Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **477,** L21–L24 (2018) doi:10.1093/mnrasl/sly045
Advance Access publication 2018 March 21

Pre-discovery transits of the exoplanets WASP-18b and WASP-33b from *Hipparcos*

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Accepted 2018 March 16. Received 2018 March 13; in original form 2018 February 5

ABSTRACT

We recover transits of WASP-18b and WASP-33b from *Hipparcos* (1989–1993) photometry. Marginal detections of HAT-P-56b and HAT-P-2b may be also present in the data. New ephemerides are fitted to WASP-18b and WASP-33b. A tentative ($\sim$1.3σ) orbital decay is measured for WASP-18b, but the implied tidal quality factor ($Q^{'} \sim 5 \times 10^5$) is small and survival time ($<10^6$ yr) is too short to be likely. No orbital decay is measured for WASP-33b, and a limit of $Q^{'} > 2 \times 10^5$ is placed. For both planets, the uncertainties in published ephemerides appear underestimated: the uncertainty in the period derivative of WASP-18b would be greatly reduced if its current ephemeris could be better determined.

Key words: planets and satellites: dynamical evolution and stability – planets and satellites: individual: WASP-18b – planets and satellites: individual: WASP-33b – planet–star interactions – stars: variables: δ Scuti.

1 INTRODUCTION

Exoplanetary science is a relatively young field, hence many long-term evolutionary characteristics of planetary systems remain unknown. Pre-discovery archival data can provide, e.g. more precise orbital properties. Changes in these properties may come from transit timing variations (TTVs) caused by a second planet in the system (e.g. Steffen et al. 2013), or by long-term orbital expansion or decay, due to stellar mass loss or tidal inspiral (e.g. Mustill & Villaver 2012). In particular, historical data let us constrain the tidal quality factor of exoplanet hosts, allowing us to model tidal effects from stars more generally (e.g. Penev et al. 2012).

Few historical observations have sufficient sensitivity or cadence to detect exoplanets. Photometric accuracy of better than $\sim$0.01 mag is generally required, while duty cycles of transits are typically only a few per cent of the orbit, so dozens of repeated visits are necessary to secure a transit. Of the literature data available, only the *Hipparcos* satellite (Perryman & ESA 1997; van Leeuwen 2007) has sufficient accuracy and cadence to reliably search for exoplanets *en masse*. *Hipparcos* operated between 1989 and 1993, and returned broad-band photometry to an accuracy of a few millimagnitudes on around 120 000 nearby stars. Transits of HD 209458b and HD 189733b have had their *Hipparcos* photometry published already (Robichon & Arenou 2000; Hébrard & Lecavelier Des Etangs 2006). In this article, we search for transits of other known exoplanets in the original *Hipparcos* data.[1]

2 TRANSITING EXOPLANETS IN THE *HIPPARCOS* DATA SET

Exoplanets in the *Hipparcos* data set were selected from the Exoplanets Data Explorer (EDE;[2] Han et al. 2014), using the parameters ‘`TRANSIT == 1 && HIPP > 0`’. This returned 17 unique systems. We further restricted our criteria to a transit depth >5 mmag (`DEPTH > 0.005`), returning the 11 systems listed in Table 1.

For HAT-P-56 and HD 189733, outliers in the *Hipparcos* data were removed using a $\kappa\sigma$-clipping routine: i.e. an iterative pass of the data was performed, removing points more than κ standard deviations from the mean. A cutoff of $\kappa = 3.5$ was applied, which was chosen so as not to remove points in the expected transit regions. As stars have between 54 and 187 data points, any choice of $\kappa \gtrsim 2.7$ is not expected to remove valid data from the fit.

The photometric data were folded on literature orbit ephemerides (Table 1). Four transiting planets were expected to be detected (>1σ): WASP-18b, WASP-33b, HD 189733b, and HD 209458b, and all four were recovered. Transits of KELT-2Ab were not recovered due to the low signal-to-noise ratio. Transits of HAT-P-56b and HAT-P-2b were expected just below the 1σ detection limit, and measurements of the recovered transit depth are close to the 1σ limit. Since this measurement effectively uses a boxcar transit, and since the *Hipparcos* photometric transmission curve is relatively blue ($\lambda_{\rm eff} \approx 5275$ Å), a limb-darkened model is expected to recover these transits at just above 1σ. However, since the photometry would

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[1] VizieR catalogue I/311.

[2] http://exoplanets.org

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Table 1. *Hipparcos* stars exhibiting transits of >5 mmag.

Name	HIP	d	T_0 (TJD)	P	T_{14}	Depth	*Hip.* rms	N	Expected detection	Observed depth	
		(pc)	(d)	(d)	(d)	(mmag)	(mmag)		(σ)	(σ)	(mmag)
WASP-18b	7562	126 ± 5	4644.905 31	0.941 452 99	0.090 89	9.16	18.8	9	1.38	2.81	14.6
WASP-33b	11 397	118 ± 3	4163.223 73	1.219 869 75	0.112 24	11.36	12.9	15	3.29	3.12	10.8
HD 17156b	13 192	79.8 ± 1.6	4756.7313	21.216 63	0.1338	5.29	19.0	0	0.00	...	...
KELT-7b	24 323	138 ± 5	6223.9592	2.734 7749	0.146 30	8.28	16.7	0	0.00	...	...
KELT-2Ab	29 301	134 ± 6	5974.603 35	4.113 791	0.2155	5.21	21.0	2	0.25	–0.79	–16.6
HAT-P-56b	32 209	319 ± 23	6553.616 45	2.790 8327	0.094 63	11.11	15.1	6	0.74	0.83	12.5
HD 80606b	45 982	65.2 ± 1.1	4876.344	111.436 70	0.504	11.17	16.7	0	0.00	...	...
GJ 436b	57 087	10.1 ± 0.2	4415.620 74	2.643 850	0.031 70	6.96	75.0	0	0.00	...	...
HAT-P-2b	80 076	129 ± 4	4397.493 75	5.633 4729	0.1787	5.22	19.7	9	0.75	0.94	6.6
HD 189733b	98 505	19.8 ± 0.1	4279.436 71	2.218 575 67	0.0760	24.12	15.1	4	2.76	3.73	32.6
HD 209458b	108 859	48.9 ± 0.5	2826.628 51	3.524 748 59	0.1277	14.61	14.8	5	1.97	3.56	26.4

Notes: Distances come from *Gaia* Data Release 1 (Gaia Collaboration 2016), with the exception of GJ 436, which comes from van Leeuwen (2007). Transit parameters are sourced from the EDE [values for WASP-18 b and WASP-33 b explicitly come from Wilkins et al. (2017) and Zhang et al. (2017)]; truncated Julian dates are given as TJD = JD − 2450 000 d. N is the number of observations expected during transit.

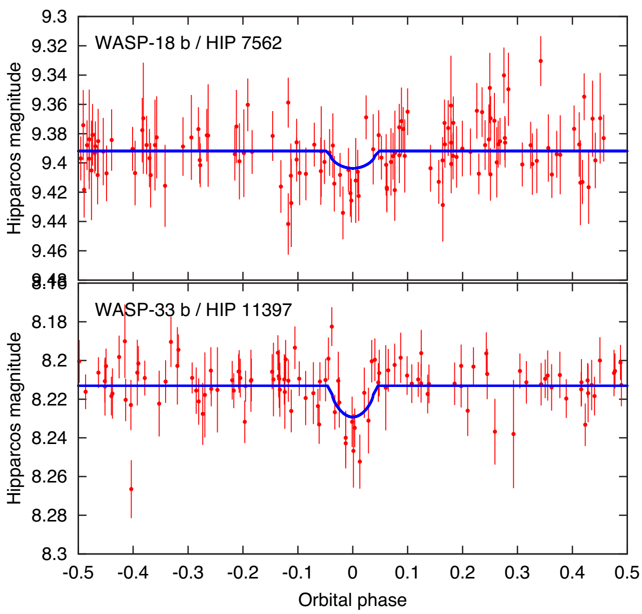

Figure 1. *Hipparcos* photometry, phase-folded on a modern ephemeris. Lines show the expected transit position, width, and depth.

be of insufficient quality to model further, they are neglected for the remainder of this paper.

WASP-18 b and WASP-33 b have never previously been recovered from *Hipparcos* data. Their light curves are shown in Fig. 1, folded on the empherides from Table 1. Data sampling is sparse: 132 points over 1190 d for WASP-18b and 113 points over 930 d for WASP-33b (one point has been cleaned by $\kappa\sigma$-clipping from the latter). Consequently, a blind search for planets in the *Hipparcos* data would have been liable to miss these transits, which are not apparent in the unfolded light curves.

3 ORBITAL SOLUTIONS AND EVOLUTION

As in previous analyses of *Hipparcos* photometry (Robichon & Arenou 2000; Hébrard & Lecavelier Des Etangs 2006), we note that fitting a two-parameter ephemeris (mid-transit epoch and period, T_0 and P) to data of this quality is less accurate than taking an established ephemeris and providing a refined period. In each case, T_0, t_{14}, and R_p/R_* were held fixed to the values in Table 1, and the *Hipparcos* data were folded on a range of periods spanning 0.000 015 d either side of these ephemerides.

The transit was represented by a trapezoid ingress and egress, based on the above parameters. The impact of including limb darkening on the precision of the resulting fit was found to be significant, but the exact treatment of limb darkening was not. Hence, the transit between second and third contact was modelled as a point source crossing a limb-darkened star, with limb-darkening coefficients taken from JKTLD (Southworth 2008): inputs of $T_{\rm eff} = 6400$ and 7430 K, $\log(g) = 4.367$ and 4.300 dex and [Fe/H] = 0.0 and 0.1 dex were assumed for WASP-18 and WASP-33, respectively, while a microturbulent velocity of 2 km s^{-1} and a quadratic law with Claret (2004) models was assumed for both, and the *Hipparcos* filter was approximated by Sloan g'. A χ^2 minimization performed to identify allowed periods for the *Hipparcos* data. The reduced χ^2 minimum is close to unity in both cases (Fig. 2), so the periods where $\chi^2 \le \chi^2_{\rm min} + 1$ can be used to approximate the period uncertainty. The differences between light curves with transiting planets and flat light curves are $\Delta\chi^2 = 12$ and 16 for WASP-18b and WASP-33b, respectively, so the transits are detected with clear significance. The fitted periods and corresponding mid-transit times for this two-epoch fit are

(i) $P = 0.941\,454\,55\,^{+0.000\,000\,87}_{-0.000\,001\,32}$ d, and
(ii) $T_0 = 2448\,436.2359\,^{+0.0125}_{-0.0082}$

for WASP-18 b and

(i) $P = 1.219\,869\,98\,^{+0.000\,000\,79}_{-0.000\,000\,57}$ d, and
(ii) $T_0 = 2448\,472.5334\,^{+0.0040}_{-0.0055}$

for WASP-33 b.

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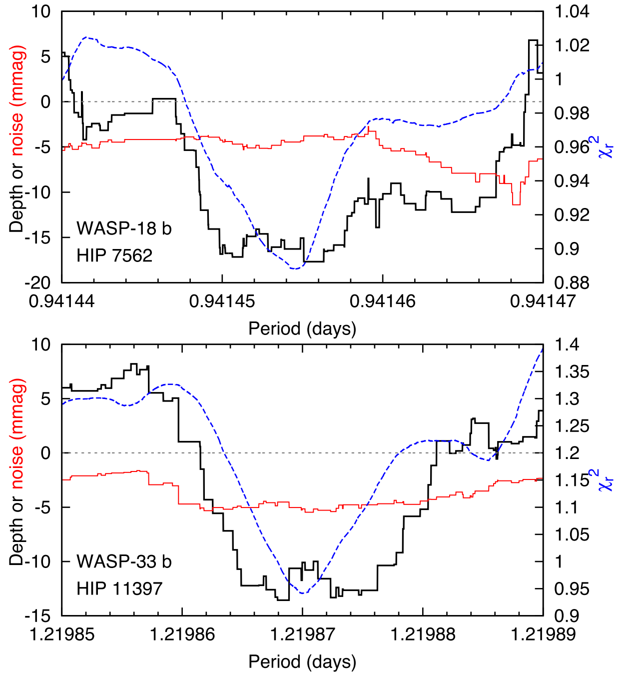

Figure 2. Goodness-of-fit of *Hipparcos*-derived periods. Dark, black lines show the mean transit depth (across t_{14}) at that period; thin, red lines show the out-of-transit noise level. Dashed, blue lines show the reduced χ^2 using the limb-darkened model (right axis).

These mid-transit times represent observations taken 16 yr (6145 and 4665 orbits) before those in the discovery papers of each planet (Hellier et al. 2009; Collier Cameron et al. 2010), and more than double the length of their observational record to 24 and 23 yr, respectively. To these transit times, we added the literature transit photometry collated for both WASP-18b and WASP-33b [Wilkins et al. (2017) and Zhang et al. (2017), respectively], and created $O-C$ diagrams for each planet (Fig. 3).

Unfortunately, the low cadence of the *Hipparcos* compared to modern data means that they do not provide constraints greatly better than those available in the current literature (Turner et al. 2016; Wilkins et al. 2017; Zhang et al. 2017).

To fit the orbits, we ran two-parameter (T_0, P) and three-parameter (T_0, P, $\delta P/P$) Monte Carlo χ^2 fits to the observed mid-transit times. A two-parameter fit for this entire data set formally provides

(i) $P = 0.941\,452\,67 \pm 0.000\,000\,11$ d,
(ii) $T_0 = 2457\,319.801\,97 \pm 0.000\,21$, and
(iii) $\chi^2_r = 5.14$

for WASP-18 b and

(i) $P = 1.219\;870\;61 \pm 0.000\,000\,15$ d,
(ii) $T_0 = 2456\,934.770\,20 \pm 0.000\,10$, and
(iii) $\chi^2_r = 2.50$

for WASP-33b. These fits are shown in the $O-C$ diagrams in Fig. 3. A three-parameter fit formally provides

(i) $\delta P/P = -6 \pm 2 \times 10^{-10}$,
(ii) $P = 0.941\,451\,86 \pm 0.000\,000\,23$ d,
(iii) $T_0 = 2457\,319.801\,67 \pm 0.000\,26$, and
(iv) $\chi^2_r = 4.64$

for WASP-18b and

(i) $\delta P/P = 2 \pm 3 \times 10^{-10}$,

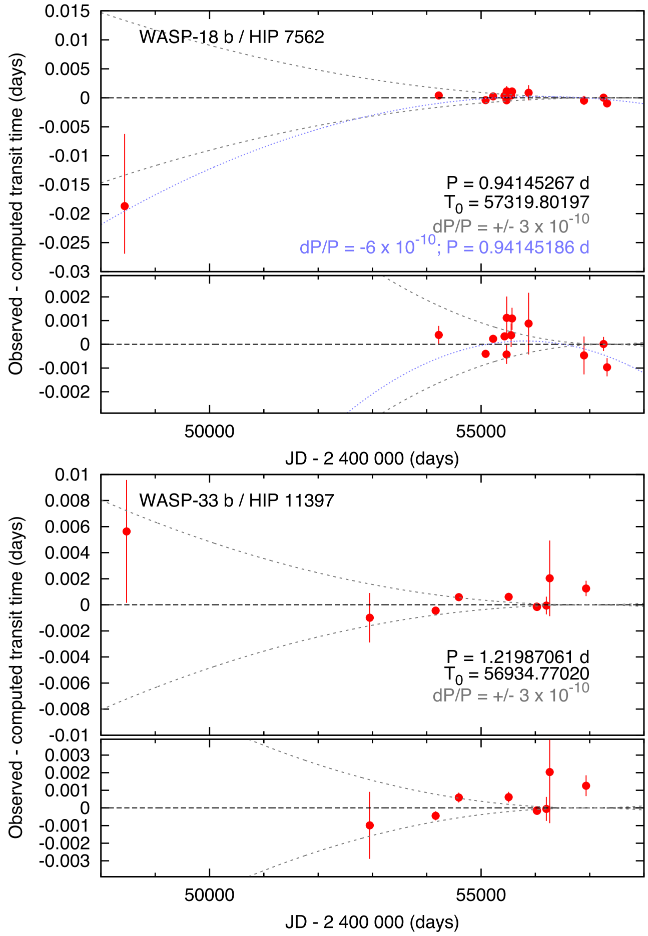

Figure 3. $O-C$ diagrams for WASP-18b and WASP-33b, modelled against the best-fitting ephemeris. Curves show models with period changes (dP/P), as indicated on each plot.

(ii) $P = 1.219\,870\,93 \pm 0.000\,000\,50$ d,
(iii) $T_0 = 2\,456\,934.770\,90 \pm 0.000\,17$, and
(iv) $\chi^2_r = 2.78$

for WASP-33b. The fit for WASP-18b is shown as the dotted line in Fig. 3.

4 DISCUSSION AND CONCLUSIONS

The reduced χ^2 minimum of these fits is substantially greater than unity: in both bodies, an unmodelled scatter of around 0.001 d (1.44 min) is seen in the $O-C$ diagrams. This suggests that the errors quoted above are likely to be underestimates, either due to physical or unmodelled instrumental sources (cf. Adams et al. 2010; Barros et al. 2013). It also implies that either the photometric uncertainties on the input data are underestimated, or that an undetected third body in the system is causing TTVs.

We used TTVFASTER (Agol & Deck 2016) to model a third-body TTV signal to the data, assuming a circular orbit, co-planar to the relevant planet. Unfortunately, the only ranges of parameters that can produce a sufficiently strong signal ($\Delta T_{\rm TTV} \gtrsim 0.0005$ d) are of dynamically unstable systems, or those where a companion would be spectroscopically detectable (e.g. a 0.25 $M_\odot$ star in a 5.7-d orbit). Unless cyclical variation of the planets' orbits are being driven by tidal interaction with their host stars, it appears that the uncertainties

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on the published transit times have been underestimated in several cases, which could be due in part to microvariability on the host stars (von Essen et al. 2014).

Given these underestimated uncertainties, and the possibility of other physical sources of TTV, the significance of the orbital change of either exoplanet cannot be precisely computed. Taking only the *Hipparcos* data at face value, we have a $\sim 1.0\sigma$ measurement of orbital expansion in WASP-33b, and a $\sim 1.3\sigma$ measurement of orbital decay in WASP-18 b, depending on the exact period adopted. These are not significant detections.

Strong orbital decay is not expected for these planets, as their host stars are relatively warm and have thin convective envelopes in which tides can be generated. The tidal quality factors for these stars are expected to be $Q^{'} \sim 10^8$ (Barker & Ogilvie 2009). Due to its spin–orbit misalignment (Collier Cameron et al. 2010), non-radial changes to the orbit of WASP-33 may also be expected (Iorio 2011; Lin & Ogilvie 2017), causing more complex TTV signals over long periods.

Using equations 4 and 5 of Wilkins et al. (2017), $\delta P/P \sim -6 \times 10^{-10}$ implies $Q^{'} \sim 5 \times 10^5$ for WASP-18. This is a much smaller value than nominally expected (cf. Collier Cameron & Jardine 2018; Penev et al. 2018), but similar to that proposed for WASP-12 b by Maciejewski et al. (2016). However, it also implies a survival time of $<10^6$ yr, thus the mere observable presence of WASP-18 b means this value of $\delta P/P$ is likely to be erroneously high. For WASP-33, $\delta P/P < -1 \times 10^{-10}$ implies $Q^{'} > 2 \times 10^5$, which is not very limiting, but interesting given the visible tides the planet generates on its star (von Essen et al. 2014).

A significant uncertainty driving the difference between the two- and three-parameter fits for WASP-18b is the period in the current epoch, which differs by $\sim 8 \times 10^{-7}$ d. A few high-precision measurements of transit times in the current epoch could greatly constrain these uncertainties, determining whether the offset of the *Hipparcos* data point in the $O-C$ diagram is significant. We therefore strongly encourage monitoring of WASP-18b, to more accurately determine its orbital period in the present epoch.

ACKNOWLEDGEMENTS

The authors acknowledge support from the UK Science and Technology Facility Council under grant ST/P000649/1.

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