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NEW MID-TRANSIT TIMES FOR HAT-P-36b, TrES-3b, AND WASP-43b†

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Photometric follow-up observations of exoplanetary transits allow one to refine transit ephemeris and to search for any deviations of mid-transit times from a strictly periodic case. Those so called transit timing variations (TTV) could result from gravitational interaction with unseen, even very low mass planetary companions (see e.g. Ballard et al. 2011). In 2009, we started observing campaigns for selected transiting planets to search for TTV signals (Maciejewski et al. 2011). A number of transit light curves have been acquired for backup targets as a by-product of our project.[1] In this research note, we report on new mid-transit times for transiting planets HAT-P-36 b, TrES-3 b, and WASP-43 b. Our new data extend the timespan covered by observations of these exoplanets, and allow us to refine their transit ephemerides.

Observations were gathered with the following instruments: a 0.4-m Schmidt-Cassegrain Meade LX200 GPS telescope coupled with an Apogee ALTA-U47 CCD camera (1024×1024 pixels, FoV: $11' \times 11'$) at the Ankara University Observatory (Turkey), the 0.6-m Cassegrain telescope and an SBIG STL-1001 CCD (1024×1024 pixels, FoV: $11\rlap{.}'8 \times 11\rlap{.}'8$) at the Centre for Astronomy of the Nicolaus Copernicus University (Toruń, Poland), and the 2.2-m telescope with the Calar Alto Faint Object Spectrograph (CAFOS) in its imaging mode (2048×2048 pixels, FoV windowed to $10\rlap{.}'4 \times 4\rlap{.}'8$) at the Calar Alto Observatory (Spain). Basic information on observations is summarized in Table 1. To increase effective efficiency of the 0.6-m telescope and to decrease timing errors, observations were performed in so-called clear filter, i.e. without any filter. We assumed that the instrumental response can be approximated by the quantum efficiency of the CCD matrix with a maximum between V and R bands.

Standard procedures including debiasing, dark correction, and flat-fielding using sky flats were employed in data reduction. Magnitudes were obtained with differential aperture photometry with respect to the comparison stars available in each field of view. The

†Partly based on observations made at the Centro Astronómico Hispano Alemán (CAHA), operated jointly by the Max-Planck-Institut für Astronomie and the Instituto de Astrofísica de Andalucía (CSIC).

[1] http://ttv.astri.umk.pl

`jktebop` code (Southworth et al. 2004a, 2004b) was used to detrend the light curves by fitting a second-order polynomial function of time along with a trial transit model, based on parameters taken from the literature. The best-fitting trend was subtracted from each light curve. Magnitudes were transformed into fluxes and normalised to unity outside of the transit. The timestamps were converted to barycentric Julian dates in barycentric dynamical time (BJD_{TDB}, Eastman et al. 2010). To quantify the quality of each light curve, we used the photometric noise rate (pnr) defined as

$$pnr = \frac{rms}{\sqrt{\Gamma}} \tag{1}$$

where the root mean square of the residuals, rms, is calculated from the light curve and a fitted model, and Γ is the median number of exposures per minute (Fulton et al. 2011). The individual light curves are plotted in Fig. 1.

Table 1. List of observed transits.

Date	Telescope	Filter	pnr (mmag)	Epoch	T_0 (BJD_{TDB}) +2450000	O–C (d)
			HAT-P-36b			
2013 Mar 14	0.6-m Toruń	clear	3.8	603	$6365.5280^{+0.0025}_{-0.0020}$	+0.0005
2013 Apr 14	0.6-m Toruń	clear	2.9	627	$6397.3817^{+0.0021}_{-0.0015}$	−0.0003
			TrES-3b			
2009 Aug 05	0.4-m Ankara	R	3.8	391	$5049.2985^{+0.0015}_{-0.0015}$	−0.0017
2010 Apr 10	0.4-m Ankara	R	4.9	581	$5297.4778^{+0.0008}_{-0.0008}$	+0.0022
2010 May 11	0.4-m Ankara	R	4.0	604	$5327.5172^{+0.0008}_{-0.0008}$	−0.0006
2010 Jun 17	0.4-m Ankara	R	5.3	633	$5365.3965^{+0.0012}_{-0.0011}$	−0.0008
2013 Mar 17	0.6-m Toruń	clear	2.5	1401	$6368.54705^{+0.00061}_{-0.00063}$	−0.00089
			WASP-43b			
2012 Feb 13	2.2-m Calar Alto	R	1.6	543	$5970.58532^{+0.00049}_{-0.00056}$	−0.00062
2013 Mar 16	0.6-m Toruń	clear	3.8	1032	$6368.3745^{+0.0009}_{-0.0010}$	−0.0013

The mid-transit times were determined by modelling the light curves with the `Transit Analysis Package`[2] (`TAP`, Gazak et al. 2012). The best-fitting parameters, based on the transit model of Mandel & Agol (2002), were determined with the Markov Chain Monte Carlo (MCMC) method, employing the Metropolis-Hastings algorithm and a Gibbs sampler. The conservative uncertainties were estimated including time-correlated noise which is characterised with the wavelet-based technique of Carter & Winn (2009). A quadratic law was used to characterise limb darkening of stellar disks. The theoretical coefficients were linearly interpolated from tables of Claret & Bloemen (2011) with the `EXOFAST` applet[3] (Eastman et al. 2013) for stellar parameters taken from the The Extrasolar Planets Encyclopaedia.[4] For data collected in clear filter, values of coefficients were calculated as an average of those for V and R bands.

In the fitting procedure, relative semi-major axis, relative planet radius, and mid-transit time allowed to vary for individual light curves. We also kept the flux slope and intercept free to account for their uncertainties in the total error budget of the fit. The orbital inclination and orbital period were fixed at the literature values. The limb darkening coefficients were fixed at the theoretical values. Ten chains of a length of 10^5 steps for each light curve were used in the MCMC procedure to obtain final posterior probability

[2]http://ifa.hawaii.edu/users/zgazak/IfA/TAP.html
[3]http://astroutils.astronomy.ohio-state.edu/exofast/limbdark.shtml
[4]http://exoplanet.eu

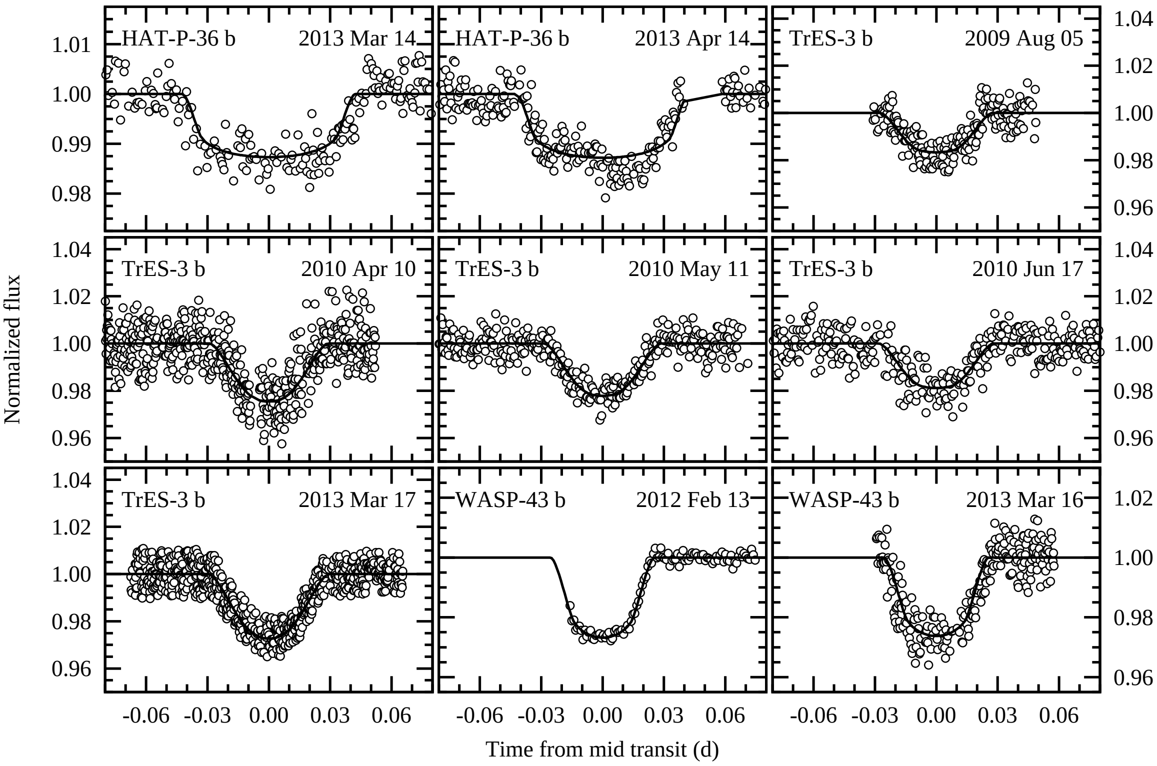

Figure 1. Transit light curves for HAT-P-36b, TrES-3b, and WASP-43b. The continuous lines show the best fitting transit models.

distributions. The first 10% of the links in each chain were discarded before calculating the best-fitting parameter values and their uncertainties. They were determined by taking the median value of marginalised posterior probability distributions. The upper and lower $1\,\sigma$ uncertainties were determined as 15.9 and 84.1 percentile values of the cumulative distributions. The new mid-transit times, which are listed in Table 1, were combined with the literature determinations, and transit ephemerides were redetermined by linear fits, weighted by individual timing errors. Figure 2 shows the O–C (observed minus calculated) diagrams for transit timing of investigated planets.

The transiting planet HAT-P-36 b was discovered by Bakos et al. (2012), and no follow-up observations have been carried out to date. The refined transit ephemeris is:

$$\begin{array}{ll} T_{\rm mid}({\rm BJD_{TDB}}) = 2455565.18221 + 1\overset{\rm d}{.}3272729 \times E, \\ \qquad\qquad\qquad\qquad \pm 0.00006 \pm 0.0000008 \end{array} \quad (2)$$

where E is a transit number starting from the initial epoch given by Bakos et al. (2012). The precision of the time of the initial epoch has been improved by a factor of 3.3, and the precision of the orbital period has been increased by a factor of 3.8, as compared to values reported by Bakos et al. (2012).

The TrES-3 planetary system was discovered by O'Donovan et al. (2007), and has become a subject of numerous follow-up studies. We refer to a recent paper by Vaňko et al. (2013) for a detailed review. Those authors report new transit observations and reanalise all available transit light curves in a homogeneous way. We used their determinations

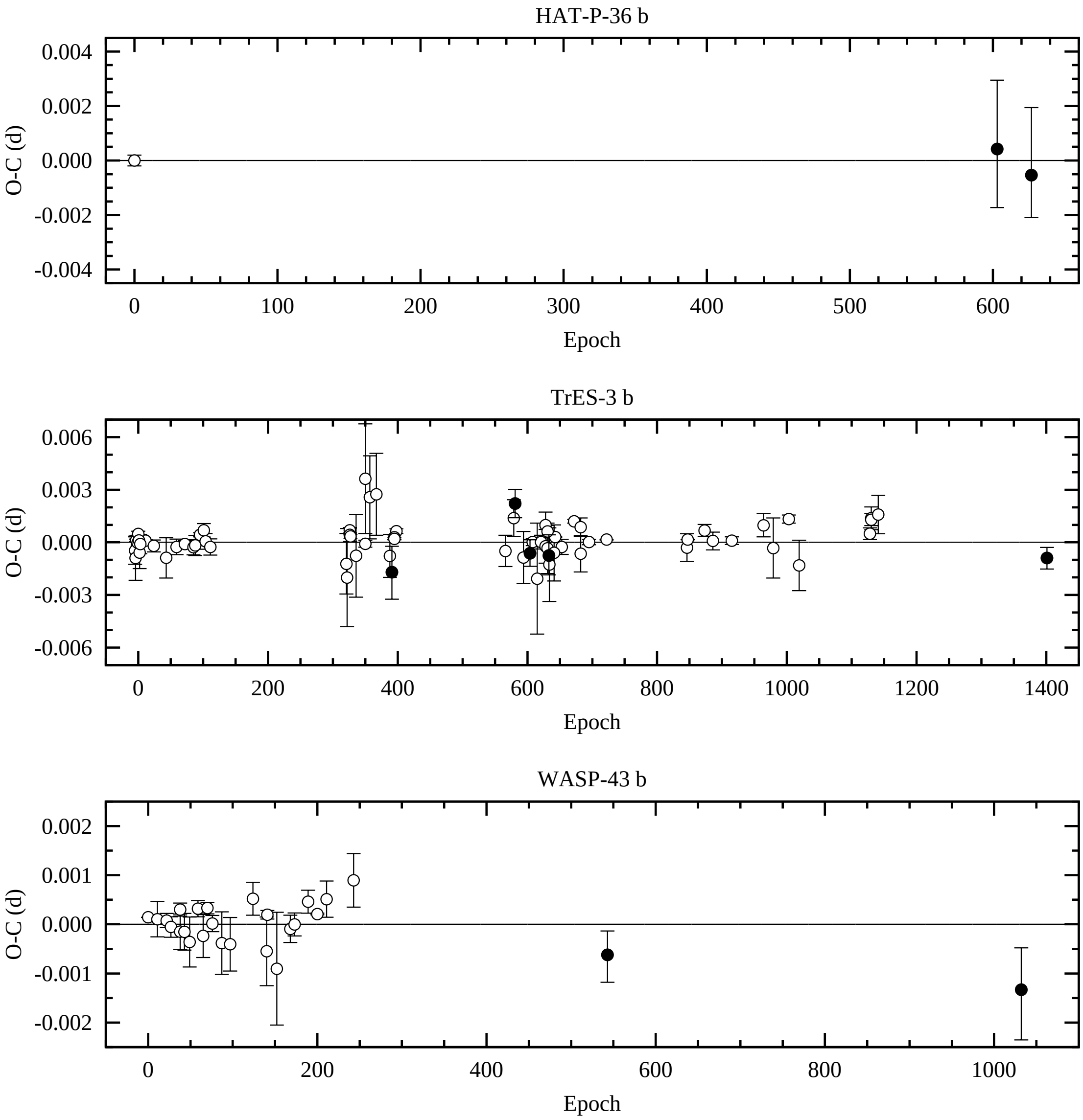

Figure 2. O–C diagram for transit timing of HAT-P-36b, TrES-3b, and WASP-43b. Open symbols denote literature data, and the filled circled mark mid-transit times reported in this work.

together with our new mid-transit times to refine the transit ephemeris:

$$\begin{aligned} T_{\rm mid}({\rm BJD_{TDB}}) = 2454538.58158 + 1\overset{\rm d}{.}30618584 \times E. \\ \pm 0.00011 \pm 0.00000023 \end{aligned} \quad (3)$$

Transit numbering is from initial epoch given by Christiansen et al. (2011). Our new ephemeris agrees within error bars with values reported by Vaňko et al. (2013).

The WASP-43b planet belongs to a population of planetary companions on orbits with periods shorter than 1 day. It was discovered by Hellier et al. (2011). Gillon et al. (2012) redetermined system parameters, based on 23 high quality transit light curves. Our new mid-transit times extend the time span covered by observations by a factor of 4, and results in the refined ephemeris:

$$\begin{aligned} T_{\rm mid}({\rm BJD_{TDB}}) = 2455528.86839 + 0\overset{\rm d}{.}8134762 \times E. \\ \pm 0.00012 \pm 0.0000009 \end{aligned} \quad (4)$$

The transit numbering starts from the epoch given by Hellier et al. (2011). Our new observations indicate that the orbital period is shorter than the value reported by Gillon et al. (2012) by 0.13 s.

New mid-transit times reported in this work were found to be consistent with linear ephemerides within 1–2σ, so there is no sign of TTVs for any planet.

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