SOLUTION OF NEWLY OBSERVED TRANSIT OF THE EXOPLANET HAT-P-24B: NO TTV AND TDV SIGNALS *

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Abstract. We present photometric observations of transit of the exoplanet HAT-P-24b using the Rozhen 2 m telescope. Its solution gives relative stellar radius r_s=0.1304 (a/R_s = 7.669), relative planet radius r_p=0.01304 and orbital inclination of 90°. The calculated planet radius is $R_p = 1.316$ R$_J$ and corresponds to planet density of $\rho_p = 0.37$ g cm^{-3}. Our parameter values are between those of the previous two solutions. We did not find evidences of TTV and TDV signals of HAT-P-24b.

Key words: planetary systems – stars: individual (HAT-P-24) – techniques: photometric; individual HAT-P-24b

Introduction

Photometric observations of transiting exoplanets (TEPs) provide accurate relative sizes of their configurations, which are important for understanding their formation and evolution (Charbonneau et al. 2000). The monitoring of transiting exoplanet allows to improve its physical parameters as well as to study existence of other planets in the system by analysis of the transit timing variation (TTV) and transit duration variation (TDV) (Agol et al. 2005; Holman & Murray 2005; Kipping 2009a,b). Moreover, the transits provide a possibility to learn the oblateness of the planets (Seager & Hui 2002; Carter & Winn 2010) and to make thermal mapping of their surfaces (Knutson et al. 2007).

During the last two decades the number of discovered and studied exoplanets rapidly increased as a consequence mostly of automated surveys as SuperWASP (Street et al. 2004), CoRoT (Baglin et al. 2007), HATNet (Bakos et al. 2004), TrES (Alonso et al. 2004), XO (McCullough et al. 2005), KELT (Pepper et al. 2007), OGLE (Udalski et al. 1998) and *Kepler* (Koch et al. 2010). The considerable part of the newly discovered exoplanets are hot Jupiters. These are a class of extrasolar planets whose characteristics are similar to Jupiter, but which have higher surface temperatures because they orbit very close (0.015–0.1 AU) to their parent (F, G and K-type) stars. That is why the probability to observe transits of hot Jupiters is bigger compared to other known types of planets. Morerover, they are the easiest extrasolar planets for confirmation via the radial-velocity method, because the induced oscillations in the star motion are relatively large and rapid. Hot Jupiters are gas giants with low density although there are examples which are denser than Jupiter: WASP-18 (7 times the density of Jupiter,

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* based on NAO Rozhen observations

Southworth et al. 2009) and HAT-P-2 (9 times the density of Jupiter, Pal et al. 2010).

It is supposed that hot Jupiters have migrated to their present positions after their formation at a distance from the star beyond the frost line. The majority of investigations show that they appear to be alone or accompanied by other planetary bodies on wide orbits (Steffen et al. 2012) but the studies of the *Kepler* candidates for hot planets reveal that some of them exhibit periodic variations in transit timing (Szabo et al. 2013). These multiple-planet systems may provide some constraints on planet formation and migration theories (Podlewska & Szuszkiewicz 2009). Moreover, the distribution of planet period ratios shows strange clumping around the low-order resonances (Fabrycky et al. 2014). On the other hand the loneliness of the gas giants is in favor of inward migration theories of massive outer planets through planet-planet scattering caused by mutual dynamical perturbations (Weidenschilling & Marzari 1996; Rasio & Ford 1996). That is why the study of hot Jupiters is important area of the modern astrophysics.

HAT-P-24b was discovered as TEP on the base of HATNet (Hungarian-made Automated Telescope Network) photometric observations and confirmed by Keck spectral observations (Kipping et al. 2010). It orbits the F8V star GSC 0774–01441 (mass of 1.191 $M_\odot$, radius of 1.317 $R_\odot$, effective temperature 6373 K, metallicity of [Fe/H] = –0.16) with a period P = 3.3552464 days on slightly eccentric orbit ($e = 0.052$) with semiaxis $a = 0.04641$ AU (Kipping et al. 2010). HAT-P-24b is classified as an inflated hot Jupiter with a mass of 0.681 M_J and radius of 1.243 R_J (mean density ρ_p = 0.439 g cm^{-3}).

Wang et al. (2013) obtained three complete transit light curves of HAT-P-24b in 2010—2012.They derived slightly bigger orbital period and larger planet radius $R_p = 1.364$ R_J.

We carried out observations and study of HAT-P-24b in order to obtain new transit solution and to search for TTV and/or TDV signal as indications of presence of other bodies in the system.

OBSERVATIONS AND DATA REDUCTION

Our CCD photometric observations in R band were obtained on Feb 18 2015 at the Rozhen Observatory. We used the 2 m RCC telescope equipped with focal reducer FoReRo-2 and the CCD camera VersArray 1300B and (1340 × 1300 pixels, 20 μm/pixel, diameter of field of 15 arcmin). The exposures were 50 s and defocusing was applied. The observations started around 1 h before the expected beginning of the transit and ended around 1 h after the event. The average photometric precision per data point was around 0.0007 mag (the atmospheric conditions during the second half of the night were not perfect).

The standard procedures were used for reduction of the photometric data by MaxImDL. We tested several sets of reduction parameters and chose the set that gave the most precise photometry for the stars of similar brightness or brighter than the target. After carefully selecting of reference stars (Table 1, Fig. 1) we performed differential aperture photometry by MaxImDL. The data were cleaned of trends.
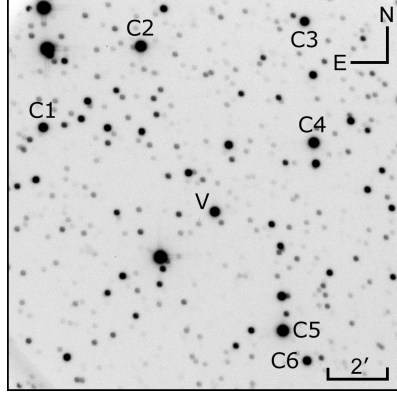
Fig. 1. The field of HAT-P-24b

The depth of the Rozhen transit (Fig. 2) is around 11.86±0.28 mmag.

**Table 1.** Coordinates and magnitudes of the target (V) and comparison (C) stars

Label	Star	RA (2000)	DEC (2000)	R (mag)
V	HAT-P-24 (2MASS J07151801+1415453)	07 15 18.01	+14 15 45.36	11.80
C1	2MASS J07154233+1418402	07 15 42.34	+14 18 40.25	12.30
C2	2MASS J07152847+1421277	07 15 28.47	+14 21 27.74	10.90
C3	2MASS J07150522+1422172	07 15 05.22	+14 22 17.26	12.00
C4	2MASS J07150390+1418079	07 15 03.90	+14 18 17.92	11.10
C5	2MASS J07150839+1411395	07 15 08.40	+14 11 39.53	10.70
C6	2MASS J07150500+1410380	07 15 05.01	+14 10 38.01	12.50

MODEL OF THE OBSERVED TRANSIT

Our observations were modelled using the method of Kjurkchieva et al. (2013) by the code TAC MAKER 1.1.1 (Kjurkchieva et al. 2014). It does not use any simplifications of the configuration (as dark planet, linear planet trajectory on the stellar disk, etc.) and works with arbitrary stellar limb-darkening law and planet temperature. Moreover, the code allows acquisition of the stellar limb-darkening coefficients from the transit solution and comparison with the theoretical values (as those of Claret 2004).

We fixed the stellar temperature $T_s = 6373$ K and used the ephemeris of Kipping et al. (2010). As the first stage of our solution we adopted linear limb-darkening law with limb-darkening coefficient corresponding to the stellar temperature according to the tables of Van Hamme (1993). The adjusted parameters were relative stellar radius $r_s = R_s/a$ (a is the orbital
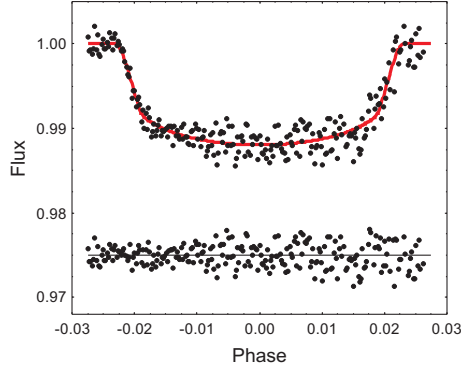
Fig. 2. Top: the Rozhen transit of HAT-P-24b and the synthetic curve corresponding to the best solution; bottom: the residuals of the fit (shifted vertically by 0.975)

radius), relative planet radius $r_p = R_p/a$, orbital inclination i, planet temperature T_p and the transit time $T_c(BJD)$. We varied them around their values from the solution of Kipping et al. (2010) to search for minimum of χ^2 (the sum of squares of the residuals).

Finally we tested different limb-darkening laws varying their coefficients.

The results of our best transit solution corresponding to quadratic limb-darkening law are given in Table 2. The synthetic curve is shown in Fig. 2 as continuous line.

The comparison of our results with the previous solutions of the target (Table 2) allows us to make several conclusions.

(1) The center of our transit is at $T_c(BJD) = 2457072.4281925 \pm 0.000480$. Our value (O − C) = 0.00019 ± 0.000480 d means absence of TTV signal. This result supports the same conclusion of Wang et al. (2013) based on their transits of HAT-P-24b.

(2) Our value of orbital inclination (Table 2) is bigger by around 1.5 % than that of Wang et al. (2013) but the same as that of Kipping et al. (2010, Table 6 last column). This value was necessary to reproduce the depth and shape of the Rozhen transit.

(3) The planet temperature was varied in the reasonable range 0 K – 2500 K. We found absolutely the same best fit quality (corresponding to equal minimum value χ^2_{min}) for planet temperature in the range 0 K – 1100 K. It turned out that the transit solution is very insensitive to the planet temperature: the value of χ^2 for the calculated planet temperature $T_{eq} = 1637$ K (from stellar temperature and planet distance) is only around 1.1×10^{-7} % bigger than χ^2_{min} while the value of χ^2 for the planet temperature 2500 K is around 0.015 % bigger than χ^2_{min}.

(4) The duration of newly-observed transit of 3.672 ± 0.024 hr (220.32 ± 1.47 min) is in the framework of the errors of the value of Kipping et al. (2010) of 3.653 ± 0.025 hr (219.18 ± 1.5 min) and that of Wang et al. (2013) of 3.684 ± 0.053 hr (221.04 ± 3.17 min). Thus, we did not find clear

indication of transit duration variation (TDV). Although the ingress and egress boundaries of hot Jupiters are harder to determine due to the low density of these gas giants, the Rozhen transit has a good time resolution and thus, the temporal quantities should be considered with a confidence.

(5) Our values of the relative stellar radius and relative planet radius are r_s=0.1304±0.0007 and r_p=0.01304±0.00006. Thus, the obtained values of a/R_s and R_p/R_s are in the framework of the errors of the previous solutions (Table 2).

Table 2. Three parameter sets of HAT-P-24b

Parameter	Kipping et al. (2010)	Wang et al. (2013)	this paper
Period, days	3.3552464±0.0000071	3.3552479±0.0000062	3.3552464, fixed
T_0, BJD	2455216.97669 ±0.00024	2455629.67053±0.00034	2455216.97669, fixed
a/R_s	7.70±0.35	7.34±0.35	7.67±0.21
R_p/R_s	0.0970±0.0012	0.10625±0.0126	0.1000±0.0009
i, degrees	90.0±1.9	88.217±0.705	90.0±0.1

(6) Using the known values of a and masses of the system components (Kipping et al. 2010) we calculated R_s=1.322 R⊙, $R_p = 0.1322$ R⊙ $= 1.316$ R_J and correspondingly $\rho_p = 0.37$ g cm^{-3}. Our value of the planet radius of HAT-P-24b is by 5 % bigger than that of Kipping et al. (2010) but almost by 4.5 % smaller than that of Wang et al. (2013).

(7) We found solutions for different limb-darkening laws which have almost the same good quality (Table 3) but the best model (minimum χ^2) corresponded to both quadratic and logarithmic limb-darkening laws with approximately equal limb-darkening coefficients (Table 3). Moreover, the freely varying of the limb-darkening coefficients led us to values appropriate for the stellar temperature of HAT-P-24 while those of Kipping et al. (2010) (linear 0.1858 and quadratic 0.3625) differ considerably from the expected ones.

Table 3. Limb-darkening coefficients u_1 and u_2 of the best fits of the Rozhen transit corresponding to different limb-darkening laws

Limb-darkening law	u_1	u_2	χ^2
linear	0.490±0.005		0.0004484
quadratic	0.47±0.01	0.05±0.01	0.0004477
squared-root	0.48±0.01	0.02±0.01	0.0004482
logarithmic	0.48±0.01	0.02±0.01	0.0004477

Conclusions

We presented data of newly observed transit of HAT-P-24b with a 2 m telescope. Its solution gives system parameters which values are between

those of the previous two solutions. The shape and depth of the new transit favor the maximum orbital inclination of $90°$.

We obtained transit solutions with the same best quality for four different limb-darkening laws. The freely-varied limb-darkening coefficients for these laws turned out almost the same and their values corresponded to the stellar temperature of HAT-P-24.

We found no evidences of TTV and TDV signals. Hence, until now HAT-P-24b has no detectable planetary companions on nearby orbits. This conclusion is in line with the result that the most hot Jupiters are alone or accompanied by other planetary bodies on wide orbits.

Acknowledgments

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