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NEW OBSERVATIONS AND TRANSIT SOLUTIONS OF THE EXOPLANETS HAT-P-53B AND XO-5B

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SUMMARY: We present photometric observations of transiting exoplanets HAT-P-53b and XO-5b by the Rozhen 2 m telescope. The modeling of the HAT-P-53b transit required bigger planet radius than the previously published value due to the bigger depth of the newly-observed transit. The transit solution of XO-5b led to values of fitted parameters within errors of the previously published results. Based on a time span of around 9 years we improved the orbital period of XO-5b to the value of 4.187751515 d. The quality of our data does not allow determination of planet temperatures by the transit solutions. Our results confirmed the Jupiter type of the two targets. The more bloated nature of HAT-P-53b is a result of its considerable closer orbit and higher temperature of the host star. The best fits of the newly-observed transits of HAT-P-53b and XO-5b correspond to the quadratic limb-darkening law of their host stars whose coefficients were determined. The high sensitivity of the transit solutions to the stellar limb-darkening law and its coefficient(s) is proposed as a tool for precise empirical investigation of the limb-darkening effect of host stars and its interpretation.

Key words. Stars: planetary systems – Techniques: photometric – Stars: individual: HAT-P-53, XO-5

1. INTRODUCTION

Transiting extrasolar planets (TEPs) give 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 new planet candidates.

Most known transiting planets have close orbits ($a < 0.1$ AU). Plausible explanations for this (besides the strong selection biases favoring shorter orbital periods) are inward migration by gravitational interaction with the protoplanetary gas disc (Lin et al. 1996) and planet-planet scattering, followed by tidal dissipation (Rasio and Ford 1996). The loneliness of the gas giant planets is in favor of inward migration theories (Weidenschilling and Marzari 1996, Rasio and Ford 1996).

Many of the hot, giant planets turned out larger than predicted by standard cooling theory of irradiated, gas-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).

The orbits of transiting planets tend to be circular that was interpreted as a signature of tidal circularization (Mazeh 2008) with a time-scale increasing sharply with orbital distance (Goldreich and Soter 1966, Pont et al. 2011).

The theory predicts a tidal orbital decay of hot Jupiters due to absence of stable equilibrium when the star rotational angular momentum is smaller than one-third of the orbital angular momentum (Hut 1980, Rasio et al. 1996, Sasselov 2003, Levrard et al. 2009, Hoyer et al. 2016, Wilkins et al. 2017). Although there is no direct evidence of orbital shrinking due to tidal orbital decay, several observational facts imply such a supposition (Patra et al. 2017): (i) The scarcity of gas giants with periods less than a day (Jackson et al. 2008, Penev et al. 2012); (ii) The anomalously rapid rotation of some hot-Jupiter host stars (attributed to transfer of the planet orbital angular momentum, Penev et al. 2016); (iii) The absence of hot Jupiters around subgiant stars (interpreted by an acceleration of orbital decay when a star leaves the main sequence); (iv) The lower occurrence of close-in planets around rapidly rotating stars, or the realignment of stars and their planetary orbits.

Regular observations of exoplanets are necessary to improve their parameters and ephemerides and to search for or to confirm transit timing variations (TTV) which may be due to a third body, orbital decay or precession. This was the main goal of our observations of the exoplanets HAT-P-53b and XO-5b.

2. TARGETS

To ensure a sufficient photometric and time precision of the data we chose to observe with the Rozhen 2-m telescope two exoplanets by two criteria: (i) the host stars to have brightness V $\leq$ 14 mag; (ii) the transit depth to be at least 10 mmag.

HAT-P-53b

This giant exoplanet was discovered very recently by the HATNet survey (Hartman et al. 2015). It transits the G0V (V = 13.7 mag) star GSC 2813-01266 with an orbital period of $\sim$2 days. The parameters of HAT-P-53b (Table 1) were determined to better than 10 % precision by Hartman et al. (2015).

Table 1. Parameters of HAT-P-53b: period P (days); epoch T_0 of transit center (HJD 2450000+); transit duration τ (hr); 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); planet mass $M_{\rm p}$ ($M_{\rm J}$); planet radius $R_{\rm p}$ ($R_{\rm J}$); planet surface gravity $g_{\rm p}$ (m s^{-2}); planet density $\rho_{\rm p}$ (g cm^{-3}); planet temperature $T_{\rm p}$ (K); Safronov number Θ (* means fixed parameter).

Parameter	Hartman et al. 2015	This paper
P	1.9616241(39)	1.9616241*
T_0	5829.44781(44)	5829.44433(1)
τ	2.7936(408)	2.843
a	0.03159(42)	0.03159*
i	86.2(1.5)	86.0(1)
$T_{\rm st}$	5956(50)	5956*
$M_{\rm st}$	1.093(43)	
$R_{\rm st}$	1.209(71)	1.223(4)
LDL	quadr	quadr
LDC	0.24, 0.34	0.19, 0.34
$M_{\rm p}$	1.484(56)	1.484*
$R_{\rm p}$	1.318(91)	1.4429(7)
$\log g_{\rm p}$	3.325	3.246
$\rho_{\rm p}$	0.80(15)	0.61(2)
$T_{\rm p}$	1778(48)	500–3600
Θ	0.0649(46)	0.05934(24)

XO-5b

The Jupiter-sized planet XO-5b was discovered by Burke et al. (2008). It transits the G8V (V = 12.1) star GSC 02959 00729 (XO-5) with an orbital period of $\sim$4 days. Burke et al. (2008) determined first the parameters of XO-5b (Table 2).

Pal et al. (2009), Southworth (2010) and Maciejewski et al. (2011) refined both the stellar and the planetary parameters by new light curve solutions (Table 2). They confirmed the anomalously high Safronov number $\Theta = (a/R_{\rm p})(M_{\rm p}/M_{\rm st})$ and surface gravity of XO-5b. Maciejewski et al. (2011) did not detect a significant TTV.

New radial velocity curve of Knutson et al. (2014) revealed a slightly eccentric orbit and $M_{\rm st}$=1.05 $M_\odot$. The last photometry by Smith (2015) led to determination of the orbital period of XO-5b to a precision of 50 ms (Table 2).

3. OBSERVATIONS AND DATA REDUCTION

Table 3 presents journal 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 2. Parameters of XO-5b.

Parameter	Burke et al. (2008)	Pal et al. (2009)	Southworth (2010)	Maciejewski et al. (2011)	Smith (2015)	This paper
P	4.187732(20)	4.187757(11)	4.187757(11)	4.1877537(170)	4.1877558(6)	4.187732*
T_0	4485.6664(4)	4552.67168(29)		4485.66842(28)	6864.3129(2)	7802.3656(1)
τ	3.13(7)	3.1368(312)			3.1176(168)	2.96
a	0.0508(5)	0.0488(6)	0.0494(11)	0.0488*	0.0515	0.0508*
i	86.8(9)	86.7(4)	87.04(65)	86.9(4)	86.8(2)	87.0(1)
$T_{\rm st}$	5510(44)	5370(70)	5370(70)*	5500	5430	5510*
$M_{\rm st}$	1.00(3)	0.88(3)	0.914(64)		1.04	
$R_{\rm st}$	1.11(9)	1.08(4)	1.065(64)	1.05(5)	1.13	1.096(1)
LDL	quadr	quadr	average	square-root	four-coefficient	quadr
LDC	0.3–0.5,0.1–0.5	Claret		0.12;0.54	0.702,-0.561,1.210,-0.561	0.62,0.1
$M_{\rm p}$	1.15(8)	1.059(28)	1.084(56)		1.19(3)	1.15*
$R_{\rm p}$	1.15(12)	1.109(50)	1.089(82)	1.03(6)	1.14(3)	1.014(1)
$g_{\rm p}$	22(5)	15.07	22.7(3.2)			28.3
$\rho_{\rm p}$	1.02(30)	0.96(13)	0.84(18)	1.27(18)	1.06(8)	1.49
$T_{\rm p}$	1244(48)	1221	1203(33)	1201(35)	1230(20)	500–3600
Θ	0.10(1)	0.105	0.1075(82)	0.114(12)		0.114

Table 3. Log of our photometric observations.

Target	Date	Exposure [sec]	Number	Error [mag]
HAT-P-53b	2015 Oct 18	40	269	0.003
XO-5b	2017 Feb 17	20	419	0.006

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 a careful selection of reference stars (Table 4) we performed the differential aperture photometry by MaxImDL. The data were cleaned of trends.

4. MODEL OF THE OBSERVED TRANSITS

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 (dark planet, linear trajectory, etc.) and may fit data by the linear, quadratic, squared-root and logarithmic stellar limb-darkening law.

We fixed values of stellar temperature $T_{\rm st}$ and period P (Tables 1 and 2) and varied the initial epoch T_0, relative stellar radius $r_{\rm st} = R_{\rm st}/a$ (a is the orbital radius), relative planet radius $r_{\rm p} = R_{\rm p}/a$, orbital inclination i, planet temperature $T_{\rm p}$ and limb-darkening coefficients. We varied the fitted parameters around their values from previous solutions (Tables 1 and 2) to search for the minimum of χ^2. It should be noted that we fitted the planet temperature $T_{\rm p}$ freely but not fixed it to the $T_{\rm eq}$ value as the previous authors. The solutions turned out insensitive to $T_{\rm p}$ for big ranges of values (Tables 1 and 2).

Initially, we adopted the linear limb-darkening law and after reaching a good fit, we tested different limb-darkening laws varying their coefficients.

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

Using the known values of orbital axis a and masses $M_{\rm p}$ of the planets (Tables 1 and 2) we calculated the stellar radius $R_{\rm st}$, planet radius $R_{\rm p}$, surface gravity $g_{\rm p}$, planet density $\rho_{\rm p}$ and Safronov number Θ.

Table 4. Coordinates and R magnitudes of the comparison stars.

Target	Comparison stars	RA (2000)	DEC (2000)	R
HAT-P-53b	2MASS J01273318+3855375	01 27 33.19	+38 55 37.56	14.34
	2MASS J01275452+3854127	01 27 54.52	+38 54 12.75	13.98
	2MASS J01280271+3857425	01 28 02.72	+38 57 42.59	14.03
	2MASS J01274233+3859297	01 27 42.33	+38 59 29.73	14.12
	2MASS J01272901+3901181	01 27 29.01	+39 01 18.17	13.81
	2MASS J01280610+3901233	01 28 06.11	+39 01 23.32	13.62
	2MASS J01271674+3902402	01 27 16.75	+39 02 40.24	12.85
	2MASS J01265743+3902518	01 26 57.44	+39 02 51.88	14.12
	2MASS J01270673+3858096	01 27 06.73	+38 58 09.67	13.07
	2MASS J01265849+3857562	01 26 58.50	+38 57 56.29	13.02
	2MASS J01270673+3856394	01 27 06.73	+38 56 39.42	14.74
	2MASS J01270313+3856478	01 27 03.13	+38 56 47.88	13.25
	2MASS J01265918+3856244	01 26 59.19	+38 56 24.45	13.87
XO-5b	2MASS J07471950+3904368	07 47 19.50	+39 04 36.85	14.03
	2MASS J07471466+3905253	07 47 14.69	+39 05 25.39	13.37
	2MASS J07461952+3903325	07 46 19.53	+39 03 32.53	12.15
	2MASS J07463425+3905465	07 46 34.26	+39 05 46.51	13.74
	2MASS J07463082+3901067	07 46 30.83	+39 01 06.72	14.36

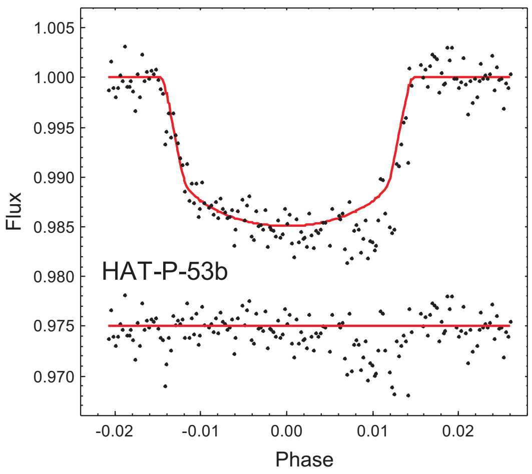

Fig. 1. *Top: the Rozhen transit of HAT-P-53b and the synthetic curve corresponding to the best solution; bottom: the residuals of the fit. The observational data are accessible in the form of tables (whose samples A1 and A2 are shown in Appendix) at www.irida-observatory.org/Observations/exo-HAT-P-53andXO-5b.rar.*

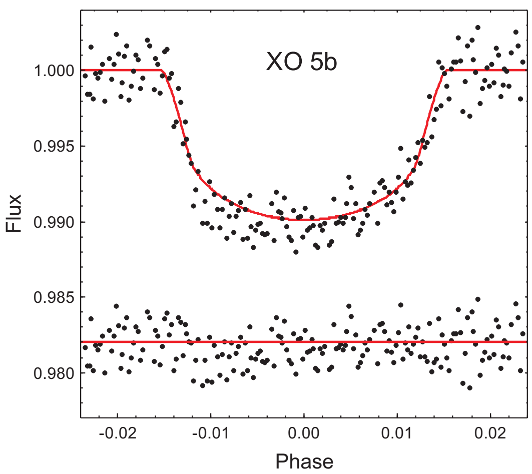

Fig. 2. *The same as in Fig. 1 but for XO-5b.*

5. ANALYSIS OF THE RESULTS

HAT-P-53b

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

(a) The orbital inclinations almost coincide.

(b) The stellar radius derived from our data is bigger by 1 % in correspondence to the slightly longer transit (Table 1).

(c) The planet radius obtained from our transit solution is bigger by around 9 % than that of Hartman et al. (2015) due to the deeper transit (by around 10 %). This result confirmed the inflated nature of the target and its Jupiter type.

(d) The bigger planet radius leads to smaller planet density and smaller surface gravity (Table 1).

(f) We found three solutions corresponding to different limb-darkening laws and fitted limb-darkening coefficients with close quality: (i) for a linear law and LDC=0.43; for a quadratic law and LDCs 0.19 and 0.34; (iii) for a squared-root law and LDCs 0.19 and 0.39. But the χ^2 value corresponding to the quadratic limb-darkening law was by around 1 % smaller than those of the other two laws. This result illustrates the high sensitivity of the transit solutions to the stellar limb-darkening law and its coefficient(s). Hence, the modeling of transits is a power tool for investigation of stellar limb-darkening laws of host stars and their interpretation.

It should be pointed out that: (i) the solution of Hartman et al. (2015) corresponds also to the quadratic limb-darkening law with near to our coefficients (Table 1); (ii) the theoretical coefficients in the R band for the quadratic limb-darkening law of HAT-P-53 are 0.25 and 0.46 (Van Hamme 1993).

(e) Varying of the planet temperature $T_{\rm p}$ in the range 500–3600 K led to changing of χ^2 by only 0.003 % (with formal minimum at 2900 K). This means that the quality of our data does not allow determination of the planet temperature.

(f) The new initial epoch T_0 (Table 1) led to decreasing of χ^2 by around 3 %.

XO-5b

There are several solutions of photometric (and spectral) data of XO-5b which differ by stellar parameters as well as the orbital and planet parameters (Table 2). That is why we used the values of Burke et al. (2008) for the fixed parameters of our solution.

The comparison of our fitted parameters (Table 2) with these of Burke et al. (2008) 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 Burke et al. (2008) but almost at the low limit of possible values of this parameter.

(c) The smaller planet radius leads to a bigger planet density and surface gravity (Table 2).

(d) The earlier solutions correspond to different limb-darkening laws of the host star (Table 2). We found three solutions corresponding to different limb-darkening laws and fitted limb-darkening coefficients with close quality: (i) for a linear law and LDC 0.69; (ii) for a quadratic law and LDCs 0.62 and 0.1; (iii) for a squared-root law and LDCs 0.63 and 0.1. The χ^2 value corresponding to the quadratic limb-darkening law was by around 0.13 % smaller than those of the other two laws. It should be noted that the sums of LDCs of our three solutions and the earlier ones (Table 2) are close (within the range 0.62–0.75).

(e) Similar to HAT-P-53b, varying of the planet temperature T_p of XO-5b in the range 500–3600 K led to changing of χ^2 by only 0.0028 % (with formal minimum at 3100 K).

(f) The ephemeris of Burke et al. (2008) did not phase well our data. We derived new value of the initial epoch T_0 (Table 2). The times of the transits of Burke et al. (2008) and ours, separated by 792 cycles, allowed us to obtain the XO-5b period value of 4.187751515 d.

(g) The deviation of the residual curve around the phase -0.01 (Fig. 2) from the horizontal course 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 oblique orbit (similarly to the case KOI-13.01 in Szabo et al. 2011).

6. CONCLUSIONS

We presented observations of transits of the exoplanets HAT-P-53b and XO-5b.

The modeling of the HAT-P-53b transit led to a bigger planet radius than the previously published value. It is due to the bigger depth of the newly-observed transit.

The transit solution of XO-5b led to values of fitted parameters which are within errors of previously published results. We improved the orbital period of XO-5b based on time span of around 9 years.

The quality of our data does not allow determination of planet temperatures by transit solutions.

The best fits of the newly-observed transits of HAT-P-53b and XO-5b correspond to the quadratic limb-darkening law of their host stars whose coefficients were determined. The high sensitivity of the transit solutions to the stellar limb-darkening law and its coefficient(s) could be used for empirical study of the limb-darkening effect of host stars and its physical interpretation.

Our results confirmed the Jupiter type of the two targets. The more bloated nature of HAT-P-53b is a result of its considerable closer orbit and higher temperature of the host star.

The quantity and quality of the available data of HAT-P-53b and XO-5b do not allow detection of TTV signals.

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APPENDIX

Table A1. Photometric data of HAT-P-53b.

HJD	R	Error
2457314.31160879	13.1513	0.0063
2457314.31229166	13.1533	0.0063
2457314.31297453	13.1502	0.0063
...	...	...

* The complete table is available at http://saj.math.rs/196/HAT-P-53b.dat.

Table A2. Photometric data of XO-5b.

HJD	R	Error
2457802.26716435	12.0349	0.0081
2457802.26761574	12.0346	0.0081
2457802.26806712	12.0362	0.0081
...	...	...

* The complete table is available at http://saj.math.rs/196/XO-5b.dat.

НОВА ПОСМАТРАЊА И РЕШЕЊА ЗА ТРАНЗИТЕ ЕГЗОПЛАНЕТА HAT-P-53B И XO-5B

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Оригинални научни рад

Представљамо фотометријска посматрања транзита егзопланета HAT-P-53b и XO-5b добијена 2м-телескопом НАО Рожен. Моделовање транзита HAT-P-53b захтева већи радијус у односу на раније објављену вредност, због дубљег новопосматраног транзита. Решење за транзит XO-5b даје параметре система чије вредности су у границама грешака параметара добијених у претходним студијама. На основу расположивих посматрања XO-5b у интервалу од око 9 година добили смо побољшани орбитални период од 4.187751515 дана. Квалитет наших посматрања не омогућава одређивање температура планета из транзита. Резултати потврђују да се у оба случаја ради о планетама Јупитеровог типа. Прошireност HAT-P-53b се може објаснити његовом много ближом орбитом и већом температуром матичне звезде. Најбољи фитови за HAT-P-53b и XO-5b одговарају квадратном закону потамњења ка рубу звезда, за који су одређени коефицијенти. Велика осетљивост решења за транзите на закон потамњења ка рубу и одговарајуће коефицијенте предложена је као алатка за прецизно емпиријско утврђивање и интерпретацију ефеката потамњења ка рубу звезда.