Original Research By Young Twinkle Students (ORBYTS): Ephemeris Refinement of Transiting Exoplanets III

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We report photometric follow-up observations of thirteen exoplanets (HATS-1 b, HATS-2 b, HATS-3 b, HAT-P-18 b, HAT-P-27 b, HAT-P-30 b, HAT-P-55 b, KELT-4A b, WASP-25 b, WASP-42 b, WASP-57 b, WASP-61 b and WASP-123 b), as part of the Original Research By Young Twinkle Students (ORBYTS) programme. All these planets are potentially viable targets for atmospheric characterisation and our data, which were taken using the LCOGT network of ground-based telescopes, will be combined with observations from other users of ExoClock to ensure that the transit times of these planets continue to be well-known, far into the future.

Keywords: *exoplanets, transit observations, ground-based telescopes, HATS-1 b, HATS-2 b, HATS-3 b, HAT-P-18 b, HAT-P-27 b, HAT-P-30 b, HAT-P-55 b, KELT-4A b, WASP-25 b, WASP-42 b, WASP-57 b, WASP-61 b, WASP-123 b*

http://dx.doi.org/etc

INTRODUCTION

A Brief History of Exoplanet Detections

The concept of extrasolar planets, worlds which orbit other stars, has existed since at least the era of the Ancient Greeks, with Democritus and Epicurus believing in the idea that there existed an infinite amount of worlds, some of which possessed their own organisms. Much later, Italian cosmological theorist Giordano Bruno encouraged the idea of the countless star were other suns and which could host planets similar to those in our own Solar System. Additionally, he reinforced the idea that there are other inhabited worlds that exist in the universe. After Neptune was mathematically predicted (Le Verrier, 1846) and then successfully detected (Galle, 1846), attention turned to applying these methods to searching for planets around other stars.

A number of different detection techniques were devised and several detection claims were made (Jacob, 1855; See, 1896; van de Kamp, 1969), each of which in turn was shown to be spurious (Sherrill, 1999; Boss, 2009). The effectiveness of several of the detection techniques were underestimated due to the expectation that other planetary systems would resemble our own. While many early efforts focused on astrometry, studying the perturbations in the positions of stars, the radial velocity method, which uses Doppler shifts in the star light to infer the presence of a companion, delivered first detection of a planetary body around a main-sequence star (Mayor & Queloz, 1995). Several years prior to this, a planetary system had been detected around a pulsar via precise timing measurements of the pulses (Wolszczan & Frail, 1992) and a previous potential detection of a planetary body around Gamma Cephei (Campbell, Walker, & Yang, 1988) was later verified (Hatzes et al., 2003).

After the discovery of 51 Pegasi b, numerous other detections were made using the radial velocity method, with many of these being worlds which are now referred to as hot Jupiters, large planets that have orbital periods of less than around 10 days. Notably, it had been argued more than 40 years earlier that, with the best spectrographs available at the time, such planets could be detected by the radial velocity method (Struve, 1952). While the radial velocity method can provide the mass and period of the planet, the radius cannot be determined. However, if the geometry of the system is aligned in the correct way, the planet can be seen to pass between the observer and its host star. The decrease in the flux is dependent upon the ratio of the planet's and the star's radii, thus providing a key additional bulk characteristic. Therefore, many studies searched for transits of these planets with HD 209458 b being the first planet to be seen to occult its host star (Charbonneau, Brown, Latham, & Mayor, 2000; Henry, Marcy, Butler, & Vogt, 2000).

Current Status

Since these early detections, there has been a rapid increase in the number of known exoplanets, with over 4400 having been identified to date. While many different methods have been successfully used to detect planets, by far the most lucrative thus far has been the transit technique with a number of ground-based and space-based surveys contributing to this deluge of detections. Indeed, of the 4438 exoplanets discovered to date, 3382 (76.2%) have been detected using the transit method[1]. The Kepler space telescope is perhaps the most famous and influential transit survey, contributing more than 2500 planets and many more candidates (Borucki et al., 2010). The most recent major exoplanet discovery mission to be launched is the Transiting Exoplanet Survey Satellite (TESS). Beginning operations in mid-2018, this mission will survey over hundreds of thousands stars across the entire sky (Ricker et al., 2015) and has already been successful in finding nearly 4400 candidate signals as well as confirming the existence of around 150 exoplanets.

Many of the planets found by TESS will be around bright stars, making them amiable for further characterisation. While current ground-based and space-based facilities have begun characterising the atmospheres of a handful of exoplanets, it is the next generation of facilities that offer the opportunity to truly move into an era of characterisation. The future of space-based facilities is especially promising and the launch of the James Webb Space Telescope (JWST) later this year is eagerly anticipated, with several programmes dedicated to studying transiting exoplanets (Bean et al., 2018). Furthermore, Twinkle, an upcoming, 0.45 m space-based telescope, will conduct a dedicated extrasolar survey which will include the characterisation of many exoplanetary atmospheres (Edwards, Rice, et al., 2019). Finally, Ariel is the M4 mission in ESA's Cosmic Vision programme which is

[1] https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

scheduled to launch in 2029. Ariel aims to investigate the atmospheres of over 1000 transiting exoplanets using visible and near-infrared spectroscopy (Tinetti et al., 2018, 2021).

These three facilities, in addition to continued observations from the ground and with Hubble, offer a golden future for characterising transiting exoplanets. However, the next generation of telescopes will require rigorous scheduling to minimise overheads and maximise science outputs. As such, interesting science targets could see their observing priority degraded if their ephemerides are not accurate enough, even if they are excellent targets for atmospheric characterisation. Many currently known planets have large ephemeris uncertainties and analysis suggests many TESS targets will have errors of >30 minutes less than a year after discovery due to the short baseline of TESS observations (Dragomir et al., 2020). Therefore, detections by this mission, as well as other transiting planets, will have to be regularly followed-up to ensure their ephemerides remain well-known.

Aims of the Project

Our project was undertaken as part of the ORBYTS programme, which unites academic researchers with secondary school students. As part of the programme, pupils work on original research linked to space science (Sousa-Silva et al., 2018). Since the programme's foundation in 2016, over 150 school students have published research in academic journals through ORBYTS. The topic of this research has varied, from calculating molecular lines lists (McKemmish et al., 2017, 2018; Chubb, Joseph, et al., 2018; Chubb, Naumenko, et al., 2018; Darby-Lewis et al., 2019), analysing data of our Sun from the Hinode spacecraft (French et al., 2020) or studying protostellar outflows (Holdship et al., 2019), to counting craters on Mars (Francis et al., 2020), monitoring X-rays from Jupiter's Auroras (Wibisono et al., 2020) and active galactic nuclei (Grafton-Waters et al., 2021).

In this project, we continued the work of previous ORBYTS groups (Edwards et al., 2020, 2021) in aiming to observe the transits of extrasolar planets which were suitable for atmospheric characterisation. By doing so, we aim to help ensure the planets' ephemerides will be well-known such that future facilities can characterise the atmospheres of these planets.

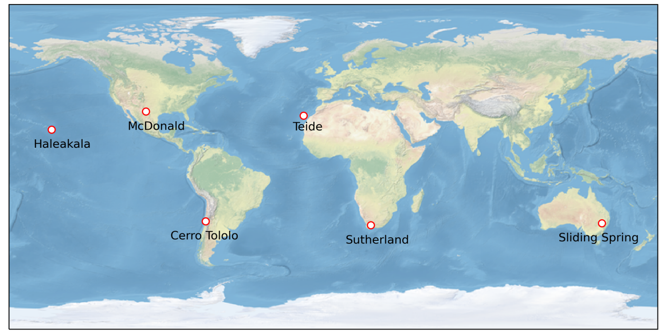

Fig. 1. Locations of the LCOGT's network of robotic 0.4 m telescopes.

METHODS

We utilised the Las Cumbres Observatory Global Telescope (LCOGT) network's ground-based 0.4 m telescopes (Brown et al., 2013), with access provided via the Global Sky Partners programme[2] and the Faulkes Telescope Project[3]. The network has six sites which host 0.4 m telescopes and these are spread across both the northern and southern hemispheres as shown in Figure 1.

Target Selection and Data Collection

We used ExoClock[4] (Kokori et al., 2020) to select high priority targets for ephemeris refinement. The site contains a database of all the exoplanets that could potential be studied with Ariel (Edwards, Mugnai, Tinetti, Pascale, & Sarkar, 2019). These are ranked as low, medium or high priority based upon the current uncertainty on their transit times, the predicted precision in 2028, and the time since they were last observed. By loading in the size and location of your telescope(s), ExoClock provides a list of potential observations over the coming days. An example of this schedule is shown in Figure 2 and, from the long list of potential planets to observe, we focused only on those ranked as high priority.

Before using the LCO portal to book an observation of a potentially suitable target, we first had to calculate an exposure time using the LCO exposure time calculator[5]. To do this, we used the R-band magnitude of the host star from the ExoClock site and ensured the 0.4 m telescope option was selected as shown in Figure 3.

[2] https://lco.global/education/partners/
[3] http://www.faulkes-telescope.com/
[4] https://www.exoclock.space/
[5] https://exposure-time-calculator.lco.global/

We calculated the required signal to noise ratio (SNR) for our observations from:

$$SNR > 5 \times \frac{1000}{Depth_R} \quad (1)$$

where Depth_R is the transit depth in mmag in the R-band which was taken from the ExoClock site. Having ensured that the required SNR could be reached without saturation, we booked our observations through the LCO portal. Due to issues with the weather or competing schedules, not all our observing requests were successful. However, we acquired data for thirteen planets: HATS-1 b (Penev et al., 2013), HATS-2 b (Mohler-Fischer et al., 2013), HATS-3 b (Bayliss et al., 2013), HAT-P-18 b (Hartman et al., 2011), HAT-P-27 b (Anderson et al., 2011; Béky et al., 2011), HAT-P-30 b (Johnson et al., 2011), HAT-P-55 b (Juncher et al., 2015), KELT-4A b (Eastman et al., 2016), WASP-25 b (Enoch et al., 2011), WASP-42 b (Lendl et al., 2012), WASP-57 b (Faedi et al., 2013), WASP-61 b (Hellier et al., 2012) and WASP-123 b (Turner et al., 2016).

Data Reduction and Analysis

We used the HOlomon Photometry Software (HOPS, (Tsiaras, 2019)), which is freely available on GitHub[6], to analyse the datasets we acquired.

The first step of the analysis within HOPS is usually an initial reduction of the datasets (dark, flat and bias subtraction). Luckily, LCO already does the initial reduction for us: we obtained the reduced (BANZAI) data from the LCO archive and proceeded to process the data by uploading it onto HOPS. The filter needed to be set to the R filter, which is the optical filter we used to observe all exoplanets in this study, and the co-ordinates of the host-star were obtained from the Right Ascension/Declination data found in the file's header. Within HOPS, we inspected frames for which sudden changes in the sky ratio or PSF were seen and any images that were deemed poor quality were removed. Due to the Earth's rotation, and slight errors in the telescope's ability to track the host star, the position of stars on the detector focal plane can change over the course of a night. Therefore, HOPS aligns the images to ensure the location of each star within the image is constant so the star's flux can be accurately measured over time.

Next, we extracted the flux from the target star. HOPS was simple to use in this regard, we only needed to pick our target star, and comparison stars

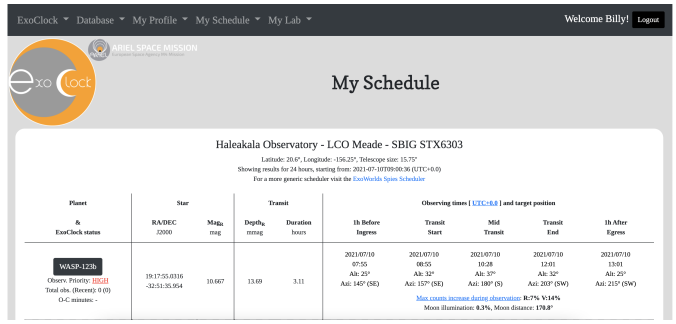

Fig. 2. Screenshot of the ExoClock schedule tool, which provides a list of potential transit observations that could be conducted with the telescopes listed under your account.

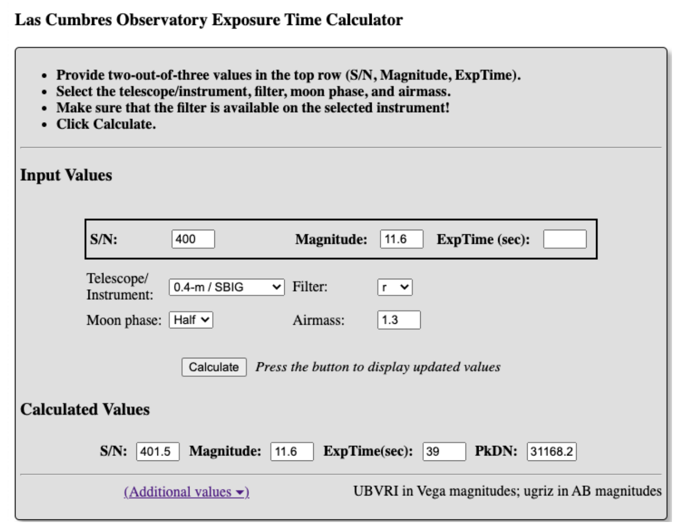

Fig. 3. The LCO Exposure Time Calculator that we used to check the predicted quality of our observations and to ensure the telescope's detector didn't saturate.

to remove variations in the star's flux that were not due to the planet. Given that comparison star's may be variable, we inspected the photometry to ensure no spurious signals were being inserted into the host star's flux. If any comparison stars were deemed inappropriate, we removed them, replacing them to achieve more stable light curves.

Finally, we used the built-in transit fitting feature of HOPS, which uses pylightcurve[7] (Tsiaras et al., 2016), to fit our data. The parameters used for the fitting were those in the ExoClock database, which were in turn taken from the following papers: HATS-1 b (Penev et al., 2013), HATS-2 b (Mohler-Fischer et al., 2013), HATS-3 b (Bayliss et al., 2013), HAT-P-18 b

[6] https://github.com/ExoWorldsSpies/hops

[7] https://github.com/ucl-exoplanets/pylightcurve

Table 1. Summary of observations undertaken as part of this project.

Planet	Star Mag [R]	Exposure Time [s]	Filter	Facility	Date
HATS-1 b	12.08	60.284	SDSS-rp	Cerro Tololo	21/02/2021
HATS-2 b	13.40	120.237	SDSS-rp	Sliding Spring	22/02/2021
HATS-3 b	11.69	45.280	SDSS-rp	Teide	17/05/2021
HAT-P-18 b	12.61	90.285	SDSS-rp	McDonald	07/05/2021
HAT-P-18 b	12.61	90.288	SDSS-rp	McDonald	18/05/2021
HAT-P-27 b	11.98	59.937	SDSS-rp	Haleakala	18/04/2021
HAT-P-30 b	10.104	20.281	SDSS-rp	Teide	03/02/2021
HAT-P-55 b	12.87	61.939	SDSS-rp	Haleakala	16/05/2020
HAT-P-55 b	12.87	69.945	SDSS-rp	Haleakala	31/03/2021
KELT-4A b	9.90	10.282	SDSS-rp	Teide	01/03/2021
WASP-25 b	11.82	30.286	SDSS-rp	Sutherland	23/02/2021
WASP-42 b	11.71	45.233	SDSS-rp	Sliding Spring	17/05/2021
WASP-57 b	12.90	90.288	SDSS-rp	Sliding Spring	21/04/2021
WASP-61 b	11.88	60.285	SDSS-rp	McDonald	15/12/2020
WASP-123 b	10.67	20.288	SDSS-rp	Cerro Tololo	28/07/2021

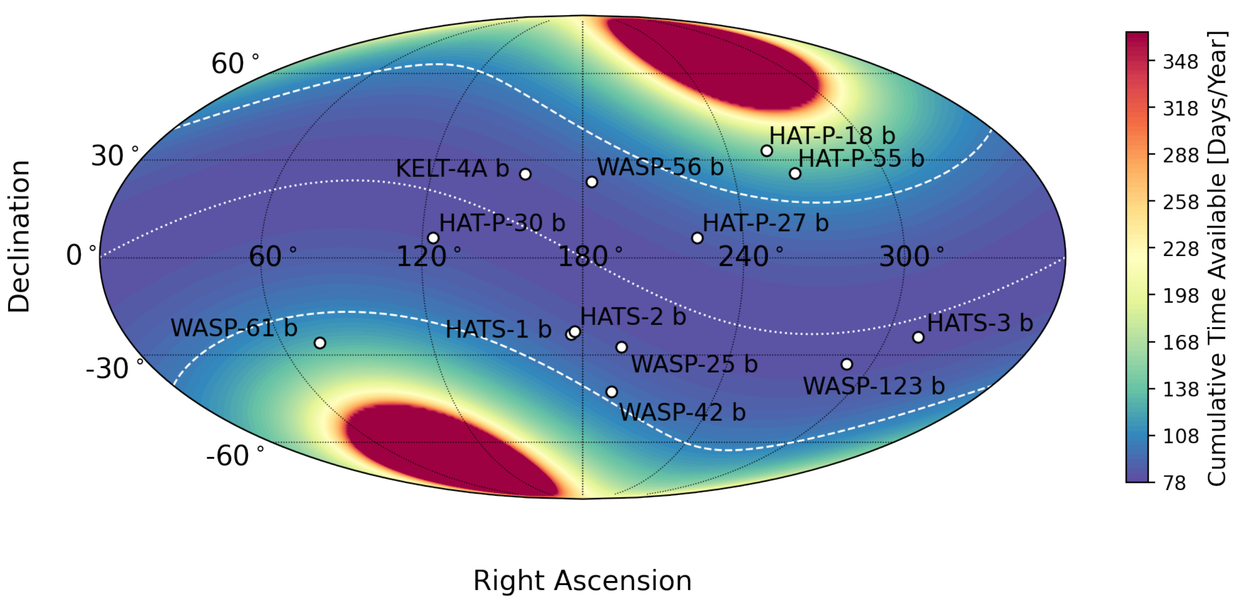

Fig. 4. The sky coverage of Ariel, given in days available per year, with the planets studied here over-plotted. The dashed white line shows the ecliptic plane while the dotted white lines represent the extent of Twinkle's field of regard, indicating that, of the planet studied here, only HAT-P-18 b, HAT-P-55 b and WASP-61 b are not also potential targets for this mission.

(Seeliger et al., 2015), HAT-P-27 b (Seeliger et al., 2015), HAT-P-30 b (Maciejewski et al., 2016), HAT-P-55 b (Juncher et al., 2015), KELT-4A b (Eastman et al., 2016), WASP-25 b (Southworth et al., 2014), WASP-42 b (Southworth et al., 2016), WASP-57 b (Southworth et al., 2015), WASP-61 b (Hellier et al., 2012), WASP-123 b (Turner et al., 2016). In each case, the only free parameters in the fit, other than those describing a quadratic model for the out-of-transit systematics, were the transit mid time and the planet-to-star radius ratio.

RESULTS

Figure 4 shows the position in the sky of the planets we observed and the coverage of the Ariel mission. Ariel will have continuous viewing zones at the ecliptic poles and, while none of the planets lie within it, HAT-P-18 b is the closest meaning there will be many potential observing windows for this planet. JWST will also be able to observe the whole sky but Twinkle's field of regard is limited to planets within ±40° of the ecliptic plane, meaning HAT-P-18 b, HAT-P-55 b and WASP-61 b cannot be studied by this mission.

Across these 10 planets, our project acquired 12 transit lights curves and the final fits of these are given in Figure 5. In each case, the best-fit transit model is given in red while the shaded regions indicate the time window of the fitted mid time (red) and expected mid time (blue). For each observation, we compared the fitted mid time to the expected, calculating the observed minus calculated residual (O-C). The transit mid times and O-C values are given in Table 2.

We note that, for the first observation of HAT-P-18 b and our observation of WASP-123 b, HOPS struggled to fit the data when the planet-to-star radius ratio was a free parameter due to the poor coverage of the transit. Therefore, for HAT-P-18 b we fixed the planet-to-star ratio to that observed in the second observation of the planet for which a complete coverage of the transit had been obtained. While the measured O-C residuals are slightly different for these two observations, they are consistent within 1σ. For WASP-123 b, we fixed the plant-to-star radius ratio to that from (Turner et al., 2016).

DISCUSSION

In general, all our light curves are of a good quality as in each case the transit can be clearly seen and is well-fitted with no significant correlations within the residuals. The precision achieved on the transit mid time varies from less than a minute to nearly 3 minutes. We have identified a number of potential reasons for this, as discussed below.

Table 2. Transit mid times for each light curve analysed in this project as well as the subsequent observed minus calculated (O-C) residual.

Planet	Mid Time [BJD_{TDB}]	O-C [min]
HATS-1 b	$2459266.7521^{+0.0008}_{-0.0010}$	$-0.0^{+1.2}_{-1.4}$
HATS-2 b	$2459268.1531^{+0.0008}_{-0.0007}$	$4.4^{+1.2}_{-1.1}$
HATS-3 b	$2459352.5818^{+0.0017}_{-0.0015}$	$-0.1^{+2.4}_{-2.1}$
HAT-P-18 b	$2459341.7681^{+0.0015}_{-0.0015}$	$1.7^{+2.1}_{-2.1}$
HAT-P-18 b	$2459352.7832^{+0.0010}_{-0.0009}$	$0.2^{+1.5}_{-1.3}$
HAT-P-27 b	$2459322.8860^{+0.0013}_{-0.0009}$	$-3.9^{+1.8}_{-1.2}$
HAT-P-30 b	$2458882.5893^{+0.0009}_{-0.0009}$	$-12.3^{+1.3}_{-1.3}$
HAT-P-55 b	$2458985.9487^{+0.0015}_{-0.0015}$	$-10^{+2.1}_{-1.9}$
HAT-P-55 b	$2459305.0323^{+0.0016}_{-0.0019}$	$-14.8^{+2.4}_{-2.7}$
KELT-4A b	$2459275.5584^{+0.0012}_{-0.0011}$	$-5.8^{+1.8}_{-1.6}$
WASP-25 b	$2459269.4859^{+0.0005}_{-0.0006}$	$1.9^{+0.7}_{-0.9}$
WASP-42 b	$2459351.9514^{+0.0012}_{-0.0011}$	$-8.0^{+1.8}_{-1.6}$
WASP-57 b	$2459326.1416^{+0.0016}_{-0.0014}$	$-3.9^{+2.3}_{-2.0}$
WASP-61 b	$2459198.7400^{+0.0030}_{-0.0030}$	$2.8^{+3.7}_{-4.3}$
WASP-123 b	$2459423.8129^{+0.0014}_{-0.0012}$	$5.8^{+2.0}_{-1.7}$

Firstly, while many of our light curves cover the full transit duration plus a significant amount of baseline, several were interrupted due to bad weather, reducing the coverage. For instance, our observations of HATS-3 b and WASP-57 b do not have many data points post-egress while both observations of HAT-P-55 b do not have any pre-ingress data. However, the worst affected amongst our light curves were the observation of HAT-P-18 b on 7th May 2021 and the transit of WASP-123 b as these datasets only covered ingress and a small amount of time pre-ingress. Despite this, the precision on the transit mid time in each case is not the worst amongst the sample.

A second cause of differences in the precision of our observations is the brightness of the host star which dictates the amount of flux received. While a brighter star leads to additional flux, if it is too bright

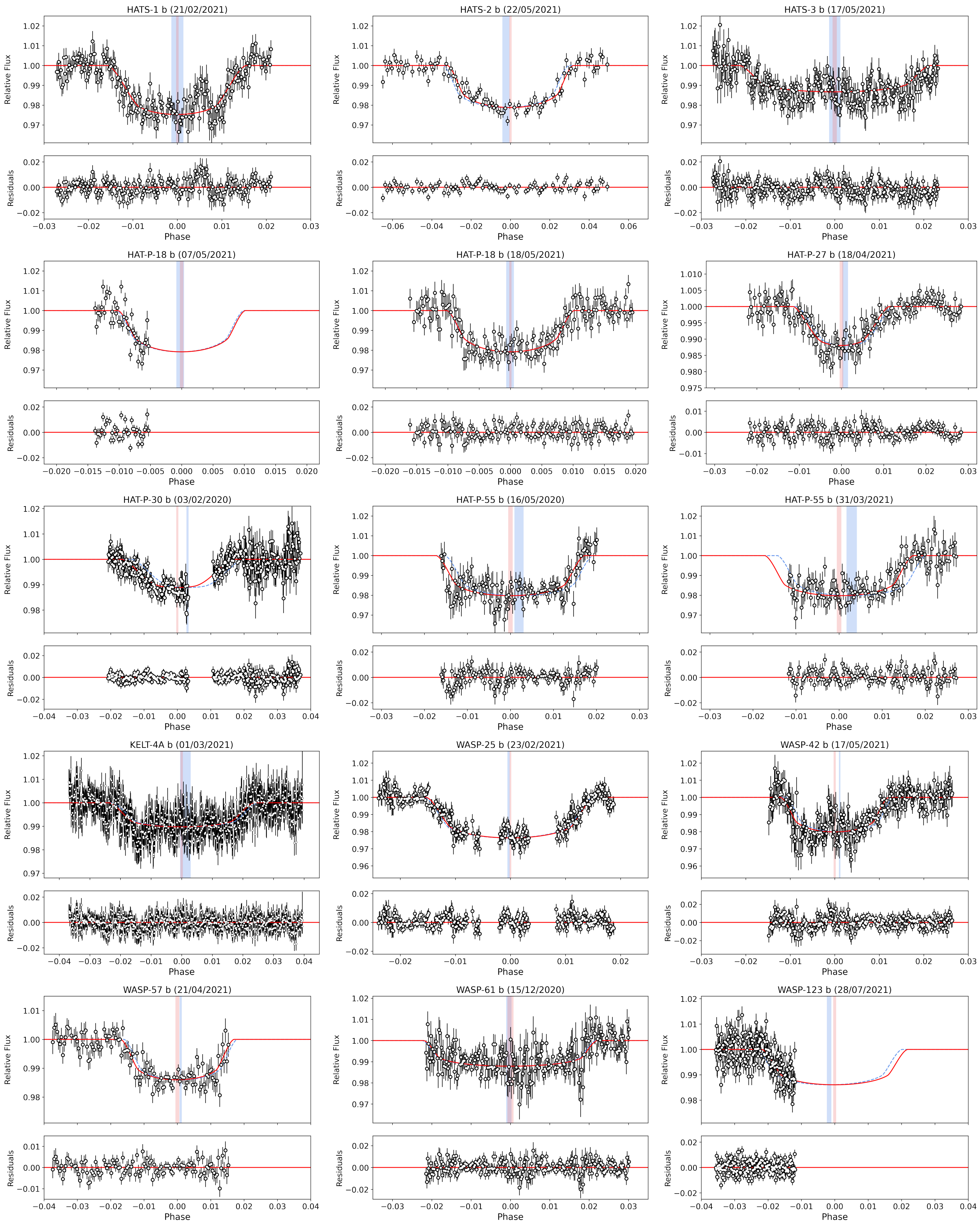

Fig. 5. Transit light curves obtained during this project. In each case, the data is shown in black with the best-fit transit model in red and the predicted transit model represented by a blue dashed line. For each observation, the red filled region indicates the fitted mid time and associated uncertainty. Meanwhile, the blue filled region represents the predicted transit mid time and current uncertainty on this.

the detector must be read out at a faster rate, leading to a lower duty cycle as the detector spends more time being read. Additionally, very short exposures could be dominated by read noise instead of photon noise from the star. Each of these would lead to a poorer overall quality for the light curve with HATS-3 b, HAT-P-30 b, KELT-4A b, WASP-42 b and WASP-123 b, the five planets with the brightest host stars, being good examples of this.

Additionally, the depth of the planet's transit will affect the ability of HOPS to accurately fit the mid time. A deeper transit leads to a higher the signal to noise ratio, allowing the start and end of the transit to be more easily discerned. HAT-P-27 b and WASP-25 b, where both host stars are a similar brightest (11.98 and 11.82, respectively) but the transit depths differ: 13 mmag and 20 mmag, respectively. However, here the transit duration may also be having an effect as HAT-P-27 b also has a shorter transit time (1.68 hours) than WASP-25 b (2.76 hours). As HAT-P-18 b has a relatively deep transit, this could explain the relatively higher precision on the mid time obtained from the visit of the 7th May although constraints on the mid time of partial transits are also often over-estimated.

Finally, other effects which are harder to quantify are likely to be affecting our observations. One such effect is the airmass, the amount of atmosphere we were observing the star through and particularly changes in this over the observation period. Furthermore, the phase of the moon and proximity to the host star could also have an effect by increasing the background noise. The comparison star chosen will also effect the precision of our light curves and, while some host stars had many potential comparison stars to chose from, others did not. In truth, the comparative precision of our mid times is a combination of all these effects, with the dominate cause of a higher uncertainity being hard to determine definitively.

The majority of the planets had observed mid times which were within 1σ of the expected transit time. However, for several planets we found significant offsets and of particular note are HAT-P-30 b, HAT-P-55 b, WASP-42 b and WASP-123 b. Our observed O-C residuals for HAT-P-30 b and HAT-P-55 b are consistent with those found by other ExoClock users[8]. On the other hand, WASP-42 b and WASP-123 b do not have, at the time of writing, any observations listed on ExoClock. Therefore, further transits will need to be observed to verify our results, particularly for WASP-123 b as only a partial transit light curve was obtained here.

All the planets observed here are excellent targets for atmospheric characterisation with upcoming facilities. In fact, HAT-P-18 b has already been studied through transit spectroscopy using the Hubble Space Telescope (Tsiaras et al., 2018), the William Herschel Telescope (Kirk et al., 2017), and the Hale Telescope at Palomar Observatory (Paragas et al., 2021). These, respectively, have identified the presence of water vapour, observed the effects of Rayleigh scattering, and detected helium in the atmosphere of HAT-P-18 b. Our work, combined with that of previous ORBYTS projects (Edwards et al., 2020, 2021) and other ephemeris follow-up projects (Mallonn et al., 2019; Kokori et al., 2020; Zellem et al., 2020) to study the atmospheres of these planets, confident in the knowledge that they will transit at the expected time.

[8](Kokori et al., 2020) and https://www.exoclock.space/database/planets/HAT-P-55b/

CONCLUSION

We present observations of ten exoplanets which were rated by the ExoClock site as high priority for photometric follow-up. All these planets are potential targets for future space-based facilities and our observations will help ensure their transit ephemerides are well-known. As TESS and other surveys continue to find planets, projects such as this will become ever more important for maintaining transit times for the next generation of telescopes.

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The observation of HAT-P-55 b from 2020 was taken via the Faulkes Telescope Project which is coordinated by Cardiff University and Swansea University.

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SOFTWARE

Astropy (Astropy Collaboration et al., 2018), cartopy (Met Office, 2010 - 2015), corner (Foreman-Mackey, 2016), emcee (Foreman-Mackey, Hogg, Lang, & Goodman, 2013), ExoTETHyS (Morello et al., 2020), HOPS (Tsiaras, 2019), Matplotlib (Hunter, 2007), Numpy (Oliphant, 2006), Pandas (McKinney, 2011), pylightcurve (Tsiaras et al., 2016), SciPy (Virtanen et al., 2020).

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