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Monitoring of transiting exoplanets and their host stars with small aperture telescopes

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ABSTRACT

Exoplanet research is now target rich with a wide diversity of systems making it difficult for high demand observatories to undertake follow up observations over extended periods of time. We investigate the effectiveness of using 0.4m-class telescopes for monitoring transiting hot Jupiters and their host stars. We consider two representative case studies: WASP-52b with 13 new transits, and HAT-P-23b with 17 new transits and concurrent photometric monitoring covering 78 days. We present updated system parameters and combine our new transit times with previously published results to calculate new ephemerides for both systems. Our analysis of transit mid-times for WASP52b results in a slight preference for a quadratic ephemeris ($\Delta\chi^2 = 0.07$, $\Delta BIC = 1.53$ over a linear ephemeris. We discuss the reality of this quadratic ephemeris indicating a period change of $\delta P/\delta t = -38.6 \pm 4 \text{ ms yr}^{-1}$ and consider possible causes. WASP-52 is known to be an active star with previous publications reporting many spot crossing events, however no such events are seen in our new photometry. Our analysis shows that WASP-52 is still active and that the latitude of the spots has likely migrated away from the transit chord. We confirm the inflated nature and circular orbit for HAT-P-23b. Our monitoring of HAT-P-23 reveals a periodicity of 7.015 days with an amplitude of 0.011 mag which we interpret as the rotation period of HAT-P-23. The photometric and transit timing precision achieved in the case studies shows that this class of telescope is capable of precise characterisation and long-term monitoring of transiting hot Jupiters in support of dedicated ongoing and future ground and space based observations.

1. Introduction

We now know of 465 hot Jupiters,¹ defined as planets with $0.5R_J < R_p < 2R_J$ and periods $< 10\text{d}$, and further discoveries are expected from SuperWASP, HATNet, NGTS, TESS and PLATO. Exoplanet research is now target rich with a wide diversity of systems making it difficult for large, high demand, observatories to undertake follow up observations over extended periods of time. Conversely small telescopes, including those associated with educational institutions and amateur operated observatories are plentiful, for example there are 1125 listed contributors to the Exoplanet Transit Database maintained by the the Czech Astronomical Society.² These small observatories are available for the monitoring of bright transiting hot Jupiters and their host stars over extended time periods. Such observations can provide invaluable insight into exoplanet system properties including the existence of companion bodies (e.g. Sokov et al., 2018) and the formation and

dynamical histories of the systems due to orbital period evolution (Maciejewski et al., 2016; Patra et al., 2017; Bouma et al., 2019; Chontos et al., 2019). Here we illustrate the capabilities of small (~ 0.4 m) aperture telescopes to contribute to our understanding of exoplanet systems with our study of two known transiting exoplanets. HAT-P-23b and WASP-52b were observed from June to October 2018 with the OpenScience Observatories (OSO) facility. The OSO are part of the Open University OpenSTEM Labs³ used for teaching practical science to undergraduate distance learners and for postgraduate research. Additional observations were made using a small private observatory (POST) located in the United Kingdom.

1.1. HAT-P-23b

HAT-P-23b is a short period (1.21d) hot Jupiter discovered in 2011 by the HATNet transit survey orbiting a $V = 12.43$ magnitude G0 host

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¹ NASA Exoplanet Archive, accessed 3rd January 2020.

² <http://var2.astro.cz/ETD/>, accessed 11th February 2020.

³ learn5.open.ac.uk

star. Discovered by Bakos et al. (2011), they found HAT-P-23b is an inflated hot Jupiter with a mass of $2M_J$ and a radius of $1.37R_J$, almost 10% greater than the maximum theoretical radius for a planet of its mass Fortney et al. (2007). In addition they found HAT-P-23b has a marginally significant orbital eccentricity of 0.106 ± 0.044 . Ciceri et al. (2015) subsequently found considerably smaller stellar and planetary radii (Fig. 3), which we can speculate results from adopting a mass-radius relationship based on a younger age for HAT-P-23 and using a fixed circular orbit in their transit modelling. Rossiter-McLaughlin effects have shown HAT-P-23b is in an aligned prograde orbit with a projected angle between the orbital plane and the stellar equatorial plane of $15^\circ \pm 22^\circ$ (Moutou et al., 2011). Previous studies have taken different approaches to the suspected eccentricity with some authors leaving eccentricity as a free parameter, e.g. Bakos et al. (2011); Sada and Ramon-Fox (2016), while others have fixed the orbit as circular in their analyses e.g. Ciceri et al. (2015); Maciejewski et al. (2018). HAT-P-23b has a similar orbital period to that of WASP-12b. The latter has been shown to exhibit a decreasing orbit (Maciejewski et al., 2016; Patra et al., 2017; Maciejewski et al., 2018; Yee et al., 2019) hence HAT-P-23b could be expected to exhibit a similar decreasing orbital period which may require transit measurements over decades to detect. Ciceri et al. (2015) presented O-C results (their Fig. 6) that appear to show a quadratic deviation indicative of period change, but this was not commented upon. The transit timing observations available on the Exoplanet Transit Database⁴ (ETD) show a change in reported O-C values over the period between transit epochs 1900 and 2050. Maciejewski et al. (2018) published results of a further 13 new transits and reanalysis of the previously published transit times looking for evidence of orbital decay. They conclude that the best fit ephemeris is linear and that there is no sign of orbital period change which they attributed to inefficient tidal dissipation in the main sequence host star.

1.2. WASP-52b

WASP-52b is an inflated hot Jupiter on a 1.75d circular orbit around a K2V star (Hèbrard et al., 2013). The $0.79R_\odot$ stellar radius and the inflated $1.27R_J$ planet radius results in 3% deep transits. Due to its large radius and low mass the difference in transit depth of a single scale height equates to 4.4×10^{-4} (Kirk et al., 2016). This makes WASP-52b an excellent target for transit spectroscopy; such studies reveal that WASP-52b has a cloudy atmosphere with no indication of Rayleigh scattering (Kirk et al., 2016; Loudén et al., 2017), in which sodium has been detected (Chen et al., 2017). WASP-52 is an active star with transit photometry often showing spot crossing events complicating the analysis of transit spectroscopy results. Photometrically determined rotational periods between $13.1 \pm 0.4d$ to $17.79 \pm 0.05d$ have been reported, possibly indicative of differential rotation at changing spot latitudes (Hèbrard et al., 2013; Mancini et al., 2017; Loudén et al., 2017). Measurements of crossings of the same spot has allowed the sky projected and real orbital obliquities to be determined as $3.8^\circ \pm 8.4^\circ$ and $20^\circ \pm 50^\circ$ respectively, providing the first measurement of a true orbital obliquity using this method (Mancini et al., 2017).

This paper is laid out as follows. In Section 2 we describe the telescopes and methods used to obtain and analyse the observations. Section 3 presents our analysis. Section 4 places our results in the context of the published literature. Section 5 discusses the performance of the small aperture telescopes and their capacity to contribute to the forefront of exoplanet research. In Section 6 we summarise our findings.

2. Methods

2.1. OpenScience Observatories

The OpenScience Observatories (OSO) consist of three robotic telescopes, two optical telescopes located at Observatorio del Teide, part of the Observatorios de Canarias on the island of Tenerife, $28^\circ 18' 00''$ N, $16^\circ 30' 35''$ W at an altitude of 2390 m (Kolb et al., 2018). The third, ARROW a remotely controlled radio telescope based in Milton Keynes UK, was not used in this work. The two telescopes in Tenerife are COAST, a 0.35 m f11 Schmidt-Cassegrain optical system, and PIRATE, a 0.45 m f6.8 Corrected Dall-Kirkham astrograph. Each telescope is located in its own robotic dome on a German Equatorial mount which can be operated completely autonomously via a scheduler or remotely in real time. Both observatories are controlled using the autonomous telescope control software, ABOT (Sybilski et al., 2014), the COAST telescope is also available for public use as part of telescope.org. PIRATE is equipped with an FLI ProLine 16803 $4k \times 4k$ 9μ pixel CCD camera producing a field of view $42'$ square with plate scale of $0.62''/\text{pixel}$. COAST is equipped with an FLI ProLine 9000 $3k \times 3k$ 12μ pixel CCD camera producing a field of view $32'$ square with plate scale of $0.63''/\text{pixel}$. Both CCD cameras were operated at a temperature of -30°C . In July 2018 both telescopes were upgraded with the addition of a GPS controlled shutter timing system. All observations were made through Johnson B or Cousins Rc filters without guiding.

2.2. POST observatory

The POST observatory, located at $51^\circ 15' 51''$, $01^\circ 14' 58''\text{E}$ at 20 m altitude, hosts a 0.4 m, f6.8 telescope on a German Equatorial mount. It is equipped with an SBIG ST10-XME 2184×1472 6.8μ pixel CCD camera providing a field of view $19' \times 13'$ with a plate scale of $0.52''/\text{pixel}$. All observations were made using Johnson V or Cousins Rc filters. Observations where the telescope was not defocussed were guided using an on-axis tip-tilt guiding corrector at rates between 0.1-2 Hz depending on the brightness of the available guide star. Where defocussed observations were made, off axis guiding was employed with correction rates ~ 0.2 Hz.

2.3. Observations

Transit observations of both targets made using PIRATE and COAST were scheduled in advance and obtained in autonomous mode, observations with the POST observatory were made in attended mode with hands-on control of the telescope during each observation. The observations were planned using existing ephemerides and timed to include pre and post transit data where possible. Observations with all telescopes were made with the CCD on-chip binning of 2×2 or 1×1 . Exposure times were set to ensure ADU counts remained within the linear response region of the CCD for the target and comparison stars and the same exposure duration was used throughout each individual transit observation. Full details of the observations made can be found in Table 1.

Monitoring observations were obtained of HAT-P-23 using PIRATE scheduled to take up to six 150 second frames per night using the Rc filter with the CCD in 1×1 bin mode when the target was higher than 40 degrees altitude. 218 observations covering 39 nights over a 78-day period were made between 18th August 2018 and 4th November 2018. The number of frames obtained each night varied depending on weather conditions and telescope schedule commitments. Out-of-transit measurements from before and after each transit, where available, were added to the monitoring data to extend the measurement timeline and allow HAT-P-23's magnitude to be measured at the time of each transit recorded with PIRATE. Dark, bias and sky flat-field calibration frames were obtained for each night of science observation. Due to the limited number of dusk/dawn flat frames obtainable by PIRATE each night

⁴ <http://var2.astro.cz/ETD/>

Table 1

Table of observations made. The line between observations 9 and 10 for HAT-P-23 b indicates the point at which the upgrade to the PIRATE telescope was undertaken. # is the observation reference number, Nobs is the number of observations per transit. Dur.(min) is the total duration of the observations and Exp.(s) is the exposure time used. RMS(ppp) is the out-of transit residual RMS scatter from the transit fit in part per thousand. CCD Mode indicates the on-chip binning used. TSNR is the Transit Signal to Noise Ratio (Ioannidis et al., 2016).

#	Date	Tele-scope	Dur (min)	Filter	Exp. (s)	N _{obs}	Airmass	RMS (ppt)	CCD Mode	TSNR	Notes
HAT-P-23b											
1	05 October 2017	UK	205	Rc	150	66	1.27-2.41	2.07	2 × 2	4.95	
2	20 June 2018	PIRATE	164	R	60	158	1.26-1.02	2.36	2 × 2	6.63	Incomplete ingress coverage.
3	26 June 2018	PIRATE	213	R	60	199	1.14-1.02-1.11	2.71	2 × 2	4.71	
4	30 June 2018	PIRATE	192	R	60	178	2.12-1.07	3.50	2 × 2	4.11	
5	30 June 2018	UK	180	Rc	120	85	1.58-1.21	2.56	2 × 2	6.19	
6	06 July 2018	PIRATE	216	R	60	199	1.33-1.02-1.04	3.02	1 × 1	4.95	
7	06 July 2018	UK	264	Rc	120	126	1.55-1.21-1.27	2.59	2 × 2	5.13	
8	12 July 2018	PIRATE	210	R	60	196	1.05-1.02-1.25	3.25	2 × 2	3.78	
9	17 July 2018	UK	200	Rc	120	94	1.55-1.21	1.83	2 × 2	6.16	
10	03 August 2018	PIRATE	196	Rc	180	63	1.41-1.02	1.61	1 × 1	9.05	
11	09 August 2018	PIRATE	255	Rc	180	67	1.14-1.02-1.20	1.25	1 × 1	15.80	Gap in data post egress.
12	26 August 2018	PIRATE	234	Rc	150	92	1.08-1.02-1.24	1.73	1 × 1	7.30	
13	23 September 2018	PIRATE	195	Rc	180	62	1.06-1.02-1.17	1.53	1 × 1	12.71	
14	23 September 2018	UK	181	Rc	180	57	1.21-1.49	1.79	2 × 2	9.08	
15	29 September 2018	PIRATE	156	Rc	180	51	1.02-1.24	1.48	1 × 1	8.73	Ingress only, no transit mid time.
16	29 September 2018	UK	212	Rc	180	53	1.26-2.38	2.27	2 × 2	5.82	Gap mid transit.
17	16 October 2018	PIRATE	229	Rc	180	75	1.03-2.12	2.02	1 × 1	8.02	
WASP-52b											
1	10 November 2013	UK	148	Rc	90	93	1.44-1.40	3.02	3 × 3	12.80	
2	27 October 2017	UK	214	Rc	180	66	1.4-1.35-1.63	1.74	2 × 2	16.47	
3	01 August 2018	PIRATE	196	Rc	120	92	1.34-1.06	1.78	1 × 1	16.13	
4	08 August 2018	PIRATE	197	Rc	180	55	1.25-1.06-1.10	1.78	1 × 1	14.69	Gap at egress.
5	29 August 2018	PIRATE	201	Rc	120	95	1.09-1.06-1.29	1.76	1 × 1	16.33	
6	19 September 2018	PIRATE	157	Rc	150	60	1.07-1.58	1.98	1 × 1	13.10	
7	03 October 2018	PIRATE	139	Rc	150	52	1.19-2.13	1.76	1 × 1	12.73	
8	05 October 2018	UK	183	Rc	120	77	1.78-1.35	3.23	2 × 2	6.57	
9	10 October 2018	PIRATE	111	Rc	150	43	1.28-2.15	2.46	1 × 1	-	No out of transit coverage.
10	17 October 2018	COAST	133	Rc	240	32	1.21-2.17	1.92	1 × 1	16.65	Ingress only, no transit mid time.
11	17 October 2018	PIRATE	132	B	240	33	1.21-2.17	3.16	1 × 1	10.99	Ingress only, no transit mid time.
12	02 November 2018	UK	252	Rc	120	113	1.53-1.35-1.55	1.91	2 × 2	12.30	
13	07 December 2018	UK	110	Rc	240	25	1.36-1.55	1.19	1 × 1	29.33	Ingress only, no transit mid time.

frames from multiple nights either side of the observation were combined. For POST a flat field light box is used so an average of 27 flat field frames was obtained on each night of observation.

As one of the key aims of the observations was to measure the transit mid-times a cross check was carried out between the timing accuracy of both the PIRATE and POST telescopes by simultaneously observing the deeply eclipsing post common envelope binary V1828Aql. Unfiltered observations were made using the same 1-minute integration time on both telescopes. The observations from both telescopes agreed on the eclipse minimum times to within 4 seconds for the two primary eclipses, well within typical Exoplanet transit mid-time uncertainties of 30 to 50 seconds.

2.4. Data reduction and photometry

The calibration frames obtained for each night of science observation were median combined using the Data Processing module of AstroImageJ v3.2.1 (Collins et al., 2017), hereafter AIJ, to create master calibration frames for each transit observation. Individual calibration frames were visually inspected to ensure consistency and any with artifacts were discarded. All science frames were plate solved and individual mid exposure times converted to BJD_{TDB}. Ensemble photometry was carried out within AIJ using up to 25 comparison stars of suitable brightness from across the entire field of view. The photometry was compared with a transit model created in AIJ and the photometry apertures adjusted to minimise the residual RMS and Bayesian Information Criterion (BIC) values. Where it produced superior results the sky aperture was varied by a fixed multiplier of the target stellar FWHM. Following selection of the optimum aperture sizes each individual comparison star was removed from the ensemble in sequence

to test if its inclusion increased or decreased the RMS and BIC values. Stars found to increase these values were removed, typically leaving 15-20 comparison stars in the photometry ensemble for each transit data set. Frames producing outlying data points were removed from the photometry where visual inspection revealed cosmetic effects such as cosmic ray strikes or satellite trails.

Two archive observations, one of WASP-52b from 2013 and one of HAT-P-23b from 2017, made with POST were also included in the analysis. Both transits were re-analysed from the original images and calibration files in the same way as the newly obtained data.

To ensure that uncertainties associated with lightcurve detrending were properly accounted for in the transit fit, the airmass values and, where necessary, a pier flip time were recorded for subsequent application as part of the transit model fitting process in ExofastV2. The lightcurve was recorded with flux normalised to unity and photometric uncertainties calculated within AIJ following Equation B1 in Collins et al. (2017). ExofastV2 allows airmass and pier flips to be treated as multiplicative detrend parameters, modifying the baseline flux to achieve the best transit model fit. In total the transit observations resulted in 1821 and 695 individual photometric measurements covering 17 and 13 transits of HAT-P-23b and WASP-52b respectively, see Figs. 1 and 2.

2.5. Analysis

Combined transit and radial velocity model fitting was carried out with the most recent version of ExofastV2 (Eastman et al., 2019) using our new transit data and previously published radial velocity (RV) measurements. For HAT-P-23b 13 radial velocity measurements obtained using the HIRES instrument on the Keck telescope (Bakos et al.,

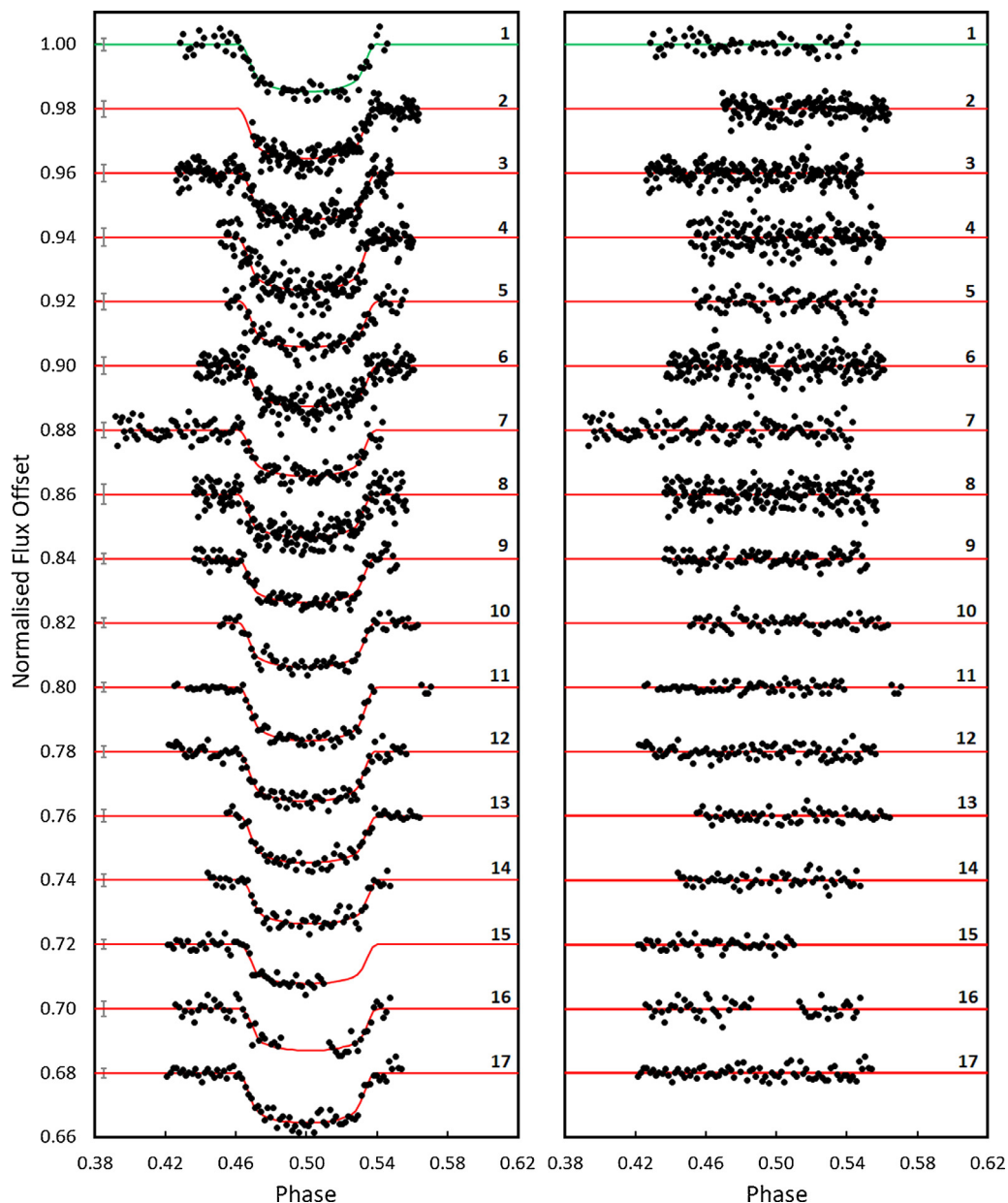


Fig. 1. 17 new HAT-P-23b Transit lightcurves obtained as part of this study where the transit numbering refers to the observations detailed in Table 1. Black dots are individual data points, the solid lines are the best fit ExofastV2 model for each transit. Green lines represent fits to V filter observations and red lines represent fits to Rc observations. On the left is an indication of the mean photometric uncertainty from each night's observation.

2011) were used. For WASP-52b 16 measurements obtained with CORALIE instrument on the ESO Euler telescope and 29 measurements obtained with the SOPHIE instrument on the 1.93m OHP telescope (Hèbrard et al., 2013) were used. The RV data from SOPHIE was divided into separate inputs for the HE1, HE2 and HR measurements allowing different zero-points to be set for each. The HE-RM data set was not used in our analysis. Stellar parameters were determined through combined MESA Isochrones and Stellar Tracks (MIST) evolutionary track and spectral energy distribution (SED) fitting by ExofastV2 using broadband photometry obtained from published catalogues as shown in Table 2, complemented with Johnson B, V and SDSS g' , r' and i' photometry from release 10 of the AAVSO Photometric All-Sky Survey (APASS).⁵ Priors for the parallax were obtained from GAIA DR2 (Brown and Gaia Collaboration., 2018) and following the findings

of Stassun and Torres (2018), 0.082 mas was added to the reported parallax and 0.033 mas was added in quadrature to the DR2 reported uncertainty. An upper limit for the V band extinction parameter (A_V) for each system was obtained from the Schegel dust maps⁶ and multiplied by 3.1 to convert to the V band extinction used in ExofastV2. This approach imposes a tight constraint on the stellar radius and the planetary parameters derived from R_p (Eastman et al., 2019).

All transit lightcurves, including those with partial coverage but excluding the 2013 transit of WASP-52b which showed a significant suspected spot crossing event, were included to produce a single global model fit in ExofastV2 for each system. The transit mid-time for each lightcurve was allowed to vary within the global model fit and the transit mid-times were output from ExofastV2 and combined with previously published transit times to calculate a refined ephemeris for

⁵ <https://www.aavso.org/apass>

⁶ <https://irsa.ipac.caltech.edu/applications/DUST/>

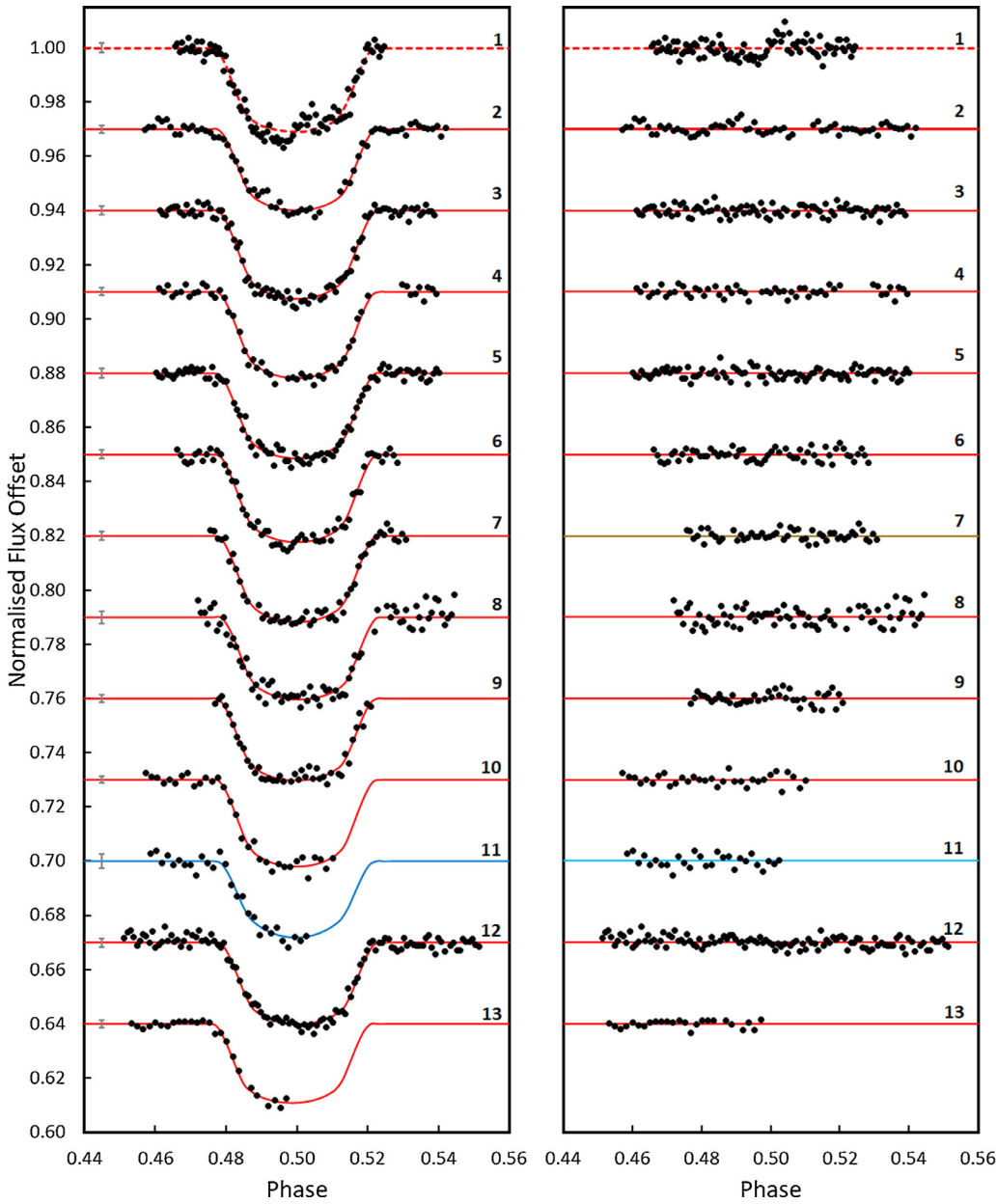


Fig. 2. 13 new WASP-52b transit lightcurves and ExofastV2 model fits obtained as part of this project. Black dots are individual data points, the solid lines are the best fit ExofastV2 model for each transit. Red lines represent fits to Rc observations and blue lines represent fits to B filter observations. The numbers refer to the transits detailed in Table 1. On the left the mean photometric uncertainty for each observation is indicated. Only complete transits with full t1-t4 coverage were used in the updated ephemeris calculation, transit 1 (shown with a dotted line) was excluded from the global model fit in ExofastV2 due to the significant spot crossing event.

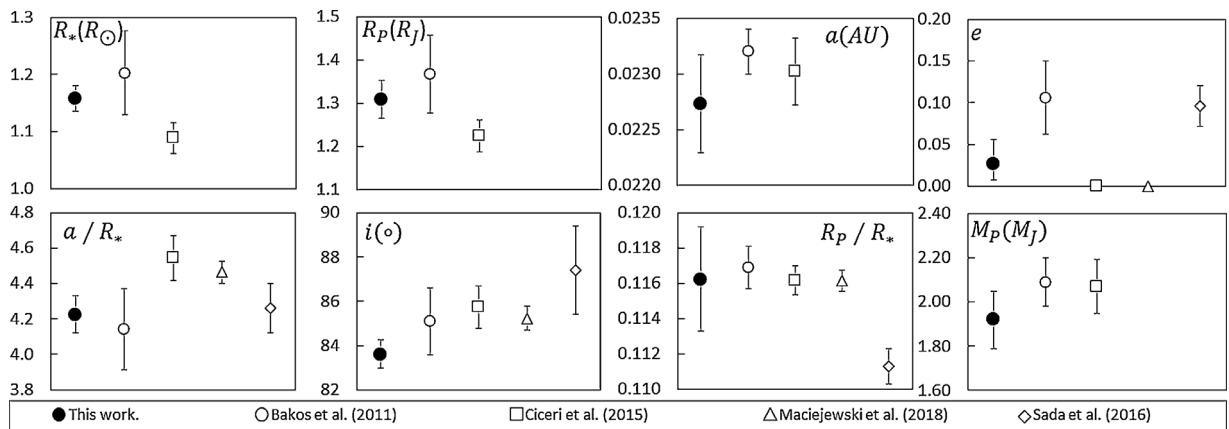


Fig. 3. HAT-P-23b results from ExofastV2 model analysis for our new transits (filled circles) compared with results from other published works where values are available (open symbols). Open circles are from Bakos et al. (2011), squares are from Ciceri et al. (2015), triangles are Maciejewski et al. (2018) and diamonds are the values from Sada et al. (2012).

Table 2
Broadband photometry used in Exofastv2 SED fitting.

Band	HAT-P-23	WASP-52	Catalogue
B(T)	13.362 ± 0.378	-	Tycho
V(T)	12.061 ± 0.195	-	Tycho
B	12.965 ± 0.036	13.116 ± 0.042	APASS R10
V	12.189 ± 0.047	12.231 ± 0.062	APASS R10
gSDSS	12.586 ± 0.043	12.617 ± 0.025	APASS R10
rSDSS	11.969 ± 0.089	11.901 ± 0.095	APASS R10
iSDSS	11.774 ± 0.143	11.698 ± 0.047	APASS R10
J	11.103 ± 0.020	10.588 ± 0.020	2MASS(via UCAC4)
H	10.846 ± 0.020	10.186 ± 0.030	2MASS(via UCAC4)
K	10.791 ± 0.020	10.086 ± 0.030	2MASS(via UCAC4)
WISE1	10.748 ^{+0.030} _{-0.023}	10.011 ^{+0.030} _{-0.020}	AllWISE
WISE2	10.793 ^{+0.030} _{-0.020}	10.094 ^{+0.030} _{-0.021}	AllWISE
WISE3	10.816 ± 0.122	9.983 ± 0.061	AllWISE
Gaia	12.174 ^{+0.020} _{-0.001}	11.954 ^{+0.20} _{-0.001}	Gaia DR2
GaiaBP	12.518 ^{+0.020} _{-0.002}	12.444 ^{+0.020} _{-0.004}	Gaia DR2
GaiaRP	11.679 ^{+0.020} _{-0.002}	11.331 ^{+0.020} _{-0.003}	Gaia DR2

each system. Only transits with full coverage of all transition points t_1 to t_4 were used in the ephemeris analysis. All transit lightcurves with their best fit Exofast models can be found in Fig. 1 for HAT-P-23b and in Fig. 2 for WASP-52b.

For the HAT-P-23 monitoring data a photometry template was created in AIJ incorporating stars from the UCAC4 catalogue (Zacharias et al., 2013) with known B, V and r' filter magnitudes. Six suitable comparison stars were selected and a seventh, with B-V = 1.375 similar to HAT-P-23 (B-V = 1.301), was used as a check star. AIJ does not take into account catalogue magnitude uncertainties so we report the uncertainties for the calculated magnitudes based on the standard error in the measurements of the check star.

3. Results

3.1. HAT-P-23b

At discovery Bakos et al. (2011) found a marginally significant orbital eccentricity of 0.106 ± 0.044 . The subsequent study by Sada and Ramon-Fox (2016) also found an orbital eccentricity of 0.096 ± 0.024 , however using secondary occultation measurements, O'Rourke et al. (2014) determined that the orbit was probably circular, a result supported by subsequent RV studies (Bonomo et al., 2017). Subsequent studies of HAT-P-23b made by Ciceri et al. (2015) and Maciejewski et al. (2018) assumed a circular orbit. Maciejewski et al. (2018) reported that the increased value they found for the scaled system parameter a/R_* , over that seen by Bakos et al. (2011) and Sada and Ramon-Fox (2016) is due to the adoption of a non-zero eccentricity in those studies. To ensure we did not bias our results we left the orbital eccentricity as a free parameter in our ExofastV2 fits. This resulted in $e = 0.027^{+0.029}_{-0.019}$, consistent with a circular orbit within 1.4σ . We also calculated the same model with a eccentricity forced to zero finding exactly the same results for the scaled a/R_* parameter as we found with the eccentricity left as a free parameter indicating this unlikely the cause of the difference seen by Maciejewski et al. (2018). Our result for a/R_* is consistent with that determined by Bakos et al. (2011) and Sada and Ramon-Fox (2016), Fig. 3.

From our global model we find the stellar radius and mass of HAT-P-23 to be $1.157^{+0.023}_{-0.022} R_\odot$ and $1.063^{+0.063}_{-0.060} M_\odot$ which is 3.8% and 5.9% smaller respectively than found by Bakos et al. (2011). Our results are also 6.2% larger and 3.7% smaller respectively than the only other published stellar mass and radius values by Ciceri et al. (2015). As a result of our new stellar radius measurement we find the radius of HAT-P-23b to be $1.308^{+0.44}_{-0.43} R_J$. We find $a/R_* = 4.22^{+0.11}_{-0.10}$, consistent with the previous studies which assumed a non-zero eccentricity (Bakos et al.,

Table 3

HAT-P-23b transit times for complete new transits. Transit numbers follow Table 3. All transit times used in the ephemeris calculations can be found in the supplementary material.

Transit No.	Epoch	Tc (BJD _{TDB})	Tc Uncertainty	Linear O-C	Telescope
1	2622	2458032.45353	0.00076	0.000075	POST
3	2839	2458295.65089	0.00057	0.001074	PIRATE
4	2843	2458300.50097	0.00075	-0.000392	PIRATE
5	2843	2458300.50190	0.00120	0.000538	POST
6	2848	2458306.56787	0.00071	0.002075	PIRATE
7	2848	2458306.56574	0.00070	-0.000055	POST
8	2853	2458312.62941	0.00078	-0.000817	PIRATE
9	2857	2458317.48136	0.00054	-0.000413	POST
10	2871	2458334.46187	0.00066	-0.000313	PIRATE
11	2876	2458340.5272	0.00045	0.000585	PIRATE
12	2890	2458357.50703	0.00060	0.000004	PIRATE
13	2913	2458385.40434	0.00068	0.000926	PIRATE
14	2913	2458385.40582	0.00075	0.002406	POST
16	2918	2458391.47024	0.00093	0.002393	POST
17	2932	2458408.44838	0.0006	0.000123	PIRATE

2011; Sada and Ramon-Fox, 2016) and approximately 6% smaller than that found by studies which fixed orbital eccentricity to zero (Ciceri et al., 2015; Maciejewski et al., 2018). Stellar and planetary parameters are shown in Fig. 3 and Table 5.

To calculate an updated ephemeris for HAT-P-23b the transit mid times for all complete transits were combined with those from the literature. Full transit lightcurves published by Ciceri et al. (2015) and Maciejewski et al. (2018) which were available on-line were reanalysed in ExofastV2 in exactly the same way as for our new transit data. We generally reproduced the published mid times within the measurement uncertainties. We included only the R filter data from the simultaneous transit measurements made by Ciceri et al. (2015) using the BUSCA instrument. Where the lightcurve data was not available, transit mid times from other publications were taken from the literature corrected to BJD_{TDB} as required. The resulting transit mid-time data set contained a number of simultaneous observations of the same transit either by the same or by different authors. In these cases a simple mean value for the transit mid-time was used. The transit mid-times from our newly obtained lightcurves can be found in Table 3, and a full list of the transit times used in the ephemeris calculation is available in the supplementary material. The new linear ephemeris found using this data set is

$$T_c(\text{BJD}_{\text{TDB}}) = 2454852.265165(120) + 1.212886457(54)d \times E \quad (1)$$

where E is the epoch of observation and values in brackets are the uncertainties relative to the last digit. The χ^2_ν of the linear fit is 2.08 and the Bayesian Information Criterion (BIC) is 33.01. We also calculated a quadratic ephemeris of the form;

$$T_c(\text{BJD}_{\text{TDB}}) = T_0 + P_{\text{orb}} \times E + 0.5(\delta P_{\text{orb}}/\delta E) \times E^2 \quad (2)$$

resulting in $\chi^2_\nu = 2.20$ and BIC = 37.75. Therefore we find no departure from a linear ephemeris for HAT-P-23b, in agreement with the results from Maciejewski et al. (2018). The timing residuals to our linear ephemeris are shown in Fig. 4. The monitoring data obtained for HAT-P-23b was analysed to look for periodic variations due to star spots on the rotating stellar surface. A Lomb-Scargle periodogram analysis over the period range of 0.1d to 100d reveals a 7.015d period with an amplitude of 1.1%, substantially less than the 3% seen by Sada and Ramon-Fox (2016) (Fig. 5). Moutou et al. (2011) measured HAT-P-23b's rotational velocity as $7.8 \pm 1.6 \text{ km s}^{-1}$ which, given our newly determined stellar radius results in an equatorial rotation period of 7.50 ± 1.55 days, consistent with our measured period of variation. We therefore attribute the variability seen to the rotation period of HAT-P-23 at the (unknown) latitude of the surface spots.

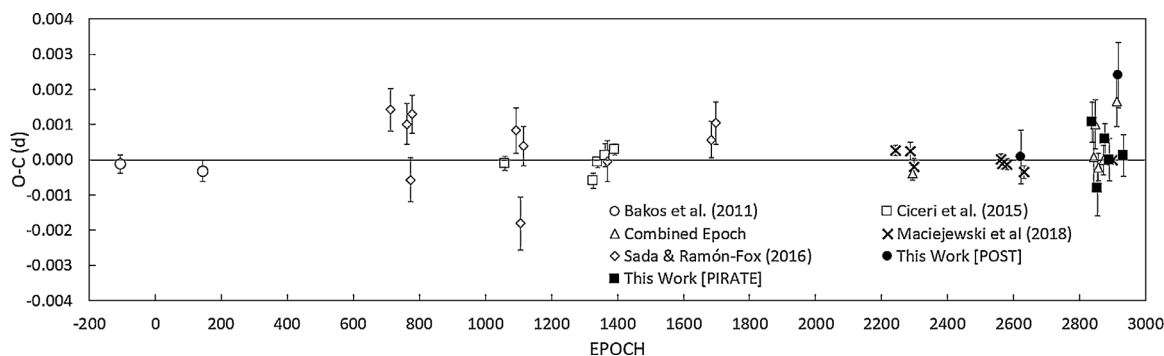


Fig. 4. Transit observed - calculated (O-C) times for HAT-P-23b from the literature and this work calculated using our new ephemeris. Transit times for complete transits from the literature where lightcurve data was available were recalculated (Bakos et al., 2011; Ciceri et al., 2015; Maciejewski et al., 2018). Other transit times were taken from the literature and converted to BJD_{TDB} as required. The mean value derived for simultaneous observations of the same transit are shown as open triangles.

3.2. WASP-52b

As with HAT-P-23b a joint transit and RV fit was undertaken using all new full and partial transit data sets, except transit number 1 which exhibits a large suspected spot crossing event. Again to avoid bias through fixing model parameters we left orbital eccentricity as a free parameter in the ExofastV2 fits, resulting in $e = 0.05^{+0.033}_{-0.030}$, within 1.6σ of a circular orbit, thus the eccentricity found is consistent with zero. We find a stellar radius of $0.834 \pm 0.013R_{\odot}$ which is 5.6% larger than that found by Hébrard et al. (2013) and 6.1% larger than found by Mancini et al. (2017). This larger stellar radius value results in a planetary radius of $1.319^{+0.026}_{-0.027}R_{J}$, 3.9% and 5.3% larger respectively than found in those studies. The larger value we find for the stellar radius results from the use of an extinction corrected SED model with Gaia parallax to constrain the system distance. We find the distance to WASP-52b is $173 \pm 1.6pc$, 24% greater than the $140 \pm 20pc$ found by Hébrard et al. (2013). Our result for the semi-major axis remained within 2% of the results from previous studies so our derived scaled system parameter a/R_{\star} is smaller than previous results by 5.8% and 3.8% respectively. Other parameters determined are consistent with

previously published results. Our results for key parameters are presented in Fig. 6 along with previously published values. Our derived effective temperature of $5039^{+40}_{-39}K$ is consistent with $T_{eff} = 5000 \pm 100K$ from Hébrard et al. (2013), though with improved uncertainties. The age reported for WASP-52 varies widely in the literature from $0.4^{+0.3}_{-0.2}Gyr$ (Hébrard et al., 2013) to $9.4^{+4.7}_{-4.3}Gyr$ in Mancini et al. (2017). We find an age of $8.5^{+3.7}_{-4.6}Gyr$ agreeing within 1σ with Mancini et al. (2017).

The transit mid times for all 9 new transits with complete coverage (excluding archive transit number 1) were combined with those from the literature from Hébrard et al. (2013), Swift et al. (2015), Bruno et al. (2018), Mancini et al. (2017), Öztürk and Erdem (2019) and Baluev et al. (2019). Table 4 lists the new transit times determined from our observations, the full table of transit times used in the ephemeris calculations can be found in the supplementary material to this paper. The transit times calculated by Baluev et al. (2019) make extensive use of observations recorded on the Exoplanet Transit Database; only those results classified as being from “high quality” lightcurves by those authors were included in our analysis. The transit times published by Mancini et al. (2017) have extremely small uncertainties and

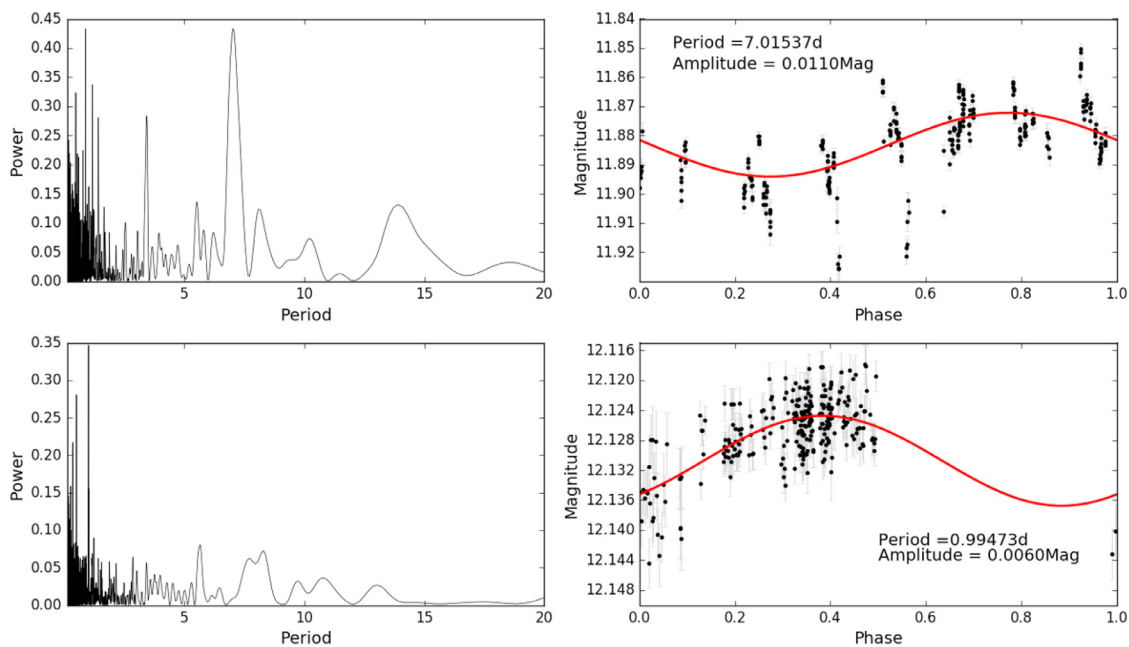


Fig. 5. Lomb Scargle periodograms and phase folded results showing the detected rotation period for HAT-P-23 (top) and for the check star (bottom). The period region shown is between 0.1d and 20d, no periods were detected outside of this range. The period detected in the check star is the one day observing cadence (and its aliases).

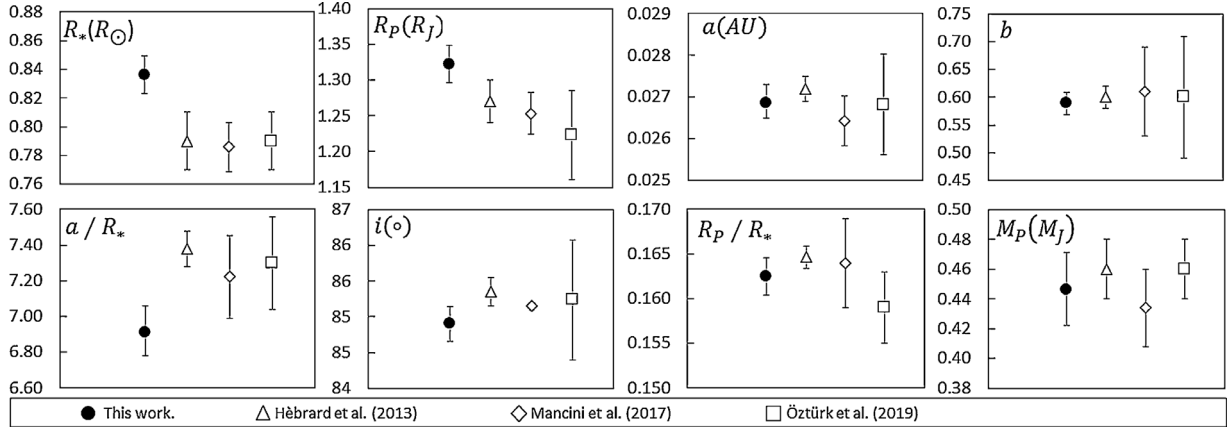


Fig. 6. WASP-52b key system parameters from both this work (filled circles) compared with those from Hèbrard et al. (2013) (open triangles), Mancini et al. (2017) (open diamonds) and Öztürk and Erdem (2019) (open squares). Semi-major axis and impact parameter shown for the Öztürk and Erdem (2019) results were calculated from published parameters as was the scaled R_p/R_* and impact parameter for Mancini et al. (2017)

including these times in our fit was found to increase the χ^2_ν of the ephemeris. The authors noted that their linear ephemeris had a χ^2_ν of 8.98 and they subsequently multiplied the uncertainties on their linear ephemeris by this value. We applied this same multiplier to their individual transit mid-time uncertainties prior to calculating our new ephemerides. We first calculated a linear ephemeris resulting in a fit with $\chi^2_\nu = 1.58$ and BIC = 59.41.

$$T_c(\text{BJD}_{\text{TDB}}) = 2455793.681914(141) + 1.749781099(126)d \times E \quad (3)$$

A quadratic ephemeris of the form from Eq. (2) was also modelled resulting in a slightly lower $\chi^2_\nu = 1.51$ and BIC = 57.88.

$$T_c(\text{BJD}_{\text{TDB}}) = 2455793.680977(141) + 1.749783241(177)d \times E + (-2.14 \pm 0.24) \times 10^{-9}d \times E^2 \quad (4)$$

Using Mancini et al. (2017)'s originally published uncertainties results in the linear model being preferred over the quadratic result while increasing the χ^2_ν values to 2.3 for the linear model and 2.8 for the quadratic model. Thus the small published uncertainties on these results appear to have masked previous detection of a non-linear ephemeris for WASP-52b. Excluding the transit times reported by Mancini et al. (2017), including their recalculation of the three transit times from Hèbrard et al. (2013), produces increased χ^2_ν for both ephemerides but retains a preference for the quadratic model. Finally, we removed our new transit times and find the quadratic model is still preferred, though again with an increased χ^2_ν . In our quadratic ephemeris we found that the values for the quadratic term between 1.90 and 2.38 resulted in the same χ^2_ν values (measured to 2 decimal places), therefore we increased our formal uncertainty on the period derivative to reflect this range of possible values. The quadratic term $\frac{\delta P}{\delta E} = (-2.14 \pm 0.24) \times 10^{-9}$ can be used to calculate the period derivative of

$$\frac{\delta P}{\delta t} = \frac{1}{P} \frac{\delta P}{\delta E} = (-1.22 \pm 0.14) \times 10^{-9} = -38.6 \pm 4 \text{ ms y}^{-1} \quad (5)$$

This is 34% larger than seen for the largest secure period change detected for WASP-12b (Yee et al., 2019). We discuss the quadratic ephemeris in Section 4.2. Fig. 7 shows the O-C values.

WASP-52 is an active star with many spot crossing events previously recorded, e.g. Mancini et al. (2017); Kirk et al. (2016). No suspected spot crossing events are visible in our transits observed during the 2018 season however transit number 1 obtained in 2013 shows a large brightening during the transit. This was the same season as the observations made by Mancini et al. (2017) who detected spot crossing events at 5 of their 8 observation epochs, thus we interpret this event as a significant spot crossing.

Fig. 2 shows how ExofastV2 can significantly underestimate the transit depth, and potentially transit time, where a large spot crossing occurs therefore this transit was excluded from the ExofastV2 model fit and ephemeris calculation for WASP-52b. The final derived system parameters and uncertainties are detailed in Table 5.

4. Discussion

4.1. HAT-P-23b

Previous results for the radius of HAT-P-23b have varied from an inflated $1.368 \pm 0.09 R_J$ Bakos et al. (2011) to the 1.6σ smaller radius of $1.224^{+0.036}_{-0.007} R_J$ (Ciceri et al., 2015). Our derived radius of $1.308^{+0.044}_{-0.043} R_J$ is between these two values with a slightly smaller mass. This places HAT-P-23b very close to two other inflated hot Jupiters, TrEs-3b (O'Donovan et al., 2007) and WASP-135b (Spake et al., 2016) in terms of planetary radius, mass and semi major axis. It is notable though that HAT-P-23b receives almost twice the incident flux resulting in an

Table 4

WASP-52b transit times for complete new transits. Results for both the linear and quadratic ephemerides are shown along with the difference between the two results. Transit numbers follow Table 3. All transit times used in the ephemeris calculations can be found in the supplementary material.

Transit No.	Epoch	$T_c(\text{BJD}_{\text{TDB}})$	T_c Uncertainty	Linear O-C	Quad O-C	Δ O-C	Telescope
2	1292	2458054.39890	0.00039	-0.000194	-0.000238	0.000044	POST
3	1451	2458332.61424	0.00026	-0.000049	0.000033	-0.000082	PIRATE
4	1455	2458339.61298	0.00031	-0.000433	-0.000347	-0.000086	PIRATE
5	1467	2458360.61083	0.00031	0.000044	0.000141	-0.000097	PIRATE
6	1479	2458381.60813	0.00036	-0.000029	0.00008	-0.00011	PIRATE
7	1487	2458395.60619	0.00035	-0.000218	-0.0001	-0.000118	PIRATE
8	1488	2458397.35716	0.00054	0.000971	0.00109	-0.000119	POST
9	1491	2458402.60516	0.00076	-0.000373	-0.000251	-0.000122	PIRATE
12	1504	2458425.35296	0.00029	0.000273	0.000409	-0.000136	POST

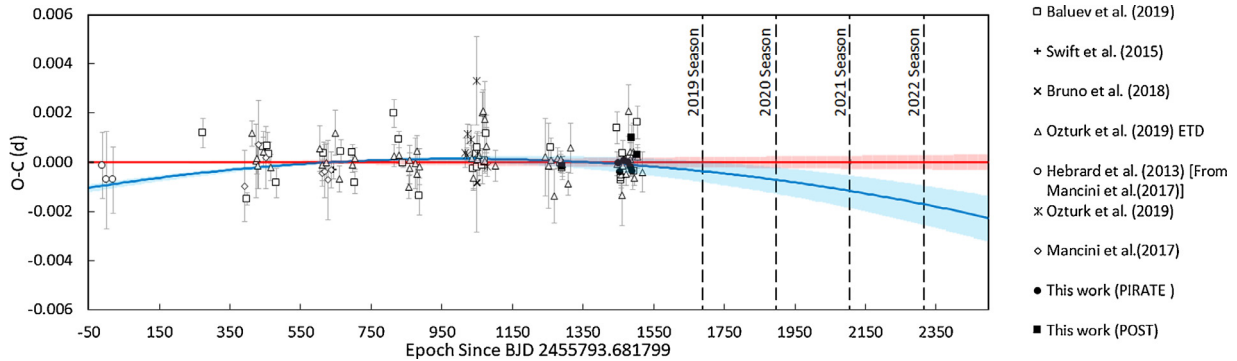


Fig. 7. Predicted transit times for WASP-52b based on both the linear and quadratic ephemerides shows that it should be possible to clearly differentiate between the two models with data from the 2021 observing season.

equilibrium temperature that is 300-400 K greater than for the other two planets, Table 6. A strong dependency on radius with incident flux was found by Weiss et al. (2013) who derived an empirical relationship for planetary radius dependent on mass and incident flux noting that for planets with $M_p > 150 M_\oplus$ the radius depends only very weakly on mass, thus the incident flux is the most important factor affecting planetary radius in this mass range. Using this empirical relation and our

new planetary mass and incident flux we calculate a theoretical radius for HAT-P-23b of $1.355 \pm 0.008 M_J$ which is larger than the radius we measure, closer to that determined by Bakos et al. (2011), though our measured and the theoretical radii are close to agreement at 1σ . It is likely that factors other than just incident flux such as core mass fraction, atmospheric composition or age play an important role in determining the radius of HAT-P-23b. The determination of precise

Table 5
Median parameter values and 68% confidence interval for WASP-52b and HAT-P-23b.

Parameter	Description	WASP-52b	HAT-P-23b
M_*	Mass (M)	$0.844^{+0.042}_{-0.034}$	$1.063^{+0.063}_{-0.060}$
R_*	Radius (R)	0.836 ± 0.013	$1.157^{+0.023}_{-0.022}$
L_*	Luminosity (L)	0.399 ± 0.013	$1.460^{+0.087}_{-0.079}$
ρ_*	Density (cgs)	$2.04^{+0.14}_{-0.21}$	$0.967^{+0.075}_{-0.069}$
$\log g$	Surface gravity (cgs)	$4.52^{+0.024}_{-0.021}$	4.338 ± 0.028
T_{eff}	Effective Temperature (K)	5017 ± 41	5899^{+71}_{-68}
[Fe/H]	Metallicity (dex)	0.13 ± 0.11	0.150 ± 0.015
Age	Age (Gyr)	$8.5^{+3.7}_{-4.6}$	$5.5^{+3.0}_{-2.5}$
A_V	V-band extinction (mag)	$0.060^{+0.034}_{-0.039}$	$0.132^{+0.079}_{-0.072}$
d	Distance (pc)	173.1 ± 1.6	$360.0^{+6.0}_{-5.8}$
R_p	Planetary Radius (R_J)	1.322 ± 0.026	$1.308^{+0.044}_{-0.043}$
M_p	Planetary Mass (M_J)	$0.446^{+0.025}_{-0.024}$	1.92 ± 0.13
a	Semi-major axis (AU)	$0.02686^{+0.00044}_{-0.00037}$	0.02273 ± 0.00044
i	Inclination (Degrees)	84.90 ± 0.24	$83.60^{+0.67}_{-0.61}$
e	Eccentricity	$0.05^{+0.026}_{-0.027}$	$0.027^{+0.029}_{-0.019}$
ω_*	Argument of Periastron (Degrees)	$85^{+3.7}_{-4.6}$	178^{+93}_{-91}
T_{eq}	Equilibrium temperature (K)	1349^{+13}_{-14}	2029^{+29}_{-28}
τ_{circ}	Tidal circularisation timescale (Gyr)	$0.00402^{+0.00052}_{-0.00053}$	$0.00435^{+0.00090}_{-0.00074}$
K	RV semi-amplitude (m/s)	$83.8^{+4.0}_{-3.9}$	349^{+19}_{-20}
R_p/R_*	Radius of planet in stellar radii	0.1625 ± 0.0021	$0.1162^{+0.0030}_{-0.0029}$
a/R_*	Semi-major axis in stellar radii	$6.91^{+0.15}_{-0.13}$	$4.22^{+0.11}_{-0.10}$
δ	Transit depth (fraction)	0.02640 ± 0.00069	$0.01350^{+0.00069}_{-0.00067}$
τ	Ingress/egress transit duration (days)	$0.01589^{+0.00073}_{-0.00071}$	$0.01243^{+0.00081}_{-0.00078}$
T_{14}	Total transit duration (days)	$0.07795^{+0.00069}_{-0.00066}$	$0.09406^{+0.00089}_{-0.00088}$
TFWHM	FWHM transit duration (days)	0.06206 ± 0.00039	$0.08616^{+0.00042}_{-0.00041}$
b	Transit Impact parameter	$0.590^{+0.019}_{-0.021}$	$0.472^{+0.039}_{-0.046}$
ρ_p	Density (cgs)	$0.239^{+0.020}_{-0.019}$	$1.06^{+0.13}_{-0.12}$
$\log g_p$	Surface gravity	2.801 ± 0.029	3.445 ± 0.040
Θ	Safronov Number	0.0214 ± 0.011	$0.0628^{+0.0041}_{-0.0040}$
hFi	Incident Flux (cgs)	0.75 ± 0.029	$3.85^{+0.33}_{-0.31}$
$e \cos \omega_*$		$0.002^{+0.023}_{-0.021}$	$-0.008^{+0.017}_{-0.030}$
$e \sin \omega_*$		$0.042^{+0.027}_{-0.029}$	$0.000^{+0.023}_{-0.024}$
$u_1(B)$	linear limb-darkening coeff (B)	0.882 ± 0.051	-
$u_1(V)$	linear limb-darkening coeff (V)	-	0.425 ± 0.048
$u_1(R)$	linear limb-darkening coeff (R)	0.532 ± 0.018	0.351 ± 0.016
$u_2(B) \dots u_2(V) \dots u_2(R)$	quadratic limb-darkening coeff (B) . quadratic limb-darkening coeff (V) . quadratic limb-darkening coeff (R)	$-0.026 \pm 0.051 - 0.180 \pm 0.017$	$-0.252 \pm 0.049 - 0.288 \pm 0.014$

Table 6

Parameter comparison for HAT-P-23b with TrEs-3b and WASP-135b which occupy the same location on a graph of planetary mass vs. radius vs. semi-major axis. Values for HAT-P-23b from this work and TrEs-3b are taken from NASA Exoplanet Archive (accessed 2020-01-02). WASP-135b values are from (Spake et al., 2016), except for T_{eq} which was calculated from their published parameters using (Southworth, 2010, Eq.5). See HAT-P-23b discussion.

Planet Parameter	HAT-P-23b	TrEs-3b	WASP-135b
M_p (M_J)	1.92 ± 0.13	$1.910_{-0.080}^{+0.075}$	1.90 ± 0.08
R_p (R_J)	$1.308_{-0.043}^{+0.044}$	$1.336_{-0.037}^{+0.031}$	1.30 ± 0.09
a (AU)	0.02273 ± 0.00044	$0.02282_{-0.00040}^{+0.00023}$	0.0243 ± 0.0005
Age (Gyr)	$5.5_{-2.5}^{+3.0}$	$0.90_{-0.30}^{+2.80}$	$0.60_{-0.35}^{+1.40}$
T_{eq} (K)	2029_{-28}^{+29}	1638 ± 22	1720 ± 51
$F(10^9 \text{ergs}^{-1} \text{cm}^{-1})$	$3.85_{-0.21}^{+0.23}$	1.650 ± 0.079	1.98 ± 0.24

planetary and host star parameters for known hot Jupiters along with the discovery of new examples will allow comparative planetology to tease out the relative importance of the factors affecting the radii of hot Jupiters.

The value we find for the eccentricity of $e = 0.027_{-0.019}^{+0.029}$ is consistent with zero and thus in agreement with the findings from secondary eclipse measurements and revised RV analysis (O'Rourke et al., 2014; Moutou et al., 2011). Fig. 3 shows previous studies treating eccentricity as a free parameter yield a smaller scaled system parameter a/R_* than studies where the eccentricity is fixed to zero. This biases results towards larger values of a/R_* where a circular orbit assumption is made, however we see no difference in a/R_* between our free eccentricity and circular models.

We have presented an updated ephemeris for HAT-P-23b based on our new observations and remodelling of those published observations where the lightcurve data is available. We have included only transits with full coverage of both the ingress and egress phases in our ephemeris calculation and have mean combined simultaneous transit times for six epochs where the same transit was observed by multiple observers. We find a linear ephemeris is the best fit to the available data with a $\chi^2_\nu = 2.02$. Such χ^2_ν values are not uncommon in exoplanet ephemeris results that combine data sets from multiple observers, for example Southworth et al. (2019). Motivated by the detection of a 3% brightness variation by Sada and Ramon-Fox (2016) during their observing campaign between 2012 and 2014, we undertook photometric monitoring of HAT-P-23 over a 78-day period in 2018. We detected a periodic variation of 7.015 days (Fig. 5) which we attribute to the rotation of spots on the surface of HAT-P-23b. The amplitude of the variation seen was 1.1%, significantly less than that seen by Sada and Ramon-Fox (2016), suggesting that the activity cycle of HAT-P-23 has declined since their observations were made.

4.2. WASP-52b

Long term monitoring of known transiting hot Jupiters has revealed several systems suspected of exhibiting a non-linear ephemeris such as WASP-12b (Maciejewski et al., 2016), WASP-4b (Bouma et al., 2019) and Kepler-1658 (Chontos et al., 2019). Orbital decay is postulated as the cause of the declining orbits while apsidal precession is an alternative explanation and it is difficult to distinguish between these explanations with the available timeline of observations. This is the motivation for extending the timeline of precise transit mid-time observations for short period hot Jupiter systems using readily available small aperture telescopes.

We have presented an updated ephemeris for WASP-52b using our new observations obtained with multiple small aperture telescopes combined with previously published results and those available from the Exoplanet Transit Database (ETD) and find a quadratic ephemeris provides the best fit to the available data. The $\Delta\chi^2_\nu = 0.07$ between the

linear and quadratic ephemerides is small and has not been reported in previous analysis of transit times for WASP-52b, (Mancini et al., 2017; Öztürk and Erdem, 2019; Baluev et al., 2019). Extrapolating both ephemerides shows that with timing measurements from the 2021 observing season it should be possible to determine if the linear or quadratic model is correct, (Fig. 7). Below we consider some possible causes for the period change implied by the quadratic ephemeris model result.

4.2.1. Orbital decay

Our result for the period change implies a decay time (based on linear decay to $a = 0$) of 4.1 Myr, approximately 0.05% of the derived age for WASP-52. Following equation 14 from Patra et al. (2017) and using $\delta P/\delta t = -1.22 \pm 0.14 \times 10^{-9}$ we calculate the modified tidal quality factor to be $Q'_* = 1.1 \pm 0.2 \times 10^3$. This is at least 2-3 orders of magnitude smaller than typically expected (Patra et al., 2017, and references therein), ruling out tidal decay as a potential cause of the observed period change.

4.2.2. Apsidal precession

Apsidal precession requires the planet has an eccentric orbit and with a short 1.75d period, a method of maintaining that eccentricity is not clear. Assuming a more likely maximum value for Q_*^0 of 10^5 the tidal circularisation timescale, τ_{circ} , is just 5 Myr, significantly less than the $5_{-4.6}^{+3.7}$ Gyr age of the system. Our analysis finds no significant evidence for a departure from a circular orbit, however we note a **small eccentricity is possible** and additional radial velocity monitoring or secondary occultation observations would be required to confirm the existence, or otherwise, of a small orbital eccentricity.

4.2.3. Applegate effect

In the Applegate effect (Applegate, 1992), changes in the stellar quadrupole moment drive angular momentum transfer within the star over the magnetic cycle period of the star. If angular momentum is transferred from the core to the stellar envelope the star will become more oblate. An orbiting planet period change due to the Applegate effect has been considered by Watson and Marsh (2010). To maintain a constant angular momentum in the changing gravitation potential as the star becomes more oblate the orbital speed must increase and therefore the period decrease. The opposite is true if the oblateness of the star decreases, the period will increase, giving rise to a sinusoidal change in the orbiting planet's transit times. Following Equation 13 from Watson and Marsh (2010), setting the time-scale over which the quadrupole changes occur to either the approximate 7.5 years duration of WASP-52b observations, or twice this value, the amplitude of period change is 0.244 or 0.59 seconds respectively. This equates to a period change of $37 \pm 10 \text{ ms yr}^{-1}$ for the 7.5 year quadrupole change or $53 \pm 14 \text{ ms yr}^{-1}$ if the cycle is 15 years, consistent with the detected period change value of $-38.6 \pm 4 \text{ ms yr}^{-1}$ so orbital period changes due to the Applegate effects cannot be ruled out. For a given set of stellar parameters the magnitude of the O-C value arising from the Applegate effect is sensitive to both the stellar rotation period and the assumed modulation period, with longer a rotation period reducing the O-C value and longer modulation periods increasing it. The stellar rotation period from Hébrard et al. (2013) is dependent on the poorly constrained inclination of the system. Based on spot crossing events Mancini et al. (2017) derived a rotation period of $15.3 \pm 1.96\text{d}$ which yields period change values of $28 \pm 5 \text{ ms yr}^{-1}$ for an assumed 7.5 year modulation period. The modulation period is therefore main unknown parameter and will require further observations to determine.

4.2.4. Distant perturber

Hébrard et al. (2013) identified a possible long-term RV trend of $+40 \text{ ms}^{-1}$ over a period of 15 months which they concluded could be due to a distant companion or a systematic effect resulting from combining multiple data sets. A companion in the range of $10 - 15M_J$ out to

6AU was ruled out by a lack of transit timing variation signal (Swift et al., 2015). In their re-analysis of publicly available data from the ETD Baluev et al. (2019) also find no periodic variation attributable to TTVs. A Lomb-Scargle period analysis was undertaken of the combined data set with our new observations finding no evidence of periodicity resulting from TTV's. The acceleration away from Earth of $+40 \text{ ms}^{-1}$ over 15 months would produce a radial velocity acceleration $\dot{v}_r \approx 0.09 \text{ ms}^{-1} \text{ d}^{-1}$ resulting in a positive period derivative of approximately $\dot{P} \approx \dot{v}_r P/c \approx 5 \times 10^{-10}$, of opposite sign and an order of magnitude smaller than seen. The measured \dot{P} of -39 ms yr^{-1} would require a $\dot{v}_r \approx 0.2 \text{ ms}^{-1} \text{ d}^{-1}$, which would be readily detectable in the available radial velocity measurements.

4.2.5. Star spots

The impact of star spots on transit time measurements has been considered by previous authors (E.g. Oshagh et al., 2013; Ioannidis et al., 2016). Barros et al. (2013) identified spot transits as the cause of TTVs in WASP-10b. Ioannidis et al. (2016) showed that timing from higher precision lightcurves is more affected by stellar spots, and they define the transit SNR (TSNR) as the transit depth divided by the out of transit light curve noise level. They demonstrated that for TSNR > 15 systematic timing errors introduced by spot crossing events are not distinguishable from the random noise. They also showed that the magnitude of the effect of spots on timing measurements is determined by the spot longitude on the stellar surface, peaking at $\lambda = \pm 70^\circ$, reducing the closer a spot is to the stellar limb (as the size of the projected spot is reduced) and becoming zero at the centre of the stellar disk. Therefore a spot crossing will induce a positive time variation where it occurs before the transit mid-time and a negative variation where it occurs after transit mid-time, leading to a transit time variation effect than can mimic that caused by a companion planet. For a well aligned and prograde planetary orbit such as that for WASP-52b (Hèbrard et al., 2013; Mancini et al., 2017) this TTV mimicking effect would result in detectable variations, or at least an increase in the spread of O-C measurements if the sampling is poor, rather than the declining period we see in the ephemeris of WASP-52b.

The approximately 2.7% deep transits of WASP-52b means that an out of transit noise level of 0.0018 or less is required to achieve $TSNR > 15$, a level of photometric precision marginally achieved in only a small number of our new WASP-52b transits used in the ephemeris calculation. Therefore we would not expect our transit mid-time measurements to be systematically affected by spot crossing events. While no spot crossing events were positively identified in the new photometry obtained in the 2017/18 season the 2013 archive observation from the UK shows a clear brightening during transit. This observation was obtained during the same period as those by Mancini et al. (2017) who positively detected spot crossing events at 5 of their 7 epochs with full transit coverage. The absence of spot crossing events in our 2017-18 transits could indicate that the photometric precision achieved is insufficient to resolve the spot crossings or that since the 2012-2014 seasons WASP-52's stellar cycle has either quieted or the spot latitude has migrated away from the transit chord. If the spots have ceased or migrated to a different latitude from the transit chord this would be apparent in photometric monitoring of WASP-52. Stellar spots occurring at a latitude different to the transit chord would be visible as stellar variability and potentially detectable as a correlation between stellar flux and transit depth (E.g. Kirk et al., 2016). If WASP-52 is in a reduced activity phase of its stellar cycle we would not expect to see either effect.

Unfortunately concurrent photometric monitoring of WASP-52 over the 2018 season is not available; instead the stellar magnitude was measured using out of transit data from four transits observed using PIRATE with sufficient unbroken data available on both sides of the transit (transits 3 to 6 in Table 1). As for HAT-P-23 a photometry template was generated using comparison stars from the UCAC4 catalogue. Eight stars were used in the range $r' = 13.00 - 14.90 \text{ mag}$. WASP-52 itself has no B, V or r' photometry in the UCAC4 catalogue so

$B - V = 0.9$ was taken from Hèbrard et al. (2013) and a check star of similar $B - V = 0.86$ was selected from UCAC4. Although this data set contained data from only 4 observations a variation of $\Delta R_c = 0.03 \text{ mag}$, similar to the WASP-52b transit depth, was seen.

The lack of transit spot crossing events in the 2017-18 season along with the brightness variation we see in WASP-52 indicate WASP-52 is still active but that the activity latitude has migrated away from the transit chord. Observations in future seasons, ideally with a B filter to increase spot contrast, would be required to follow the stellar activity cycle and determine its periodicity. This result shows how observations obtained using small aperture telescopes, such as those used in this study, can provide monitoring of transiting systems to identify activity cycles and help advise the planning of transmission spectroscopy observations which are complicated by activity on the host star.

5. Observatory performance and capability

We now consider the performance and capabilities of the small aperture telescopes used in this study to undertake long duration transit follow up campaigns. In observations obtained with PIRATE before 17th July 2018 and for observations made with POST the individual exposure start times were recorded in the FITS headers using the PC clock controlled using the separate application Dimension4⁷ to continually update the control PC clocks from an Internet time server. During an upgrade carried out 17th - 20th July 2018 GPS time controllers were installed at both PIRATE and COAST observatories with camera shutter timing measurement to record the exposure start and end times to sub-millisecond accuracy. Shortly before this upgrade the imaging process for the observations in this study was changed from 2×2 on-chip binning to 1×1 un-binned imaging. The observations of HAT-P-23b either side of this period allow a comparison of the timing precision achievable before and after installation of the GPS timing control. The O-C results for HAT-P-23b show a three fold reduction in the measurement scatter after the upgrade date with the RMS scatter reducing from 93.41s to 33.48 seconds. At the same time the mean individual transit mid-time uncertainties were reduced by 17% from 62.6s to 51.8 seconds, likely due to the higher precision photometry produced from the change to 1×1 binning. Over the same period the transit O-C RMS scatter determined from POST observations remain unchanged at 113.7 seconds with an individual transit mid-time uncertainty mean of 70.3s. The observations of WASP-52b obtained with PIRATE all occurred after the GPS installation and were all made un-binned, resulting in an O-C RMS scatter of 16.4s and a mean transit mid-time uncertainty of 25.9s (excluding the transit of 10th October 2018 without out of transit coverage).

It is not possible to separate the timing improvement due to the GPS timing implementation from the change to 1×1 binned observations though it is expected both will have contributed to the reduced spread in O-C measurements seen. New planned observations of transit targets with both 1×1 and 2×2 on chip binning will enable this distinction to be made. The longer integrations used resulted in a greater SNR for the 1×1 observations reducing the out of transit photometric scatter and reducing photometric noise by 36%. With a plate scale of $0.63''$ the 1×1 observations are slightly over sampled for the typical seeing conditions producing a result similar to slightly defocussing the telescope but without some of the draw backs such as contamination from flux overlap. The mid transit timing precision achievable depends on the RMS photometric noise, the transit depth and the square root of the number of data points covering ingress/egress (Deeg and Tingley, 2017, Eq. 5). As a result, even though the unbinned observations were made at a 2.5 to 3 times lower cadence than the 2×2 on-chip binned observations, the significant reduction in RMS noise has a dominant effect reducing the transit mid-time uncertainty.

⁷ (<http://www.thinkman.com/dimension4/>)

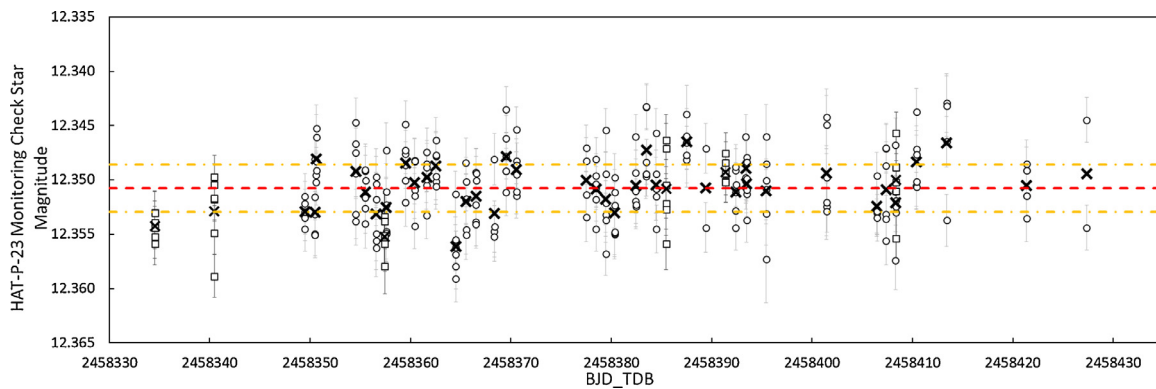


Fig. 8. Nightly monitoring (open circles) and out of transit (open squares) photometry for the check star used to compare with HAT-P-23b. The crosses are the nightly mean values and the red dashed line is the mean value of the entire data set. The dash-dot lines represent the 1σ variation of 0.002 mag over the 93 day period of observation.

Table 7

Out of transit photometric RMS scatter for published observations with medium class telescopes compared with the phase folded and binned observations from this work. ppm = parts per million.

System	RMS Scatter (ppm)	Observation	Filter	Source
HAT-P-23b	645	Calar Alto 2.2m	Thuan-Gunn r	Ciceri et al. (2015)
HAT-P-23b	746	Calar Alto 1.23m	Rc	Ciceri et al. (2015)
HAT-P-23b	415	0.4m (Binx25)	Rc	This work
WASP-52b	582	DK 1.54m	Bessell r	Mancini et al. (2017)
WASP-52b	768	Calar Alto 1.23m	Rc	Mancini et al. (2017)
WASP-52b	616	0.4 m (Binx12)	Rc	This work

Table 8

Ephemeris values for WASP-52b and HAT-P-23b

Planet	Ephemeris	Epoch	Period	Quadratic Term	χ^2_ν	BIC		
WASP-52b	Linear	2455793.681914 \pm	1.41×10^{-4}	1.749781099 \pm	1.26×10^{-7}	1.58	59.41	
WASP-52b	Quadratic	2455793.680953 \pm	1.49×10^{-4}	1.749783212 \pm	1.37×10^{-7}	$-2.14 \pm 0.24 \times 10^{-9}$	1.51	57.88
HAT-P-23b	Linear	2454852.265165 \pm	1.20×10^{-4}	1.212886457 \pm	5.39×10^{-8}	2.08	33.01	

PIRATE was used to undertake monitoring of the HAT-P-23 field allowing us to analyse the photometric precision obtained over a long duration. The nightly observations were made with groups of 6 frames which exhibited a typical spread of 0.007 mag within a night. The stability of the long-term photometry is demonstrated with the standard error of the nightly mean magnitude which is 0.002 mag over 93 days, Fig. 8. Of the 218 observations made, 95% were obtained with airmass ≤ 1.5 and no significant trend was found between measured magnitude of the check star and airmass. The magnitude measurements obtained from the out of transit data were found to have a -0.01 mag offset for the 2×2 on-chip binning compared to the un-binned observations which was corrected for prior to our analysis. The monitoring observations conducted with PIRATE were clearly able to detect the variation in HAT-P-23 of 0.011 mag in measurements spanning 93 days. Other suspected variable stars were detected in the field of HAT-P-23, the lowest amplitude being 0.005 mag with a 2.6 hour period. These results demonstrate the capability of PIRATE to monitor both long and short period low amplitude variable stars.

In Table 7 we compare the photometric precision achieved with the small aperture telescopes used in this work with those from the literature using much larger aperture telescopes, and in Fig. 9 we show our phase folded nightly and binned data for HAT-P-23b and WASP-52b along with previously published observations made with the telescopes compared in Table 7. The phase folded lightcurve for HAT-P-23b comprised 1821 individual measurements and a total observation time of 3337 minutes was binned by 25 data points. By comparison Mancini et al. (2017) used the Calar Alto 2.2 m telescope which has a

primary mirror area approximately 24 times greater than the telescopes used in this study and obtained a single transit observation of 244 minutes duration. Comparing telescope mirror area multiplied by the duration of observations we find that, in the absence of spot crossing events, the binned photometric results obtained with the small telescopes result in a lightcurve with the same or better photometric precision in half the mirror area \times observation time of the single medium class telescope observation. A similar result was found when the phase folded and binned WASP-52b transits were compared with those obtained using the Danish 1.54 m telescope Ciceri et al. (2015). As the cost of a monolithic mirror telescope typically scales with aperture to the power 2.5 (van Belle et al., 2004), the method of combining the results obtained using multiple small telescope observations is an efficient approach to obtaining precise lightcurves for parameter determination of known transiting exoplanets with the added benefit of obtaining transit timing at multiple epochs.

6. Summary

We have presented 17 new transits for HAT-P-23b and 13 new transits of WASP52b along with contemporaneous photometric monitoring for HAT-P-23, all made with 0.4 m class telescopes. For HAT-P-23b our combined radial velocity and new transit analysis results in an orbital eccentricity consistent with zero, in contrast the some previous studies (Bakos et al., 2011; Sada and Ramon-Fox, 2016), but consistent with the assumption of circular orbit by other authors (Maciejewski et al., 2018; Ciceri et al., 2015). We find a radius for HAT-

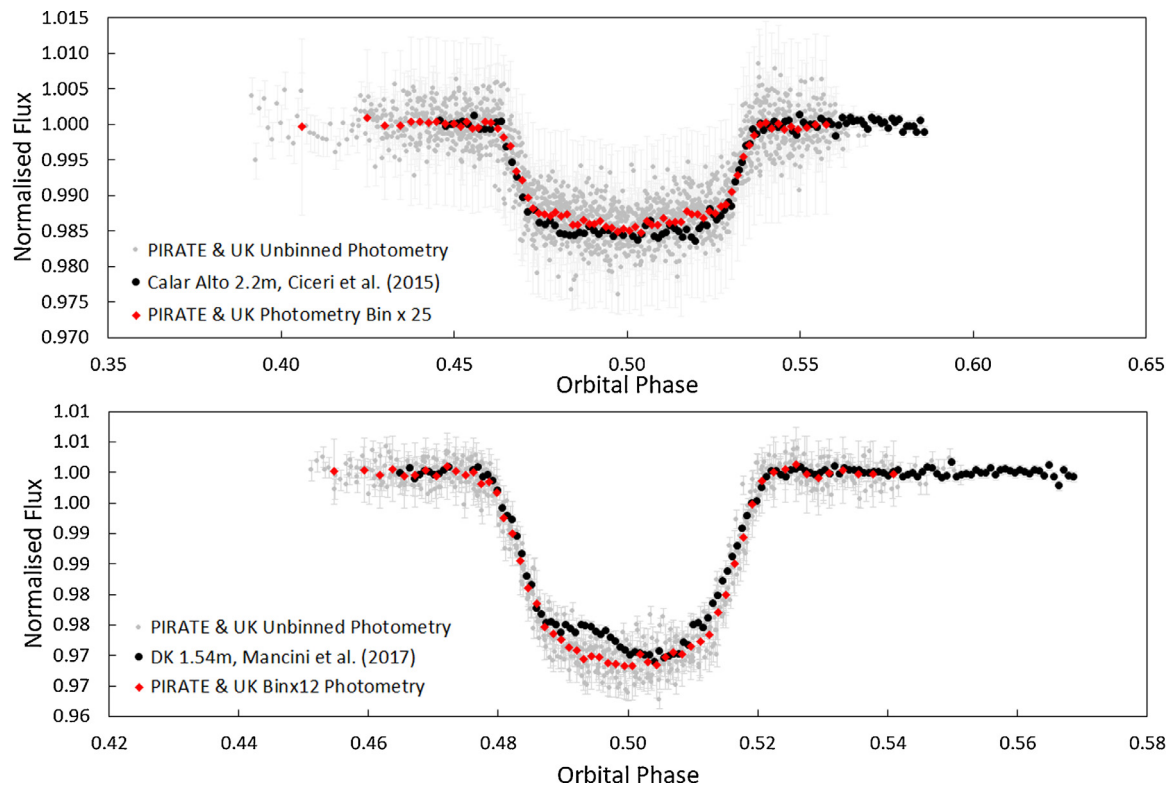


Fig. 9. A comparison of the original and binned data for HAT-P-23b (top) and WASP-52b (bottom) with previously published results for medium class telescopes. Clearly visible in the WASP-52b data from Mancini et al. (2017) is one of the spot crossing events observed.

P-23b between previously published values but conclude that the planet should still be considered inflated, though the mechanism driving the inflation is not clear as the radius is smaller than that indicated by the empirical mass/incident flux relation for planetary radius derived by Weiss et al. (2013). Our monitoring observations of HAT-P-23 have revealed a photometric modulation of 0.011mag with a period of 7.015 days which we interpret as the rotation period of HAT-P-23 due to stellar surface spots.

For WASP-52b our observations show no evidence for the large spot crossing events seen in previous works. The detection of continuing brightness variations indicates that the spot latitude has migrated away from the transit chord. Our analysis of the new and previously published transit times slightly prefers a quadratic ephemeris but only with a $\Delta\chi^2 = 0.07$ and $\Delta\text{BIC} = 1.53$. ΔBIC values of less than 2 indicate no preference for one model over the other, Table 8. We have investigated the effects of removing different new and published transit timing data sets and find the quadratic model is preferred in all scenarios except where the very small uncertainties in the timing from Mancini et al. (2017) are taken at face value. We conclude that apsidal precession and orbital decay are unlikely causes but that the Applegate effect cannot be ruled out. However, considering the small statistical preference for the quadratic ephemeris and the high spot activity level of WASP-52, it seems the most plausible explanation for the slight preference of the quadratic ephemeris is increased scatter in transit timing measurements due to the effects of spot crossings. Predicting the ephemerides forwards shows that transit observations in the 2021 season will likely reveal if the quadratic ephemeris is real.

We have demonstrated that small aperture telescopes can be used to make valuable contributions to transiting exoplanet studies when deployed for long term monitoring campaigns.

CRediT authorship contribution statement

M.A. Salisbury: Conceptualization, Formal analysis, Investigation,

Methodology, Validation, Writing - original draft. U.C. Kolb: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing - review & editing. A.J. Norton: Conceptualization, Methodology, Supervision, Validation, Writing - review & editing. C.A. Haswell: Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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References

- Applegate, J.H., 1992. A mechanism for orbital period modulation in close binaries. *Astrophysical Journal* 385, 621. <https://doi.org/10.1086/170967>. URL: <http://stacks.iop.org/1538-4357/669/i=2/a=L93%5Cnhttp://adsabs.harvard.edu/abs/1992ApJ...385..621A%5Cnhttp://adsabs.harvard.edu/doi/10.1086/170967>.
- Bakos, A.G., Hartman, J., Torres, G., Latham, D.W., Kovcs, G., Noyes, R.W., Fischer, D.A.,

- Johnson, J.A., Marcy, G.W., Howard, A.W., Kipping, D., Esquerdo, G.A., Shporer, A., Beky, B., Buchhave, L.A., Perumilly, G., Everett, M., Sasselov, D.D., Stefanik, R.P., Lazzari, J., Papp, L., S'ari, P., 2011. HAT-P-20b-HAT-P-23b: Four massive transiting extrasolar planets. *Astrophysical Journal* 742. <https://doi.org/10.1088/0004-637X/742/2/116>.
- Baluev, R.V., Sokov, E.N., Jones, H.R.A., Shaidulin, V.S., Sokova, I.A., Nielsen, L.D., Benni, P., E.M., D'Angelo, C.V., Fernandez-Lajus, E., Di Sisto, R.P., Basturk, O., Bretton, M., Wunsche, A., Hentunen, V.P., Shadick, S., Jongen, Y., Kang, W., Kim, T., Pakstiene, E., Qvam, J.K.T., Knight, C.R., Guerra, P., Marchini, A., Salvaggio, F., Papini, R., Evans, P., Salisbury, M., Garcia, F., Molina, D., Garlitz, J., Esseiva, N., Ogmén, Y., Karavaev, Y., Rusov, S., Ibrahimov, M.A., Karimov, R.G., 2019. Homogeneously derived transit timings for 17 exoplanets and reassessed TTV trends for WASP-12 and WASP-4. *Monthly Notices of the Royal Astronomical Society* 490, 1294–1312. <https://doi.org/10.1093/mnras/stz2620>. URL: <http://arxiv.org/abs/1908.04505>.
- Barros, S., Boue, G., Gibson, N.P., Pollacco, D.L., Santerne, A., Keenan, F.P., Skillen, I., Street, R.A., 2013. Transit timing variations in WASP-10b induced by stellar activity. *Monthly Notices of the Royal Astronomical Society* 430, 3032–3047. <https://doi.org/10.1093/mnras/stt111>.
- van Belle, G.T., Meinel, A.B., Meinel, M.P., 2004. The scaling relationship between telescope cost and aperture size for very large telescopes. *SPIE Proceedings* 5489, 563. <https://doi.org/10.1117/12.552181>.
- Bonomo, A.S., Desidera, S., Benatti, S., Borsa, F., Crespi, S., Damasso, M., Lanza, A.F., Sozzetti, A., Lodato, G., Marzari, F., Boccato, C., Claudi, R.U., Cosentino, R., Covino, E., Gratton, R., Maggio, A., Micela, G., Molinari, E., Pagano, I., Piovato, G., Poretti, E., Smareglia, R., Affer, L., Biazzo, C., Bignamini, A., Esposito, M., Giacobbe, P., Hébrard, G., Malavolta, L., Maldonado, J., Mancini, L., Fiorenzano, A.M., Masiero, S., Nascimbeni, V., Pedani, M., Rainer, M., Scandariato, G., 2017. The GAPS Programme with HARPS-N@TNG XIV. Investigating giant planet migration history via improved eccentricity and mass determination for 231 transiting planets. *Astronomy & Astrophysics* 602, 1–16. <https://doi.org/10.1051/0004-6361/201629882>. URL: <http://arxiv.org/abs/1704.00373v0><http://dx.doi.org/10.1051/0004-6361/201629882>.
- Bouma, L.G., Winn, J.N., Baxter, C., Bhatti, W., Dai, F., Daylan, T., Desert, J.M., Hill, M.L., Kane, S.R., Stassun, K.G., Villaseñor, J., Ricker, G.R., Vanderspek, R., Latham, D.W., Seager, S., Jenkins, J.M., Berta-Thompson, Z., Colon, K., Fauchald, M., Glidden, A., Guerrero, N., Rodriguez, J.E., Twicken, J.D., Wöhler, B., 2019. WASP-4b Arrived Early for the TESS Mission. *Astronomical Journal* 157, 217. URL: <http://arxiv.org/abs/1903.02573>.
- Brown, A.G.A., Gaia Collaboration, 2018. *Astrophysics Special issue Gaia Data Release 2. Astronomy & Astrophysics* 616, 1–22.
- Bruno, G., Lewis, N.K., Stevenson, K.B., Filippazzo, J., Hill, M., Fraine, J.D., Wakeford, H.R., Deming, D., Lopez-Morales, M., Alam, M.K., 2018. Starspot Occurrences in Infrared Transit Spectroscopy: The Case of WASP-52b. *The Astronomical Journal* 156, 124. <https://doi.org/10.3847/1538-3881/aac6db>. URL: <http://stacks.iop.org/1538-3881/156/i=3/a=124?key=crossref.4def34444f840a2904934c8407a92cf0>.
- Chen, G., Nortmann, L., Murgas, F., Parviainen, H., Nowak, G., 2017. The GTOC exoplanet transit spectroscopy survey VI. Detection of sodium in WASP-52b's cloudy atmosphere. *Astrophysics Letter to the Editor* 11, 1–6.
- Chontos, A., Huber, D., Latham, D.W., Bieryla, A., Van Eylen, V., Bedding, T.R., Berger, Buchhave, L.A., Campante, T.L., Chaplin, W.J., Colman, I.L., Coughlin, J.L., Davies, G., Hirano, T., Howard, A.W., Isaacson, H., 2019. The Curious Case of KOI 4: Confirming Kepler's First Exoplanet. *Astronomical Journal* 157, 192. URL: <http://arxiv.org/abs/1903.01591>.
- Ciceri, S., Mancini, L., Southworth, J., Bruni, I., Nikolov, N., D'Agó, G., Schroder, T., Bozza, V., Tregloan-Reed, J., Henning, T., 2015. Physical properties of the HAT-P-23 and WASP-48 planetary systems from multi-colour photometry. *Astronomy & Astrophysics* 577. <https://doi.org/10.1051/0004-6361/201425449>. URL: <http://www.aanda.org/10.1051/0004-6361/201425449>.
- Collins, K.A., Kielkopf, J.F., Stassun, K.G., 2017. *AstrolmageJ: Image Processing and Photometric Extraction for Ultra-Precise Astronomical Light Curves*. *The Astronomical Journal* 153.
- Deeg, H.J., Tingley, B., 2017. TEE, a simple estimator for the precision of eclipse and transit minimum times. *Astronomy & Astrophysics* 599, 1–7. <https://doi.org/10.1051/0004-6361/201629350>. URL: <http://arxiv.org/abs/1612.02237v0><http://dx.doi.org/10.1051/0004-6361/201629350>.
- Eastman, J.D., Rodriguez, J.E., Agol, E., Stassun, K.G., Beatty, T.G., Vanderburg, A., Gaudi, B.S., Collins, K.A., Luger, R., 2019. EXOFASTv2: A public, generalized, publication-quality exoplanet modeling code. *arXiv preprint arXiv:1907.09480*. URL: <http://arxiv.org/abs/1907.09480>.
- Fortney, J.J., Marley, M.S., Barnes, J.W., 2007. Planetary Radii across Five Orders of Magnitude in Mass and Stellar Insolation: Application to Transits. *The Astrophysical Journal* 659, 1661–1672. <https://doi.org/10.1086/512120>.
- Hébrard, G., Collier Cameron, A., Brown, D.J.A., Diaz, R.F., Faedi, F., Smalley, B., Anderson, D.R., Armstrong, D., Barros, S.C.C., Bento, J., Bouchy, F., Doyle, A.P., Enoch, B., Gomez Maqueo Chew, Y., Hébrard, E.M., Hellier, C., Lendl, M., Lister, T.A., Maxted, P.F.L., McCormac, J., Moutou, C., Pollacco, D., Queloz, D., Santerne, A., Skillen, I., Southworth, J., Tregloan-Reed, J., Triaud, A.H.M.J., Udry, S., Vanhuyse, M., Watson, C.A., West, R.G., Wheatley, P.J., 2013. WASP-52b, WASP-58b, WASP-59b, and WASP-60b: Four new transiting close-in giant planets. *Astronomy & Astrophysics* 549, A134. <https://doi.org/10.1051/0004-6361/201220363>. URL: <http://www.aanda.org/10.1051/0004-6361/201220363>.
- Ioannidis, P., Huber, K.F., Schmitt, J.H.M.M., 2016. How do starspots influence the transit timing variations of exoplanets? Simulations of individual and consecutive transits. *Astronomy & Astrophysics* 585, A72. URL: <http://arxiv.org/abs/1510.03276>.
- Kirk, J., Wheatley, P.J., Louden, T., Littlefair, S.P., Copperwheat, C.M., Armstrong, D.J., Marsh, T.R., Dhillon, V.S., 2016. Transmission spectroscopy of the inflated exoplanet WASP-52b, and evidence for a bright region on the stellar surface. *Monthly Notices of the Royal Astronomical Society* 463, 2922–2931. <https://doi.org/10.1093/mnras/stw2205>.
- Kolb, U., Brodeur, M., Braithwaite, N., Minocha, S., 2018. A Robotic Telescope For University-Level Distance Teaching. *RTSRE Proceedings* 1, 127–136. URL: <http://adsabs.harvard.edu/abs/2018RTSRE...1..127K>.
- Louden, T., Wheatley, P.J., Irwin, P.G., Kirk, J., Skillen, I., 2017. A precise optical transmission spectrum of the inflated exoplanet WASP-52b. *Monthly Notices of the Royal Astronomical Society* 470, 742–754. <https://doi.org/10.1093/mnras/stx984>.
- Maciejewski, G., Dimitrov, D., Fernandez, M., Sota, A., Nowak, G., Ohlert, J., Nikolov, G., Bukowiecki, L., Hinse, T.C., Palle, E., Tingley, B., Kjurkchieva, D., Lee, J.W., Lee, C.U., 2016. Departure From The Constant-Period Ephemeris For The Transiting Exoplanet WASP-12b. *Astronomy & Astrophysics Letters* 588, 1–6. <https://doi.org/10.1051/0004-6361/201628312>. URL: <http://arxiv.org/pdf/1602.09055v1.pdf>.
- Maciejewski, G., Fernandez, M., Aceituno, F., Martín-Ruiz, S., Ohlert, J., Dimitrov, D., Szyzka, K., VonEssen, C., Mugrauer, M., Bischoff, R., Michel, K.U., Mallonn, M., Stangret, M., Mozdziński, D., 2018. Planet-star interactions with precise transit timing. I. The refined orbital decay rate for WASP-12 b and initial constraints for HAT-P-23 b, KELT-1 b, KELT-16 b, WASP-33 b, and WASP-103 b. *Acta Astronomica* 68, 371–401. <https://doi.org/10.32023/0001-5237/68.4.4>. URL: <http://arxiv.org/abs/1812.02438>.
- Mancini, L., Southworth, J., Raia, G., Tregloan-Reed, J., Molliere, P., Bozza, V., Bretton, M., Bruni, I., Ciceri, S., D'Agó, G., Dominik, M., Hinse, T.C., Hundertmark, M., Jørgensen, U.G., Korhonen, H., Rabus, M., Rahvar, S., Starkey, D., Calchi Novati, S., Figueroa Jaimés, R., Henning, T., Juncher, D., Haugbølle, T., Kains, N., Popovas, A., Schmidt, R.W., Skottfelt, J., Snodgrass, C., Surdej, J., Wertz, O., 2017. Orbital alignment and star-spot properties in the WASP-52 planetary system. *Monthly Notices of the Royal Astronomical Society* 465, 843–857. <https://doi.org/10.1093/mnras/stw1987>.
- Moutou, C., D'Azar, R.F., Udry, S., Hébrard, G., Bouchy, F., Santerne, A., Ehrenreich, D., Arnold, L., Boisse, I., Bonfils, X., Delfosse, X., Eggenberger, A., Forveille, T., Lagrange, A.M., Lovis, C., Martinez, P., Pepe, F., Perrier, C., Queloz, D., Santos, N.C., Segransan, D., Touloukian, D., Troncin, J.P., Vanhuyse, M., Vidal-Madjar, A., 2011. Spin-orbit inclinations of the exoplanetary systems HAT-P-8b, HAT-P-9b, HAT-P-16b, and HAT-P-23b. *Astronomy & Astrophysics* 533, A113. <https://doi.org/10.1051/0004-6361/201116760>. URL: <http://www.aanda.org/10.1051/0004-6361/201116760>.
- O'Donovan, F.T., Charbonneau, D., Bakos, G.A., Mandushev, G., Dunham, E.W., Brown, T.M., Latham, D.W., Torres, G., Sozzetti, A., Kovacs, G., Everett, M.E., Balibar, N., Hidas, M.G., Esquerdo, G.A., Rabus, M., Deeg, H.J., Belmonte, J.A., Hillenbrand, L.A., Stefanik, R.P., 2007. TrES-3: A Nearby, Massive, Transiting Hot Jupiter in a 31-Hour Orbit. *The Astrophysical Journal* 663, 37–40. <https://doi.org/10.1086/519793>. URL: 740. <http://arxiv.org/abs/0705.2004>.
- O'Rourke, J.G., Knutson, H.A., Zhao, M., Fortney, J.J., Burrows, A., Agol, E., Deming, D., Desert, J.M., Howard, A.W., Lewis, N.K., Showman, A.P., Todorov, K.O., 2014. Warm spitzer and palomar near-ir secondary eclipse photometry of two hot jupiters: WASP-48b and hat-p-23b. *Astrophysical Journal* 781. <https://doi.org/10.1088/0004-637X/781/2/109>.
- Oshagh, M., Santos, N.C., Boisse, I., Boue, G., Montalto, M., Dumusque, X., Haghighipour, N., 2013. Effect of stellar spots on high-precision transit light-curve. *Astronomy & Astrophysics* 556, A19. <https://doi.org/10.1051/0004-6361/201321309>. URL: <http://arxiv.org/abs/1306.0739>.
- Öztürk, O., Erdem, A., 2019. New photometric analysis of five exoplanets: CoRoT-2b, HAT-P-12b, TrES-2b, WASP-12b and WASP-52b. *Monthly Notices of the Royal Astronomical Society* 2. <https://doi.org/10.1093/mnras/stz747>. URL: <https://academic.oup.com/mnras/advance-article/doi/10.1093/mnras/stz747/5380787>.
- Patra, K.C., Winn, J.N., Holman, M.J., Yu, L., Deming, D., Dai, F., 2017. The Apparently Decaying Orbit of WASP-12. *The Astronomical Journal* 154. URL: <http://arxiv.org/abs/1703.06582>.
- Sada, P.V., Deming, D., Jennings, D.E., Jackson, B.K., Hamilton, C.M., Fraine, J.D., Peterson, S.W., Haase, F., Bays, K., Lunsford, A., O'Gorman, E., 2012. Extrasolar Planet Transits Observed at Kitt Peak National Observatory. *Publications of the Astronomical Society of the Pacific* 124, 212–229. <https://doi.org/10.1086/665043>.
- Sada, P.V., Ramon-Fox, F.G., 2016. Exoplanet Transits Registered at the Universidad de Monterrey Observatory. Part I: HAT-P-12b, HAT-P-13b, HAT-P-16b, HAT-P-23b and WASP-10b. *Publications of the Astronomical Society of the Pacific* 128. <https://doi.org/10.1088/1538-3873/128/960/024402>. URL: <http://arxiv.org/abs/1601.02292>.
- Sokov, E.N., Sokova, I.A., Dyachenko, V.V., Rastegaev, D.A., Burdanov, A., Rusov, S.A., Benni, P., Shadick, S., Hentunen, V.P., Salisbury, M., Esseiva, N., Garlitz, J., Bretton, M., Ogmén, Y., Karavaev, Y., Ayiomamitis, A., Mazurenko, O., Alonso, D., Velichko, S.F., 2018. Transit timing analysis of the exoplanet TrES-5 b. Possible existence of the exoplanet TrES-5 c. *Monthly Notices of the Royal Astronomical Society* 480, 291–301. <https://doi.org/10.1093/mnras/sty1615>.
- Southworth, J., 2010. Homogeneous studies of transiting extrasolar planets - III. Additional planets and stellar models. *Monthly Notices of the Royal Astronomical Society* 408, 1689–1713. <https://doi.org/10.1111/j.1365-2966.2010.17231.x>.
- Southworth, J., Dominik, M., Jørgensen, U.G., Andersen, M.I., Bozza, V., Burgdorf, M.J., D'Agó, G., Dib, S., Jaimés, R.F., Fujii, Y.I., Gill, S., Haikala, L.K., Hinse, T.C., Hundertmark, M., Khalouei, E., Korhonen, H., Longa-Pena, P., Mancini, L., Peixinho, N., Rabus, M., Rahvar, S., Sajadian, S., Skottfelt, J., Snodgrass, C., Spyrtatos, P., Tregloan-Reed, J., Unda-Sanzana, E., von Essen, C., 2019. Transit timing variations in the WASP-4 planetary system*. *Monthly Notices of the Royal Astronomical Society* 490, 4230–4236. <https://doi.org/10.1093/mnras/stz2602>.
- Spake, J.J., Brown, D.J., Doyle, A.P., Hébrard, G., McCormac, J., Armstrong, D.J., Pollacco, D., Chew, Y.G.M., Anderson, D.R., Barros, S.C., Bouchy, F., Boumias, P., Bruno, G., Collier Cameron, A., Courcol, B., Davies, G.R., Faedi, F., Hellier, C., Kirk,

- J., Lam, K.W., Liakos, A., Louden, T., Maxted, P.F., Osborn, H.P., Palle, E., Prieto Arranz, J., Udry, S., Walker, S.R., West, R.G., Wheatley, P.J., 2016. WASP-135b: A highly irradiated, inflated hot jupiter orbiting a G5V star. *Publications of the Astronomical Society of the Pacific* 128, 24401. <https://doi.org/10.1088/1538-3873/128/960/024401>. <http://dx.doi.org/10.1088/1538-3873/128/960/024401>.
- Stassun, K.G., Torres, G., 2018. Evidence for a Systematic Offset of 80 micro arcsec in the Gaia DR2 Parallaxes. *The Astrophysical Journal* 862. <https://doi.org/10.3847/1538-4357/aacaaf>.
- Swift, J.J., Johnson, J.A., Wright, J.T., Wittenmyer, R.A., Muirhead, P.S., Blake, C.H., Beatty, T.G., Barnes, S.I., Gibson, S.R., Gardner, P., Robinson, C., Sliski, D.H., Vera, J.D., Szentgyorgyi, A., 2015. Miniature Exoplanet Radial Velocity Array I: design, commissioning, and early photometric results. *Journal of Astronomical Telescopes, Instruments, and Systems* 1. <https://doi.org/10.1117/1.JATIS.1.2.027002>.
- Sybilski, P.W., Pawłaszczek, R., Kozłowski, S.K., Konacki, M., Ratajczak, M., Hełminiak, K.G., 2014. Software for autonomous astronomical observatories: challenges and opportunities in the age of big data. *Software and Cyberinfrastructure for Astronomy III* 9152, 91521C. <https://doi.org/10.1117/12.2055836>.
- Watson, C.A., Marsh, T.R., 2010. Orbital period variations of hot Jupiters caused by the Applegate effect. *Monthly Notices of the Royal Astronomical Society* 405, 2037–2043. <https://doi.org/10.1111/j.1365-2966.2010.16602.x>.
- Weiss, L.M., Marcy, G.W., Rowe, J.F., Howard, A.W., Isaacson, H., Fortney, J.J., Miller, N., Demory, B.O., Fischer, D.A., Adams, E.R., Dupree, A.K., Howell, S.B., Kolbl, R., Johnson, J.A., Horch, E.P., Everett, M.E., Fabrycky, D.C., Seager, S., 2013. The mass of koi-94d and a relation for planet radius, mass, and incident flux. *Astrophysical Journal* 768. <https://doi.org/10.1088/0004-637X/768/1/14>.
- Yee, S.W., Winn, J.N., Knutson, H.A., Patra, K.C., Vissapragada, S., Zhang, M.M., Holman, M.J., Shporer, A., Wright, J.T., 2019. The Orbit of WASP-12b is Decaying. *The Astrophysical Journal Letters* 888 URL. <http://arxiv.org/abs/1911.09131>.
- Zacharias, N., Finch, C.T., Girard, T.M., Henden, A., Bartlett, J.L., Monet, D.G., Zacharias, M.I., 2013. The fourth US naval observatory ccd astrograph catalog (UCAC4). *Astronomical Journal* 145. <https://doi.org/10.1088/0004-6256/145/2/44>.