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A multi-site campaign to detect the transit of the second planet in HAT-P-13*

(Research Note)

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ABSTRACT

Aims. A possible transit of HAT-P-13c had been predicted to occur on 2010 April 28. Here we report on the results of our multi-site campaign organised to detect the event.
Methods. CCD photometric observations were carried out at five observatories in five countries. We reached 30% time coverage in a 5-day interval centered on the suspected transit of HAT-P-13c. Two transits of HAT-P-13b were also observed.
Results. No transit of HAT-P-13c was detected during the campaign. By a numerical experiment with 10^5 model systems, we conclude that HAT-P-13c is not a transiting exoplanet with a significance level from 65% to 72%, depending on the planet parameters and the prior assumptions. We present two times of transit of HAT-P-13b ocurring at BJD 2 455 141.5522 ± 0.0010 and BJD 2 455 249.4508 ± 0.0020. The TTV of HAT-P-13b is consistent with zero within 0.001 days. The refined orbital period of HAT-P-13b is 2.916293 ± 0.000010 days.

Key words. planetary systems – stars: individual: HAT-P-13

1. Introduction

Multiple planetary systems analogous to our Solar System play a key role in understanding planet formation and evolution. If planets in multiple systems display transits as well (e.g. Kepler-9, Holman et al. 2010), a very detailed analysis becomes possible, resulting in a set of dynamical parameters and even the internal density distribution of the planets (Batyigin et al. 2009). As write, three multiple systems with a transiting component have been discovered. The CoRoT-7 system has two orbiting super-Earths, one showing transits (Léger et al. 2009; Queloz et al. 2009); HAT-P-7 hosts a hot Jupiter in a polar or retrograde orbit and a long-period companion that may either be a planet or a star (Pál et al. 2008; Winn et al. 2009). But the most prominent example of such systems is HAT-P-13 (Bakos et al. 2009; Winn et al. 2010). The central star of this system is a G4 dwarf of 1.22 $M_\odot$ mass and 1.56 $R_\odot$ radius. HAT-P-13b is a 0.85 M_J hot Jupiter on a 2.9 day orbit that has almost been circularized. HAT-P-13c has a minimum mass of $M \sin i = 15.2\ M_J$ in a 428-day orbit with an eccentricity of 0.69. Winn et al. (2010) predicted a possible transit for the second planet, which, if confirmed, would make HAT-P-13 an extremely special system.

In multiple planetary systems, the most important question is whether the orbital planes are aligned. If this is the case for HAT-P-13 b and c, the exact mass of companion c can be derived. The Δi mutual inclination may be derived from the transit timing variations (TTV), of HAT-P-13b (Bakos et al. 2009). A more stringent constraint on coplanarity would be delivered if HAT-P-13c also transits. In this case, the coplanarity is highly probable, and the radius and the orbit of planet c can be measured. If the apsides are also aligned, tidal dynamics can reveal planet b's internal structure, which is a fascinating opportunity to extract unique information on an exoplanet (Batygin et al. 2009; Fabricky 2009).

It has been unknown whether HAT-P-13c transits. The dynamical models of Mardling (2010) suggest that the HAT-P-13 system is likely to be close to prograde coplanar or have a mutual inclination between 130° and 135°. She interpreted the system geometry as a result of early chaotic interactions. A hypothetical d companion was invoked at the early stages of evolution that should have escaped later and could explain the vivid scattering history. Her argument for coplanarity is that lower masses are favored for dynamical reasons, although c's high inclination itself favours a large mutual inclination. Winn et al. (2010) points to the observed small stellar obliquity $\psi_{*,b}$ as indirect evidence of orbital alignment: in Mardling's model, after planet d has escaped, $\psi_{*,b}$ oscillates about a mean value of Δi. Thus,

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[*] Photometric data are only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr` (`130.79.128.5`) or via `http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/523/A84`

Table 1. Summary of instruments involved in HAT-P-13 observations.

Code	Telescope	CCD	FoV	Resolution
K60	Konkoly 0.6 Schmidt, Piszkéstető, Hungary	1526 × 1024 KAF	25′× 17′	1.0″/pixel
K100	Konkoly 1.0 RCC, Piszkéstető, Hungary	1340 × 1300 PI VersArray 1300b NTE	7′× 7′	0.32″/pixel
SLN	INAF-OACt 0.91, Fracastoro, Italy	1100 × 1100 KAF1001E	13′× 13′	0.77 ″/pixel
TEN	0.8 RCC Tenagra II, Arizona, USA	1024 × 1024	14.8′× 14.8′	0.81 ″/pixel
LNO	Langkawi 0.5 RCC, Malaysia	1024 × 1024 SBIG 1001E CCD	20′× 20′	1.2 ″/pixel
SLT	Lulin 0.4 RCC, Taiwan	3056 × 3056 Apogee U9000	50.7′× 50.7′	0.99″/pixel

Table 2. Observations during the HAT-P-13c campaign.

Date	K60	TEN	SLT	LNO	SLN
2010–04–22	20:23–22:23 (80)				
04–25	18:40–23:33 (190)	03:01–05:17 (101)	12:17–15:03 (108)		
04–26	18:43–21:27 (134)	04:44–07:01 (100)		14:28–14:56 (34)	
04–27		03:10–05:26 (85)			20:46–23:56 (162)
04–28	18:41–22:53 (139)	05:30–06:52 (61)		13:34–14:55 (23)	20:37–00:08 (116)
04–29	18:45–23:15 (349)	04:55–06:49 (84)		13:42–15:32 (58)	20:53–23:58 (128)
04–30	18:43–23:17 (342)	04:55–06:55 (51)			
05–01	19:21–20:32 (66)	05:39–06:17 (45)	11:48–14:16 (55)	12:42–14:45 (60)	
05–03	19:25–22:50 (252)				

Notes. Telescope codes: K60: Konkoly 60 cm Schmidt, TEN: Tenagra, SLT: Lulin, LNO: Langkawi, SLN: INAF-OACt. Observation windows and the number of photometry points are indicated.

observing small value for $\psi_{*,b}$ at any time, such as now, is unlikely unless Δi is small.

The refined orbital elements suggested that the transit – if it happened – should have occurred around 2010 April 28, 17 UT, (JD 2 455 315.2) with 1.9 days *FWHM* of transit probability and a maximal duration of 14.9 h (Winn 2010). We started monitoring of HAT-P-13 for further transits in November 2009 and organised an international campaign in the 2 weeks surrounding the expected transit of HAT-P-13c.

2. Observations and data reduction

The seasonal visibility of HAT-P-13 is quite unfavorable in April. Hence the longest possible run at mid-northern latitudes may last 3–4 h after twilight with observations ending at high ($X > 2$) airmass. Our data were collected at 5 observing sites with 6 telescopes, and, due to the weather conditions, 30% time coverage was reached. The telescope parameters and the log of the observations is shown in Tables 1 and 2, respectively.

The observing strategy was the same in most observatories: a sequence of RRRVVV was repeated continuously, while Tenagra Observatory measured the first half of the light curve in R, and the second half in V. The integration time was adjusted throught the night to compensate for the air mass variation in an effort to take advantage of the full dynamic range of the camera. The average exposure times were about 65 s and 35 s in the V and R bands, respectively. Each night several bias, dark, and sky flat images were taken for calibration.

Before the multisite campaign, we observed HAT-P-13 on 8 additional nights. Two nights (2009 November 05/06 and 2010 February 21/22) included a transit of HAT-P-13b, the remainder were acquired as out-of-transit observations. In these observations, the K100 telescope was also involved. No transit signal exceeding a depth of 0.005 (3-sigma level) was observed during the following out-of-transit observation runs: 2009–11–05/06, 23:03–03:45 UT (1 RCC), 2010–01–11/12, 01:41–04:29 (1 RCC), 2010–01–14/15, 21:41–23:19 (0.6 Schmidt), 2010–01–16/17, 22:20–03:39 (0.6 Schmidt), 2010–02–21/22, 18:32–02:19 (0.6 Schmidt), 2010–03–18/19, 19:08–00:03 (0.6 Schmidt), 2010–03–18/19, 20:08-23:37 (1 RCC) 2010–03–19/20, 21:38–00:11 (0.6 Schmidt), 2010–03–28/29, 18:30–00:16 (0.6 Schmidt).

Transits of HAT-P-13b were analyzed with an automated image processing and aperture photometry pipeline developed in the GNU-R[1] environment. The flat image was constructed as the median of the normalized flat frames (i.e., each of the acquired images were divided by the mean of their pixel values), and similar procedures were performed for darks and biases. After the standard calibrations, star identification was performed. Comparison stars were selected iteratively to attain the highest signal-to-noise ratio in the light curve. Finally, 3 comparison stars were used in all images (2MASS J08392449+4723225, 2 MASS J08392164+4720500, and 2MASS J08391779+4722238) to ensure the consistency of the entire dataset. The $J - K$ colors of the comparison stars are 0.419, 0.384, and 0.337, quite close to $J - K = 0.353$ of HAT-P-13.

The data were corrected for systematics with the well-known parameter decorrelation technique (e.g. Robinson et al. 1995), in our case applying the specific implementation of the External Parameter Decorrelation (EPD) in constant mode (Bakos et al. 2010). The observed external parameters were the PSF of stellar profiles and the local photometry of the flat-field image at the same X, Y positions as the stars observed. The variation in stellar profile is a known error source which has been involved in most standard reduction pipelines of exoplanet photometry. Taking residuals of flat field correction as error source into account, dividing with the flat field under/overestimates the

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[1] http://www.r-project.org

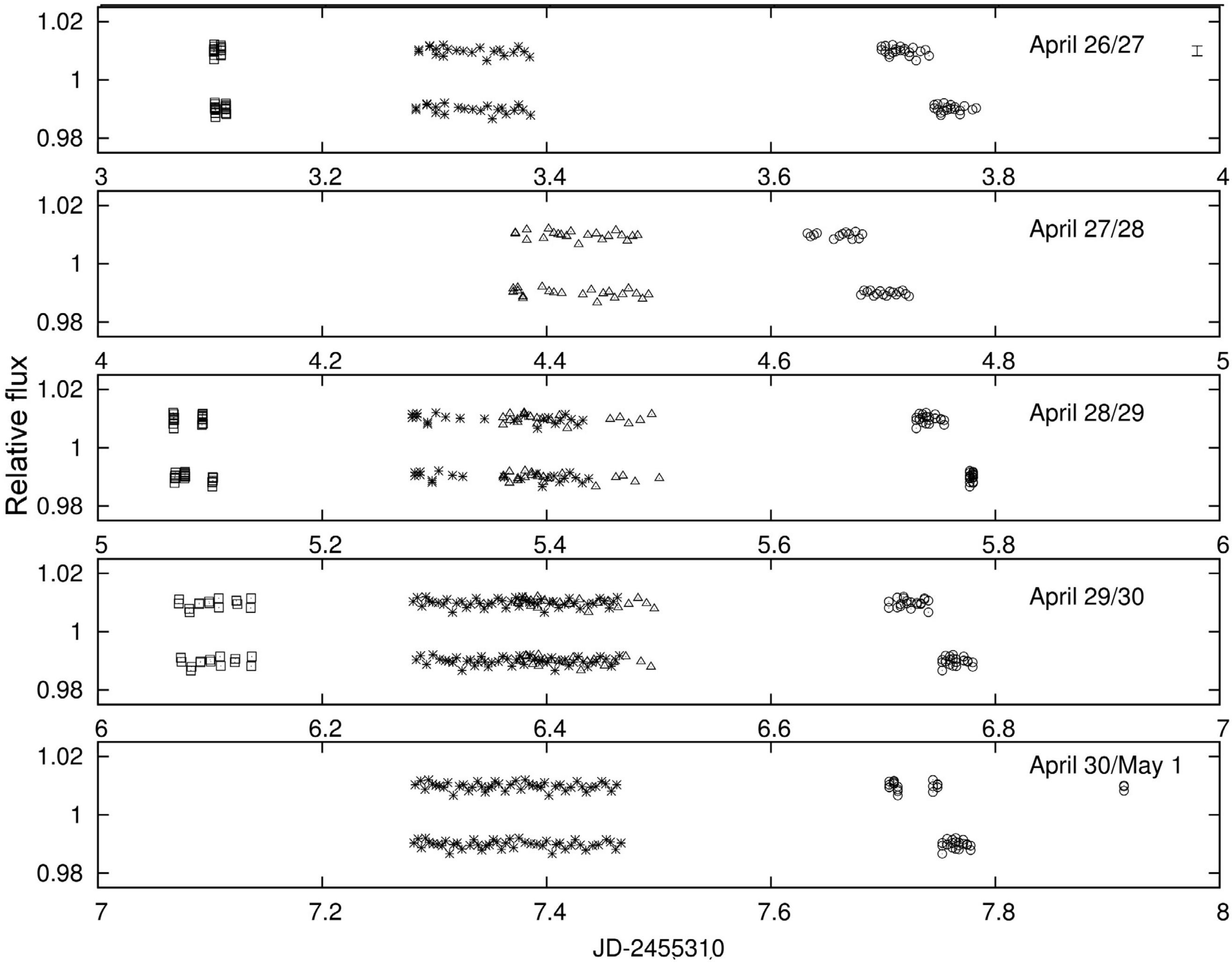

Fig. 1. Observations of HAT-P-13 during April 26–30. Observations have been shifted by +0.01 (V points) and −0.01 (R points) as indicated. Different symbols correspond to the different observatories: square: Langkawi, stars: Konkoly, triangles: INAF-OACt, circle: Tenagra. The typical standard deviation is 0.0013 in R and 0.0014 in V. A ±0.0015 error bar is indicated in the upper right corner of the top panel.

necessary correction by a factor of a few 0.1%. We found that most of the artificial patterns of the light curves is due to systematic residuals of flat field correction and could be eliminated effectively in this way. In the end, 6585 raw photometric points were extracted. We omitted points out of the 5–95% quantile interval of the measured fluxes and averaged the surviving points by 3. This resulted in 1952 data points submitted to further analysis.

3. Results

3.1. Significance analysis of the null detection

In Fig. 1, we plot sample light curves from the multisite campaign. The panels show the combined light curves from April 26, 27, 28, 29, and 30. Neither signs of ingress or egress nor significant deviations from the average brightness were observed. These features strongly imply that all observations are out of transit, and HAT-P-13c is likely to be a non-transiting exoplanet.

What is the significance of this conclusion? The time coverage of our data is 30%. Thus the first answer could be that a transit could happen anytime 70% of the time, i.e. when observations were not performed, and this null result is essentially insignificant. But this conclusion is incorrect and in fact, our observations rule out the majority of transiting orbits for HAT-P-13c.

We performed a numerical experiment to quantitatively measure the significance. A set of 10^5 exoplanets were simulated on a similar orbit to HAT-P-13 (a 428 day period around an 1.22 $R_\odot$, 1.56 $R_\odot$ star). The radius of the planet was assumed to be 1.2 R_J, which is the typical size of the most massive known exoplanets. With this choice, the density of HAT-P-13c is 8.7 times that of the Jupiter. The orbital eccentricity of the model was $e = 0.691$, the argument of periastron was $\omega = 176.7°$, coefficients for quadratic limb darkening were $\gamma_1 = 0.3060$, $\gamma_2 = 0.3229$ (planet and orbit parameters from Bakos et al. 2009). To include grazing transits, the value of the impact parameter b was allowed to be >1 and was drawn from uniform distibution between 0 and 1.08. The transit time followed a uniform distribution in the April 26.5 UT and April 30.5 UT interval. In some possible planet configurations, it is probable that data of a given run could have included only the bottom of the transit. This should be visible as a slight offset from the remaining runs, but this cannot be detected because of non-photometric conditions. What we are sure about is that ingress and egress phases were not detected within

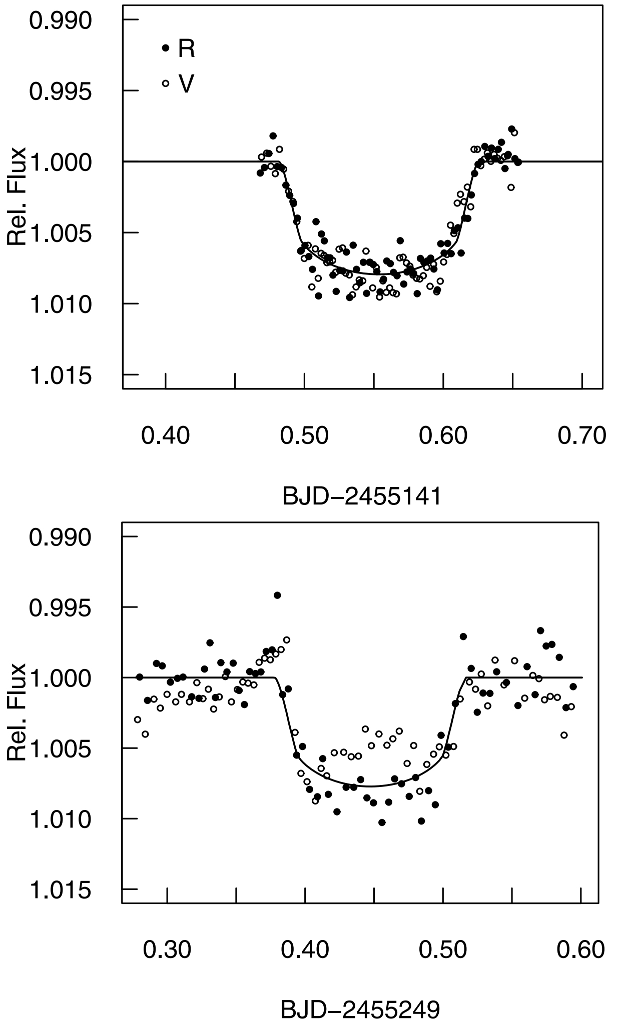

Fig. 2. Model fit to the transit on November 05/06, 2009 (*upper panel*) and February 21/22, 2010 (*lower panel*). V and R band data are plotted with open and soild dots, respectively.

our time coverage. This information also tightly constrains the possible orbits in the transit time–impact parameter space.

Model transit light curves were sampled at the times of observation points (all data in Table 2), sorted to observation runs, and the average intensity level was individually subtracted. We added bootstrap noise to the individual points (the measured light curve errors were randomly added to the simulated values with subtitution). A χ^2 test was then applied to check whether the simulations are inconsistent with zero at the 99% significance level. In this way, we identified these configurations of HATP-P-13c that should have been observed in our measurements (we call these observable configurations in the following). Because our observations are consistent with zero variation, observable configurations are explicitly excluded by our data.

We inferred that 72% of the 10^5 model transit configurations should have been observable. Therefore the hypothesis that HAT-P-13c is a transiting exoplanet can be rejected with 72% confidence. By allowing the mean transit times to be distributed normally around April 28 17 UT with 1.9 day standard deviation, the level of significance turns out to be 70%. The level of significance does not vary significantly in the range of orbits allowed by the parameter uncertainties in Bakos et al (2009), because the errors are rather small (3% in e and 0.3% in ω). We reduced the model light curves in amplitude to define the size limit where the detection efficiency begins to decrease significantly. The resulting significance was 65% when the amplitude was reduced by 0.45. The planet size corresponding to this signal amplitude is 1.04 R_J, which is our detection limit. The conclusion is that roughly three quaters of all possible transiting configurations are excluded by our observations.

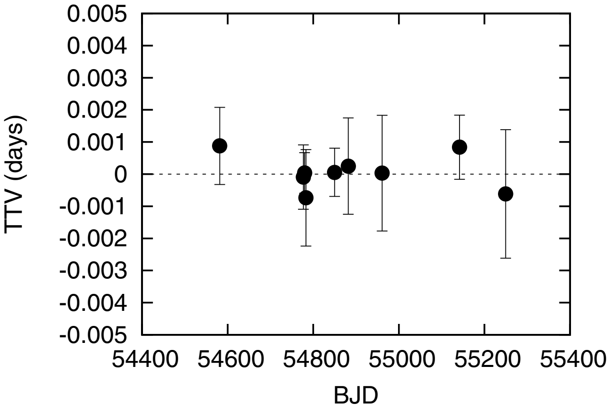

Fig. 3. Transit timing variation of HAT-P-13b.

This result does not mean that HAT-P-13c cannot orbit on an aligned orbit with HAT-P-13b. HAT-P-13c is quite far from the central star, hence the star's apparent diameter is 0.6 degrees as seen from the planet. Thus, transiting configurations require the orbit to be in a thin region, very close to our line of sight. There is a huge set of possible configurations in which HAT-P-13c is in an orbit close to that of planet b, without displaying any transits. In this case, the TTV of HAT-P-13b can help us determine the orientation of HAT-P-13c's orbital plane (Bakos et al. 2009).

3.2. Transit timing variations of HAT-P-13b

Before the suspected transit of HAT-P-13c, two transits of HAT-P-13b had been observed to help refine the period and search for TTV. Data from 2009-11-05/06 (measured with the K100 telescope, Table 1) and 2010 February 21/22 (K60 telescope) are plotted in Fig. 2. In November (upper panel in Fig. 2), the sky was photometric during the transit, but it was foggy in the evening and from 40 min after the egress phase. In February 2010, cirri were present that significantly affected the V band data, but the R light curve was well reconstructed with constant EPD (see lower panel in Fig. 2).

Times of minima were determined by fitting a model light curve, similarly to the method described in Szabó et al. (2010). For the November 2009 transit, both V and R data were included in the fitting, while we used only the R curve for the February 2010 transit. (However, even including the more noisy V curve does not change the mid-transit time by more than 0.0004 days.)

To reduce the degrees of freedom in the fit, the shape of the model was not adjusted; we used previously published parameters (Winn et al. 2010). The model light curve was calculated with our transit simulator (Simon et al. 2009, 2010). The model was shifted in time to minimise the rms scatter in the measurements. We determined new transit times of: BJD 2 455 141.5522 ± 0.001 and 2 455 249.4508 ± 0.002. Seven transit times were published by Bakos et al. (2009), which were included in the TTV analysis. After combining all data, we inferred the period of HAT-P-13b to be 2.916293 ± 0.000010 days, while the determined TTV diagram is plotted in Fig. 3. All points are consistent with zero within the error bars. It has to be noted that HAT-P-13b must exhibit some TTV, because of the perturbations by HAT-P-13c. HAT-P-13c causes 8.5 s light-time effect (LITE) and perturbations in the orbit of HAT-P-13b. On short (≈1 yr) timescales, the LITE is dominant. However, the expected LITE is smaller than the ambiguity of our transit times by a factor of 5, and therefore there is no chance of a positive detection at this level of accuracy.

4. Summary

The main results of this study can be summarised as:

- A multisite campaign was organised to observe HAT-P-13 around the expected transit of HAT-P-13c. Two transits of HAT-P-13b were also observed.
- HAT-P-13c was not observed to transit. We have concluded that HAT-P-13c is not a transiting planet with 72% significance.
- Our revised measurement of the period of HAT-P-13b is 2.916293 ± 0.000010 days. Our measured TTV is consistent with zero variation.

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