.98097	0.0006831
Ivshina & Winn (2022)	9479.78137	0.0006766
Ivshina & Winn (2022)	9483.58175	0.0007356
Ivshina & Winn (2022)	9487.38019	0.0007031
Ivshina & Winn (2022)	9491.18192	0.0006023
Ivshina & Winn (2022)	9494.97987	0.0007512

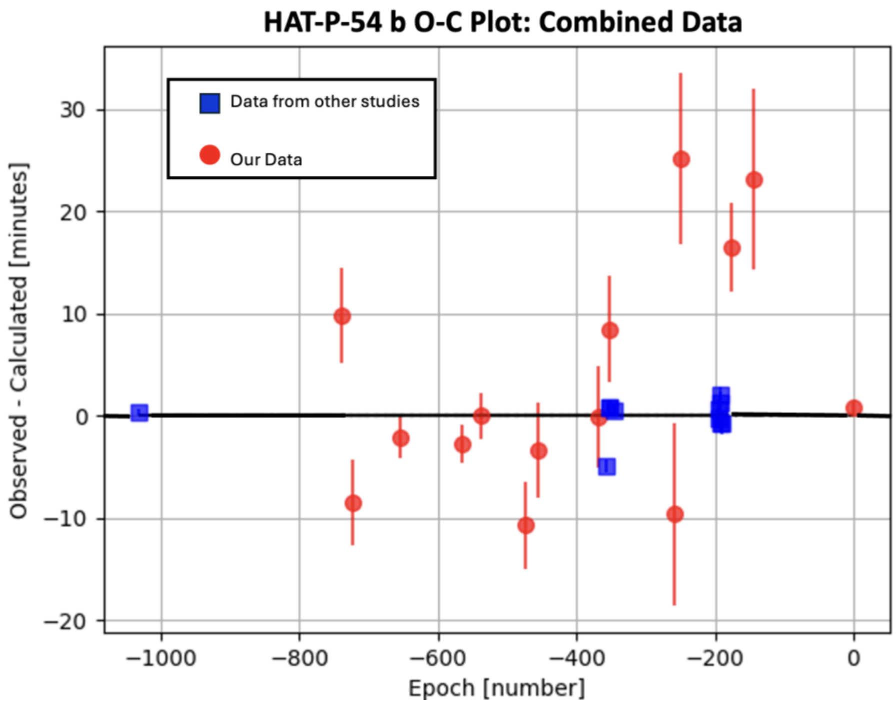

Figure 3. O-C plot for HAT-P-54 b using data from this study as well as previous observations. The priors used were $t_0 = 2460216.95298$ and $p = 3.7998529$.

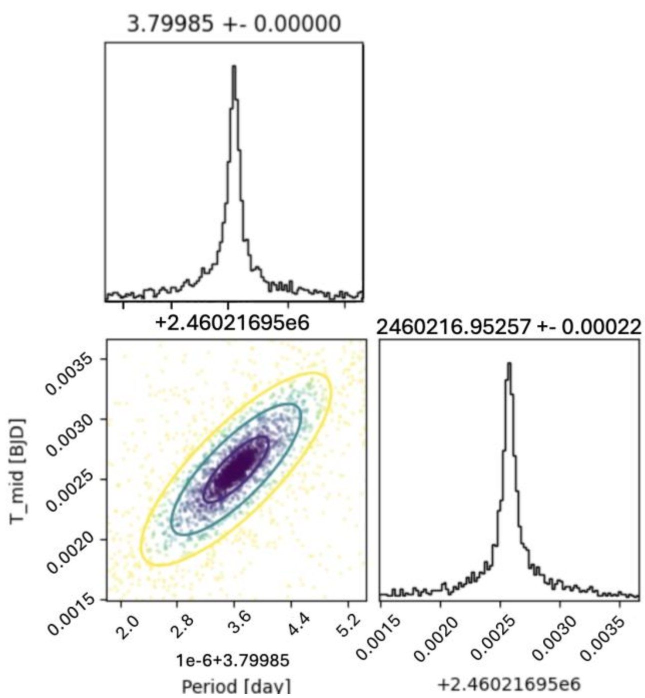

Figure 4. The posterior plot distribution for our newly calculated mid-transit time and orbital period using data from this study and previous studies.

5. Results

To compare our updated mid-transit time uncertainty (listed above) to those found previously, we forward propagated the previously cited times to our new mid-transit time. The propagated mid-transit uncertainties were calculated using the following equation from Zellem et al. (2020):

$$\Delta T_{mid} = (n_{orbit}^2 \cdot \Delta P^2 + 2n_{orbit} \cdot \Delta P \Delta T_0 + \Delta T_0^2)^{1/2} \quad (1)$$

The second term in Eq. 2 was dropped since none of the previous publications reported their covariance term (Zellem et al., 2020). Negating the covariance term led to the forward propagated mid-transit uncertainties to be slightly underestimated. The results of the propagations of the mid-transit uncertainties from Bakos et al. (2015) and Ivshina and Winn (2022) are shown in Table 3.

Table 3. Updated Ephemerides of HAT-P-54 b

Citation	*Mid-transit (BJD_TBD)*	*Mid-transit Uncertainty (Days)*	*Propagated Mid-transit Uncertainty (Days)*	*Period (days)*	*Period Uncertainty (days)*
This Work	2460216.95257	0.00022	N/A	3.79985363	0.00000037
Bakos et al. 2015	2456299.30370	0.00024	0.014	3.799847	0.000014
Ivshina and Winn 2022	2458864.20475	0.00042	0.00074	3.7998529	0.0000017

When comparing our mid-transit uncertainty to the propagated, previously published mid-transit uncertainties, we found that we decreased the mid-transit uncertainty by 98.43% since HAT-P-54 b's discovery in 2015 (Bakos et al., 2015). More notable is the decrease in the mid-transit uncertainty from Ivshina & Winn (2022) by 70.27%. We also compared our updated period uncertainty to those previously reported. We found that we decreased the uncertainty in the period by 97.36% since Bakos et al. (2015) and by 78.24% when compared to Ivshina & Winn (2022).

In the interest of viewing how our study has an impact on the future of HAT-P-54 b observations, we forward propagated the mid-transit uncertainties from Bakos et al. (2015) and Ivshina & Winn (2022), as well as our reported mid-transit uncertainty to a potential future observation. While there are many possible studies HAT-P-54 b could be a part of in the future, we chose to look at Habitable Exoplanet Observatory (HabEx), which is currently projected to be launched by the year 2039 (*Habitable exoplanet observatory*). Since we cannot be certain when it will be launched and operational, we chose December 31, 2039, at midnight (2466153.50000 JD) as a baseline time to propagate to. Assuming there are no transit timing variations present in the system (of which we find no evidence in this study), we used Equation 1 to calculate the propagated mid-transit times (Zellem et al., 2020). After calculating and comparing each study's propagated uncertainty, we arrived at the values found in Table 4. By the launch date, our mid-transit uncertainty would be 98.28% less than that of Bakos et al. (2015) and 81.21% less than that of Ivshina & Winn (2022). This highlights the importance of frequent, ground-based follow-up analyses of exoplanets such as HAT-P-54 b.

Table 4. Propagated uncertainties to 2039-12-31 and the percent our study improved them by.

Study	*Original Mid-Transit Uncertainty (Days)*	*Propagated Mid-Transit Uncertainty (Days)*	*% Improved*
Bakos et al. 2015	0.00024	0.036	98.28%
Ivshina and Winn 2022	0.00042	0.0033	81.21%
Our Data	0.00022	0.00062	N/A

In addition to Figure 3, we created two additional O-C plots to compare the updated mid-transit time and orbital period we calculated (by leveraging a combination of this study's data and previously published data) to ephemeris values obtained from (1) this study's data exclusively, and (2) previously published data alone. Figure 5 presents an O-C plot that includes only the 14 data points from this study (shown in Table 1). Similar to the O-C plot presented in Figure 3, the mid-transit time from our most recent observation and the most recently published period, from Ivshina & Winn (2022) were used as priors. Alternatively, Figure 6 presents an O-C plot using only the previously published data reported in Table 2. For this plot, the mid-transit time from Ivshina & Winn's (2022) most recent observation (2459494.97987 ± 0.0007512) and their reported period (3.7998529 ± 0.0000017) were used as priors. The posterior plot distributions corresponding to these O-C plots are presented in Figures 7 and 8. Using the ephemeris fitter with only the 14 data points obtained from this study, we calculated an updated mid-transit time of 2460216.95338 ± 0.00044 BJD_TDB and an updated orbital period of 3.79985662 ± 0.0000014 days. Using only the data found from previous studies (Bakos et al., 2015; Saha et al., 2021; Ivshina and Winn, 2022), we found the mid-transit time to be 2459494.98024 ± 0.00019 BJD_TDB and the orbital period to be 3.79985331 ± 0.00000038 days. Again, in order to compare the mid-transit uncertainties accurately, it is necessary to propagate these newly calculated mid-transit times to our original result that includes both this study's data and professional data (2460216.95257 BJD_TDB). In addition to this comparison, it is important to propagate all three mid-transit times to a future date to show the robustness of the different measurements over time. Therefore, we also propagated each of the derived mid-transit time values to the date mentioned previously (December 31st, 2029; 2466153.50000 JD). The results are presented in Table 5.

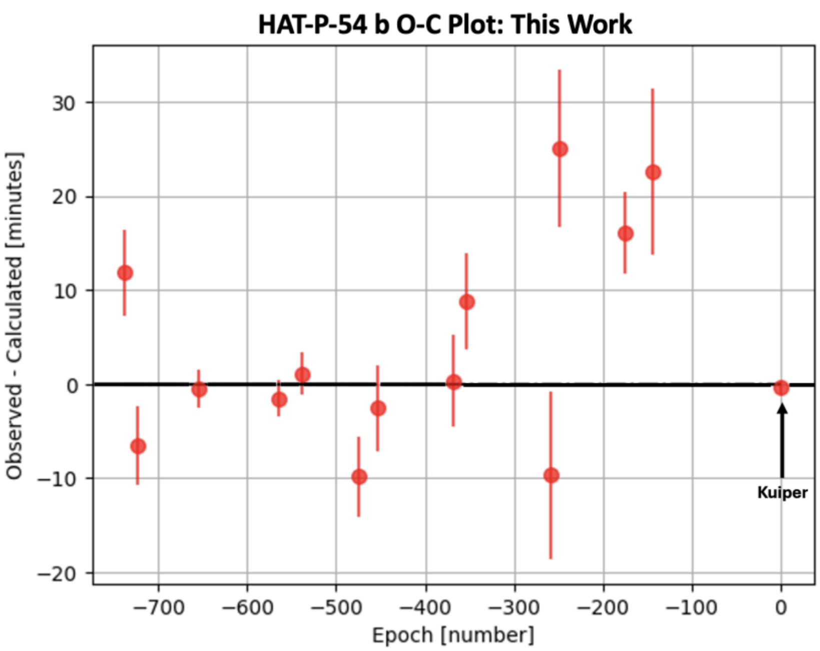

Figure **5**. O-C plot for HAT-P-54 b using t_0 = 2460216.95298 and p = 3.79985392 as priors. The Kuiper Observation is marked with an arrow to distinguish it from the MicroObservatory Observations.

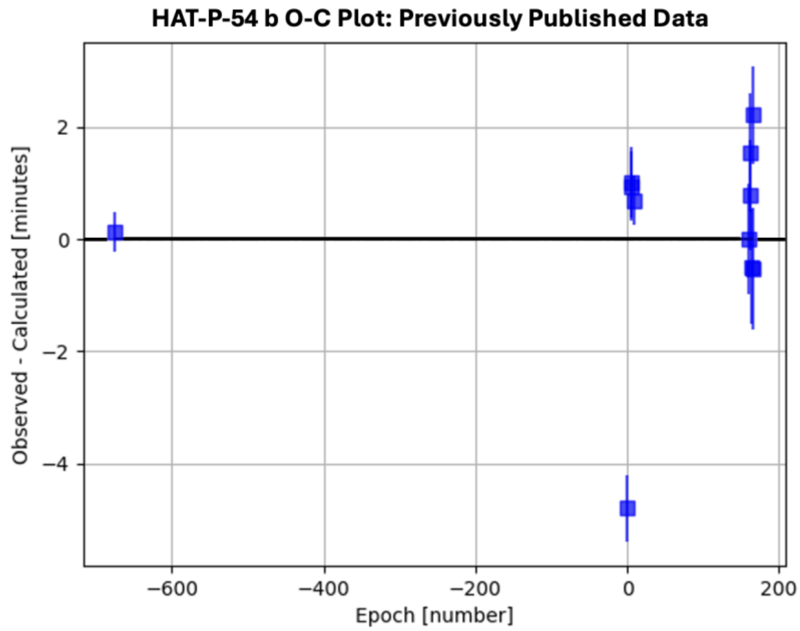

Figure 6. O-C plot using only previously published data and t_0 = 2459494.97987 and p = 3.79985392 as priors.

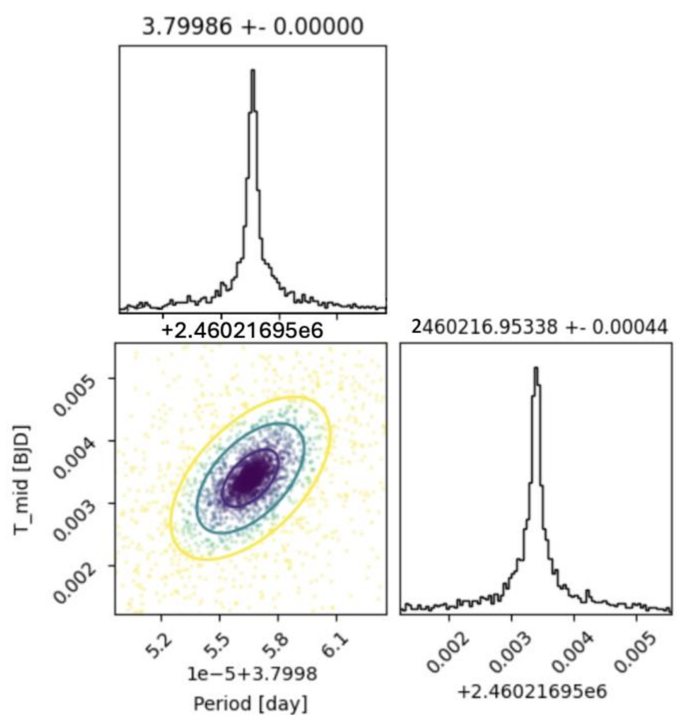

Figure **7**. The posterior plot distribution for the calculated mid-transit time and orbital period using only data from this study.

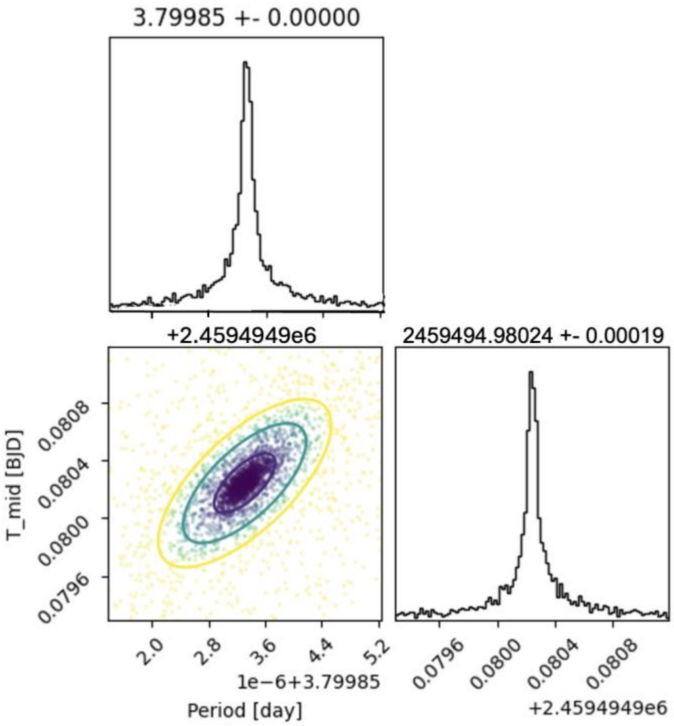

Figure 8. The posterior plot distribution for the calculated mid-transit time and orbital period using only previously published data.

Table 5. Propagations of each calculated mid-transit time to our reported mid-transit time and 2039-12-31

Data Group	*Original Mid-Transit Uncertainty (Days)*	*Propagated Mid-Transit Uncertainty to 2460216.95257 (Days)*	*Propagated Mid-Transit Uncertainty to 2039-12-31 (Days)*
Combined Data	0.00022	N/A	0.00062
Data From this Study Only	0.00044	N/A	0.0022
Previously Published Data Only	0.00019	0.00020	0.00069

Although our mid-transit time uncertainty derived from a combination of this study's data and previously published data is slightly larger (9%) than the uncertainty derived from previously published data exclusively, it is apparent that our updated mid-transit time uncertainty lends itself to a more robust solution over time. When each of the mid-transit times are propagated to December 31, 2029, we find that our combined data mid-transit time uncertainty is 10% smaller than the uncertainty calculated using previously published data alone. Additionally, although the mid-transit time and orbital period values reported from the use of the combined data from this study and previous studies is more robust, it is important to note that the values obtained using the data from this study alone were still capable of producing a mid-transit time and period with reasonable uncertainties.

6. Conclusion

In this study we demonstrate that by empowering a group of online, undergraduate students with the appropriate training and resources, citizen science is a viable option for the maintenance of exoplanet ephemerides. Leveraging data obtained from ground-based telescopes combined with data from previous studies, we were able to further reduce the orbital period and mid-transit time uncertainties for HAT-P-54 b. Most strikingly, our results showed a 70.27% improvement in the mid-transit uncertainty when compared to the most recent ephemeris update conducted by Ivshina & Winn (2022). Additionally, we found that using a combination of data from this study and previously published studies to update the mid-transit time provided the most robust solution over time. This finding in particular reaffirms the potential that citizen scientists have in contributing to the study of exoplanets, while also emphasizing the importance of ongoing efforts to improve the accuracy of exoplanet ephemerides in order to aid space-based telescopes in the efficient scheduling of observations. It demonstrates the power of leveraging both amateur and professional data.

This study and several others in the recent past (e.g. Zellem et al., 2020; Mizrachi et al., 2021; Hewitt et al., 2023a), prove that the ever-increasing number of exoplanet discoveries fosters an opportunity for collaboration between professional and amateur astronomers via citizen science projects. It confirms that small observatories and contributions from hobbyist equipment can have a direct positive impact on professional budgets for both time and money associated with projects like JWST and other large observatories through consistent and accurate updates to ephemerides over time.

The work completed in this study was done as a part of one of the first online Course-based Undergraduate Research Experiences (CUREs) for astronomy majors. CUREs make authentic research experiences accessible to a more diverse learning population and this study is a prime example of the importance of the work done by undergraduate students. A CURE’s focus on scientific practices, discovery, research that has a broader impact, collaboration, and iteration (Auchincloss et al, 2014), make studies like this possible during a 15-week online course. The development and assessment of this CURE is presented in Hewitt et al. (2023b).

7. Acknowledgments

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Appendix A: Significant Detections of HAT-P-54 b

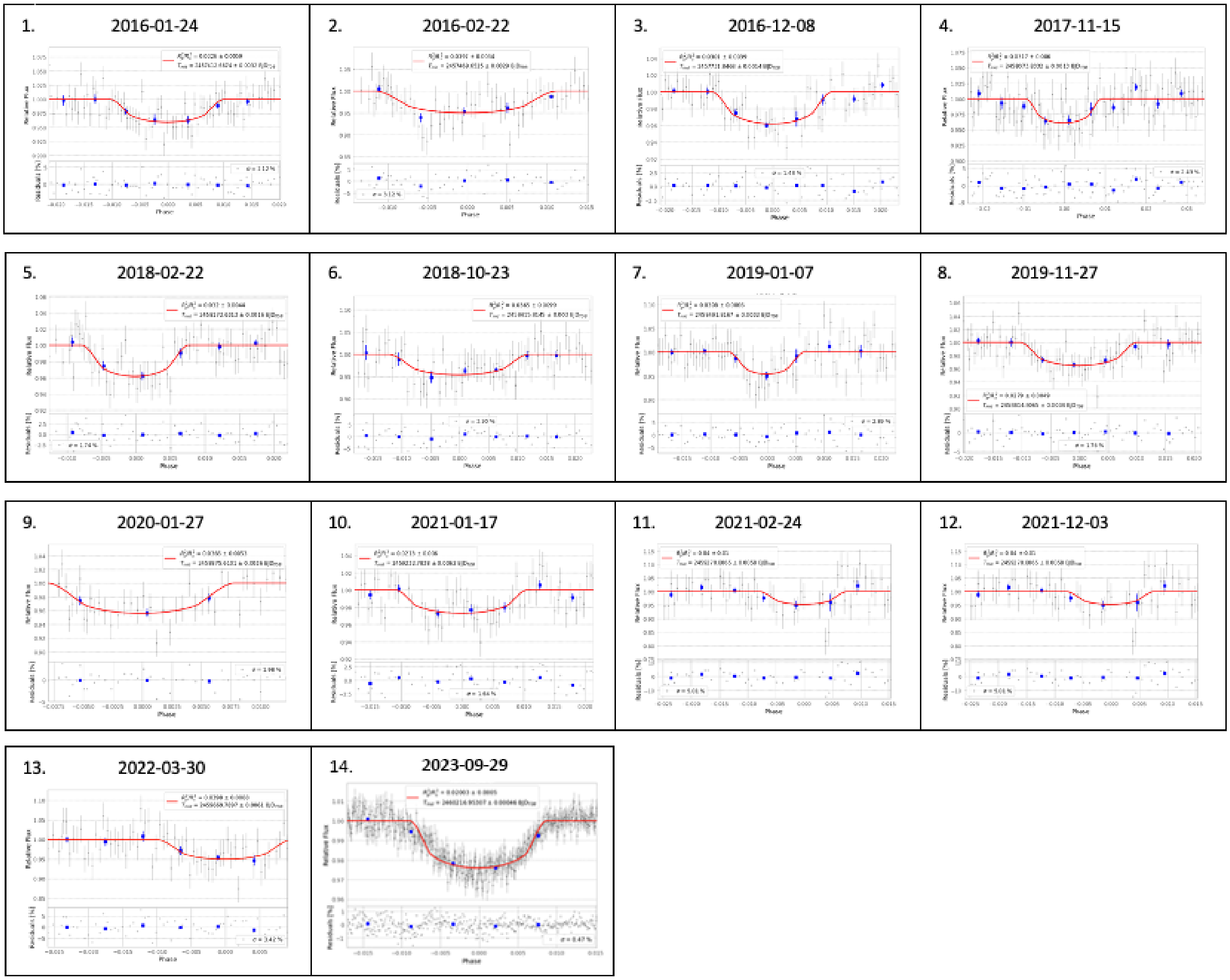

Figure A1: Light curves from this study. Light curves 1-13 were obtained using MicroObservatory and light curve 14 was obtained using the 61” Kuiper Telescope.