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NEW OBSERVATIONS AND TRANSIT SOLUTIONS OF THE EXOPLANETS HAT-P-54B AND WASP-153B

Diana Kjurkchieva[1], **Nikola Petrov**[2] **and Sunay Ibryamov**[1]

[1] *Department of Physics, Shumen University, 115 Universitetska, 9700 Shumen, Bulgaria*

E–mail: *d.kyurkchieva@shu.bg, s.ibryamov@shu.bg*

[2] *Institute of Astronomy and NAO, Bulgarian Academy of Sciences, Tsarigradsko shossee 72, 1784 Sofia, Bulgaria*

E–mail: *nip.sob@gmail.com*

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SUMMARY: We present photometric observations of the newly-discovered transiting exoplanets HAT-P-54b and WASP-153b with the Rozhen 2 m telescope. As a result we improved their periods. The modeling of the new transits led to almost identical values of orbital inclinations and stellar radii to the first published values while the planet radii were slightly different: that of HAT-P-54b was bigger and that of WASP-153b was smaller. The more bloated nature of WASP-153b is a result of its considerable close orbit and high stellar temperature. Our calculation of the WASP-153 distance is very close to that measured by *GAIA*. The best fits of the newly-observed transits of HAT-P-54b and WASP-153b correspond to the quadratic limb-darkening law of their host stars whose coefficients were determined. Our results confirmed the hot Jupiter nature of the two targets.

Key words. Stars: planetary systems – Techniques: photometric – Stars: individual: HAT-P-54b, WASP-153b

1. INTRODUCTION

The study of transiting extrasolar planets (TEPs) gives a possibility to determine their orbits, physical properties and internal structure. Until recently, these bodies were discovered mainly by wide-field ground-based transit surveys such as HATNet (Bakos et al. 2004), HATSouth (Bakos et al. 2013), WASP (Pollacco et al. 2006), XO (McCullough et al. 2005), TrES (Alonso et al. 2004), and KELT (Pepper et al. 2007). During the last decade the space mission *Kepler* (Borucki et al. 2010) led to discovery of several thousands of new planet candidates.

Most known TEPs have close orbits ($a < 0.1$ AU), which tend to be circular. This fact was interpreted as a signature of tidal circularization (Mazeh 2008) whose time-scale decreases sharply with the orbital distance decrease (Zahn 1975, Eq. 4.7).

The theory predicts the tidal orbital decay of hot Jupiters (Hut 1980, Rasio et al. 1996, Sasselov 2003, Levrard et al. 2009, Hoyer et al. 2016, Wilkins et al. 2017). Moreover, many of these exoplanets turned out larger than predicted by standard cooling theory of giant planets (Cabrera et al. 2010, Hebb et al. 2009). Several hypotheses have been proposed to explain the radius anomaly: tides (Bodenheimer et al. 2001), tides with atmospheric circulation (Guillot and Showman 2002); enhanced opacities (Burrows et al. 2007).

Regular observations of the giant exoplanets are necessary to improve their parameters and ephemerides and to search for explanations of their peculiarities. This was the main goal of our observations of the recently-discovered exoplanets HAT-P-54b and WASP-153b.

2. TARGETS

The giant exoplanet HAT-P-54b transits a late K dwarf star (magV = 13.5) with a subsolar metallicity. Bakos et al. (2015) determined the physical parameters of HAT-P-54b (Table 1). They found that the radius of HAT-P-54b is smaller than 92 % of the known transiting planets with masses greater than that of Saturn, while HAT-P-54 is one of the lowest-mass stars known to host a hot Jupiter. Bakos et al. (2015) estimated the distance to HAT-P-54 as 135.8 ± 3.5 pc using the Dartmouth isochrones (Dotter et al. 2008). The *GAIA* astrometric distance of 144 pc (Bailer-Jones et al. 2018) is very close.

WASP-153b was discovered very recently by Demangeon et al. (2018). Its host star is early G0 type star (with magV∼13) and its orbital period is 3.33 days. Demangeon et al. (2018) determined the parameters of WASP-153b (Table 2) and found that it is a hot gaseous Saturn-size object with low density. The planet exhibits a significant radius anomaly (heavy bloated) that is attributed to a big incident flux (150 times bigger than the Sun flux on the Earth). The planet is at the border of the Neptunian desert (Szabo and Kiss 2011), delineated by lower and upper mass and radius boundaries of the short period Neptunian (Mazeh et al. 2016). Demangeon et al. (2018) estimated the distance to WASP-153b as 430 ± 35 pc while the *GAIA* astrometric distance of 610 pc (Bailer-Jones et al. 2018) is considerably bigger.

Table 1. Parameters of HAT-P-54b: period P (days); epoch T_0 of transit center (HJD 2450000+); orbital semimajor axis a (AU); orbital inclination i (deg); stellar temperature $T_{\rm st}$ (K); stellar mass $M_{\rm st}$ ($M_\odot$); stellar radius $R_{\rm st}$ ($R_\odot$); limb-darkening law (LDL); limb-darkening coefficients (LDC); impact parameter $b = a\cos i/R_{\rm st}$; planet mass $M_{\rm p}$ ($M_{\rm J}$); planet radius $R_{\rm p}$ ($R_{\rm J}$); planet density $\rho_{\rm p}$ ($\rho_{\rm J}$); Safronov number Θ. Mark * means fixed parameter.

Parameter	Bakos et al. 2015	This paper
P	3.799847(14)	3.799847*
T_0	6299.30370(24)	6299.301000(1)
a	0.04117(43)	0.04117*
i	87.04(8)	87.02(1)
$T_{\rm st}$	4390(50)	4390*
$M_{\rm st}$	0.645(20)	0.645*
$R_{\rm st}$	0.617(13)	0.6180(5)
LDL	non-linear	quadr
LDC	?	0.59, 0.19
b	0.7405	0.69998
$M_{\rm p}$	0.760(32)	0.760*
$R_{\rm p}$	0.944(28)	0.987(1)
$\rho_{\rm p}$	0.9034	0.7904(8)
Θ	0.1025(50)	0.0980(1)

Table 2. Parameters of WASP-153b. Designations are the same as in Table 1.

Parameter	Demangeon et al. (2008)	This paper
P	3.332609(2)	3.332609*
T_0	3142.542(3)	3142.540(1)
a	0.048(1)	0.048*
i	84.1(7)	83.88(1)
$T_{\rm st}$	5914(64)	5914*
$M_{\rm st}$	1.336(86)	1.336*
$R_{\rm st}$	1.73(9)	1.721(1)
LDL	quadr	quadr
LDC	0.549(2),0.118(6)	0.486,0.126
b	0.61675	0.63967
$M_{\rm p}$	0.39(2)	0.39*
$R_{\rm p}$	1.55(9)	1.468(1)
$\rho_{\rm p}$	0.1047	0.1231(1)
Θ	-	0.04571(3)

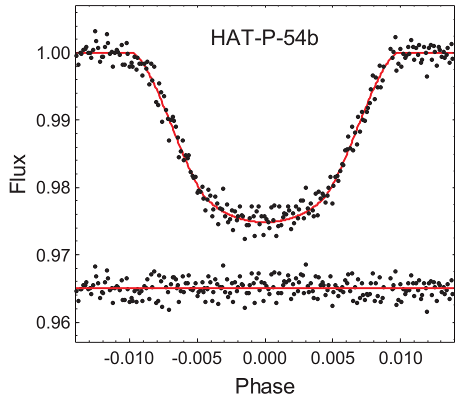

Fig. 1. *Top: the transit of HAT-P-54b and the synthetic curve corresponding to the best solution; bottom: the residuals of the fit. The observational data are accessible in the form of tables (whose samples A1–A2 are shown in Appendix).*

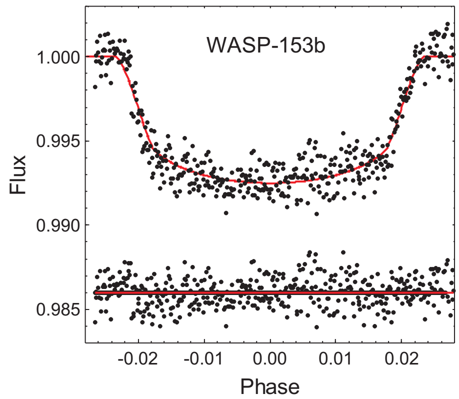

Fig. 2. *The same as in Fig. 1 for WASP-153b.*

3. OBSERVATIONS AND DATA REDUCTION

Table 3 presents the log of our photometric observations at the Rozhen Observatory (target name, dates, exposures, number of frames, photometric precision). We used the 2-m RCC telescope with the CCD camera VersArray 1300B (1340 × 1300 pixels, 20 μm/pixel, diameter of field of 15 arcmin) and R filter. The observations started around 1 h before the expected beginning of the transit and ended around 1 h after the event.

Table 3. Log of our photometric observations.

Target	Date	Exposure [sec]	Number	Error [mag]
HAT-P-54b	2018 Jan 19	20	356	0.002
WASP-153b	2018 Jul 21	30	480	0.004

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 stars of similar brightness or brighter than the target. After careful selection of reference stars (Tables 4-5), we performed the differential aperture photometry. The data were cleaned of trends (Figs. 1–2).

Table 4. Coordinates and R magnitudes of the comparison stars for HAT-P-54b.

Comparison stars	RA (2000)	DEC (2000)	R
NOMAD 1155-0126921	06 39 44.77	+25 32 17.22	12.61
NOMAD 1155-0126971	06 39 49.66	+25 34 41.46	13.60
NOMAD 1155-0126824	06 39 34.56	+25 34 20.18	12.81
NOMAD 1155-0126607	06 39 11.22	+25 32 51.43	13.69
NOMAD 1155-0126856	06 39 37.44	+25 31 06.81	12.85
NOMAD 1155-0126637	06 39 14.16	+25 30 19.84	13.05
NOMAD 1154-0127231	06 40 01.79	+25 27 55.92	13.53
NOMAD 1154-0126855	06 39 21.34	+25 26 04.14	13.22
NOMAD 1154-0126929	06 39 30.01	+25 26 13.61	13.23
NOMAD 1153-0126530	06 39 18.91	+25 23 56.42	12.43

Table 5. Coordinates and R magnitudes of the comparison stars for WASP-153b.

Comparison stars	RA (2000)	DEC (2000)	R
NOMAD 1300-0304193	18 36 55.83	+40 03 08.79	12.69
NOMAD 1300-0304174	18 36 53.13	+40 02 44.10	12.80
NOMAD 1300-0304334	18 37 15.93	+40 03 27.39	13.33

4. MODEL OF THE OBSERVED TRANSITS

Our observations were modelled using the code TAC MAKER 1.1.1 (Kjurkchieva et al. 2013, 2014). It does not use any simplifications of the configuration (dark planet, linear trajectory, etc.) and may fit data by linear, quadratic, squared-root and logarithmic limb-darkening law of the host star.

Each code for modeling of planet transits fits three independent geometric parameters. They are for instance $a/R_{\rm st}$, $R_{\rm p}/R_{\rm st}$, i for TAP (Gazak et al. 2012), and $R_{\rm p}+R_{\rm st}$, $R_{\rm p}/R_{\rm st}$, i for JKTEBOP (Southworth 2008). Our code searches for geometric parameters $R_{\rm st}$, $R_{\rm p}$, i. The limb-darkening effect leads to another type of independent parameter(s) for the transit problem which reflects the physical conditions of the stellar atmosphere. The limb-darkening coefficient(s), together with the independent geometric parameters, contributes strongly to the transit shape and weakly to their depths.

Fixed values of the orbital axis a, stellar temperature $T_{\rm st}$ and period P (known from the previous studies, Tables 1–2) were used in our procedure. We varied the initial epoch T_0, stellar radius $R_{\rm st}$, planet radius $R_{\rm p}$, orbital inclination i, and limb-darkening coefficient(s). Our code also allows to fit the planet temperature T_p but this turned out meaningless for the precision of our data (changes of T_p in the range 500–3000 K lead to changing of χ^2 by up to 0.003 %).

The values of the fitted parameters ($R_{\rm st}$, $R_{\rm p}$, i and limb-darkening coefficient(s)) from the previous studies were used as input values for our solution. Initially, we varied simultaneously all these parameters in wide ranges around the input values with big steps to search for the minimum of χ^2. This is an automatic procedure of TAC MAKER 1.1.1: the code gives a huge number of solutions (above thousand) for all possible combinations of values of the fitted parameters from the chosen ranges (and steps) and orders them by χ^2. After that we repeated this procedure several times for narrower parameter ranges around the values of the founded minimum of χ^2 with smaller steps. We carried out the procedure for the different limb-darkening laws varying their coefficients freely.

The results of our best transit solutions are given in the last columns of Tables 1–2. The synthetic curves are shown in Figs. 1–2 as continuous lines.

Using the known values of orbital axis a and masses $M_{\rm p}$ and $M_{\rm st}$ (Tables 1–2) we calculated the impact parameter b, planet density $\rho_{\rm p}$ and Safronov number Θ of the targets.

As each inverse problems, the transit solutions are not unambiguous. We are convinced that our code, allowing simultaneously obtaining of a huge number of solutions corresponding to wide ranges of values of the fitted parameters, leads to precise solutions. It would be reasonable to expect that the solutions of total transits are more confident than those of partial transits (similarly to the light curve solutions of eclipsing stars).

5. ANALYSIS OF THE RESULTS

5.1. HAT-P-54b

The comparison of our solution (Table 1) with that of Bakos et al. (2015) leads to the following results:

(a) The orbital inclinations and stellar radii coincide within the errors.

(b) The planet radius obtained from our transit solution is bigger by around 4.5 % than that of Bakos et al. (2015). The obtained $R_{\rm p}$ value confirmed the inflated nature of the planet.

(c) The bigger planet radius leads to smaller planet density (Table 1).

(d) We found solutions with close quality corresponding to different limb-darkening laws by fitting the limb-darkening coefficients. The χ^2 value corresponding to quadratic limb-darkening law was by around 0.5 % smaller than those of the other laws. The obtained limb-darkening coefficients (Table 1) are almost the same as the theoretical coefficients in R band for the HAT-P-53 temperature (Van Hamme 1993).

(e) The newly-determined (Table 1) initial epoch T_0 (484 cycles after the first observations) led to a new period value of 3.7998526 d that is slightly bigger than that of Bakos et al. (2015).

5.2. WASP-153b

The comparison of our fitted parameters (Table 2) with those of Demangeon et al. (2018) leads to the following results:

(a) The orbital inclinations and stellar radii of the two solutions coincide within the errors.

(b) The planet radius derived from our data (Table 2) is smaller than that of Demangeon et al. (2018) by around 5 %.

(c) The smaller planet radius leads to bigger planet density (Table 2).

(d) We derived a new value of the initial epoch T_0 (Table 2). The time between the Demangeon et al. (2018) observations and ours corresponds to 1584 orbital cycles. As a result we obtained a period value of 3.33261026 d that is slightly bigger than that of Demangeon et al. (2018) of 3.332609 d.

(e) The bigger residuals around phase -0.02 (Fig. 2) is a result of the transit asymmetry (the decreasing branch is steeper than the increasing one). One possible explanation is that the planet orbits an elongated star on an oblique orbit (similarly to the case KOI-13.01 in Szabo et al. 2011).

(f) The considerable difference between the distance to WASP-153 determined by Demangeon et al. (2018) and that of *GAIA* needed explanation. We calculated the distance with values of the star temperature and radius from Demangeon et al. (2018) and obtained $L = 3.28\ L_{\odot}$. Taking into account the interstellar extinction and bolometric correction of WASP-153 we obtained the distance of 646 pc (without these corrections the distance was even bigger). The last value is very close to that of *GAIA* (610 pc). Hence, the distance discrepancy is probably due to an error in the value given by Demangeon et al. (2018).

6. CONCLUSIONS

We present observations of transits of the newly-discovered exoplanets HAT-P-54b and WASP-153b. They allowed us to improve their periods.

The modeling of the HAT-P-54b transit led to a planet radius that is bigger than the previously published value and correspondingly to a smaller planet density. In opposite, the transit solution of WASP-153b led to a planet radius that is smaller than the previously published value and to a bigger planet density.

The best fits of the newly-observed transits of HAT-P-54b and WASP-153b correspond to the quadratic limb-darkening law of their host stars whose coefficients were determined.

Our results confirmed the Jupiter type of the two targets. The more bloated nature of WASP-153b is a result of its considerable closer orbit and higher temperature of the host star.

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APPENDIX

Table A1. Photometric data of HAT-P-54-b.

HJD	R	Error
2458138.36461226	12.7413	0.0062
2458138.36513310	12.7391	0.0064
2458138.36566550	12.7415	0.0063
...	...	...

* The complete table is available at http://saj.math.rs/198/HAT-P-54b.dat.

Table A2. Photometric data of WASP 153-b.

HJD	R	Error
2458321.41965277	12.4734	0.0061
2458321.42006944	12.4718	0.0062
2458321.42047453	12.4714	0.0064
...	...	...

* The complete table is available at http://saj.math.rs/198/WASP153b.dat.

НОВА ПОСМАТРАЊА И РЕШЕЊА ЗА ТРАНЗИТЕ ЕГЗОПЛАНЕТА HAT-P-54B И WASP-153B

Diana Kjurkchieva[1], **Nikola Petrov**[2] **and Sunay Ibryamov**[1]

[1]*Department of Physics, Shumen University, 115 Universitetska, 9700 Shumen, Bulgaria*
E–mail: *d.kyurkchieva@shu.bg, s.ibryamov@shu.bg*

[2]*Institute of Astronomy and NAO, Bulgarian Academy of Sciences, Tsarigradsko shossee 72, 1784 Sofia, Bulgaria*
E–mail: *nip.sob@gmail.com*

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Стручни чланак

Представљамо фотометријска посматрања транзита новооткривених егзопланета HAT-P-54b и WASP-153b добијена телескопом опсерваорије *Rozhen* пречника огледала 2m. Као резултат посматрања урађена је поправка у одређивању периода. Моделовање нових транзита дало је за орбиталне инклинације и звездане радијусе вредности скоро идентичне првобитно објављеним, а за радијусе планета нешто различите вредности: за HAT-P-54b мало већи, а за WASP-153b мало мањи радијус. Већа надувеност WASP-153b последица је њене блиске орбите и високе температуре звезде. Наша израчуната удаљеност WASP-153b веома је блиска удаљености коју је измерила мисија *GAIA*. Најбољи фит за новопосматране транзите HAT-P-54b и WASP-153b одговара квадратном закону потамњења ка рубу матичних звезда, чији коефицијенти су одређени. Наши резулати потврђују да су посматране планете типа врелих Јупитера.