Observations of transits of the southern exoplanets WASP 4b and WASP 46b by using a 40 cm telescope

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Abstract. We present photometric observations of transits of the southern exoplanets WASP 4b and WASP 46b using a 40 cm telescope. The obtained values of the orbital inclination, relative stellar radius and relative planet radius are well within the ranges of the previous solutions of the targets. The only exception is the bigger planet radius of WASP 4b that was necessary to reproduce the deeper transit observed by the *TriG* filter. Our data have a good time resolution and may be used for refinement of the ephemerides of WASP 4b and WASP 46b. The presented results confirmed that small telescopes can be used successfully for the study of exoplanets orbiting stars brighter than 13 mag.
Key words: eclipses – planetary systems – stars: individual (WASP-4b and WASP 46b) – techniques: photometric

Introduction

History shows that there are very significant discoveries, realized by small telescopes. The creating of remote controlled telescopes after the middle of the 20-th century (due to the progress of information and communication technologies) increased the role of the small telescopes. The robotized telescopes revealed new horizons by saving human and financial resources and by increased efficiency of usage of the observation time (Iliev 2014). The robotic telescopes are able to work in every part of the Earth with a good astroclimate.

The small telescopes have played an invaluable role in the discovery of transiting extrasolar planet candidates by ground-based wide-field surveys: HAT (Bakos et al. 2004), SuperWASP (Pollacco et al. 2006), TrES (O'Donovan et al. 2006), and XO (McCullough et al. 2005). Among these surveys, SuperWASP is the one showing the largest harvest so far due to the starting of the Southern counterpart (Hellier et al. 2011) of the SuperWASP-North facility giving a second field of view of 482 square degrees to the survey.

As a continuation of the ideas of the project SMARTNET (DO 02-362 of NSF) we undertook observations of exoplanet transits with a 14-inch telescope.

Targets

The exoplanets WASP 4b and WASP 46b were chosen as test targets. They have relatively deep transits and short periods and orbit bright stars. Many of these hot, giant planets turned out larger than predicted by standard cooling theory of irradiated, gas-giant planets. Several hypotheses have been proposed to explain the radius anomaly shown by some highly irradiated planets, most importantly tides (Bodenheimer et al. 2001), tides with atmospheric circulation (Guillot & Showman 2002) and enhanced opacities (Burrows et al. 2007). To solve the problem of the bloated exoplanets it is important to accurately determine their radii based on photometric data (Fortney et al. 2007).

WASP 4b

This is the first planet discovered by observations at the SuperWASP-South observatory in 2006 (Wilson et al. 2008, further Paper I). The host star is USNO-B1.0 0479-0948995, a G7 V star of visual magnitude 12.5. The model of the spectroscopy and follow-up photometry led to the first parameters of WASP 4b (Paper I): orbital axis a = 0.0230 AU; orbital inclination i = 88.59^0; planetary mass of 1.22 M_J; planetary radius of 1.42 R_J; density ρ_p = 0.428.

The theoretical models of coreless irradiated gas giant planets (Fortney et al. 2007) predict radius of WASP 4b ranging from 1.09 to 1.17 R_J and planet temperature of 1761 K. Thus WASP 4b was found to have a heavily irradiated atmosphere and inflated radius, well within the parameters of the proposed new class of pM planets (Fortney et al. 2008).

Since its discovery many observations of WASP-4b with big telescopes were made and its parameters were refined (Gillon et al. 2009, Winn et al. 2009, Southworth et al. 2009, Sanchis-Ojeda et al. 2011, Caceres et al. 2011, Beerer et al. 2011, Nikolov et al. 2012, Petrucci et al. 2013). The ranges of the main parameters of WASP 4 obtained by different authors are: i = 88–90^0; relative star radius $r_s = R_s/a$ = 0.18–0.19; relative planet radius $r_p = R_p/a$ = 0.028–0.029.

WASP 46b

The discovery of this exoplanet (Anderson et al. 2012, further Paper II) was made on the base of photometric observations in 2008 and 2009 which revealed 1.43-d periodicity of the star WASP 46 (V=12.9 mag, G6V type, [Fe/H]=–0.37) and transit-like decrease in brightness. The spectral observations exhibited RV variations with the same period and semi-amplitude consistent with planetary-mass companion. By modelling of the observed data the following system parameters were determined (Paper II): orbital axis a = 0.02448 AU; planetary radius R_p = 1.31 R_J; planetary mass M_p = 2.101 M_J; density ρ_p = 0.94 ρ_J.

Chen et al. (2014) observed a secondary eclipse of WASP 46b and reported about the first detection of the thermal emission from the dayside of WASP 46b corresponding to temperature of 2386 K which is significantly higher than the equilibrium temperature of 1654 K.

Observations and data reduction

Our CCD photometric observations of the two targets in *TriG* band were carried out at the ASTELCO Observatory TIVOLI, Namibia (Table 1) with the 40-cm Dream Astrograph using CCD camera APOGEE ALTA U16M (4096×4096 pixels, 9 μm/pixel, field of view 85 x 85 arcmin). No defocus was applied (because the targets were not so bright). Information for our observations is presented in Table 1.

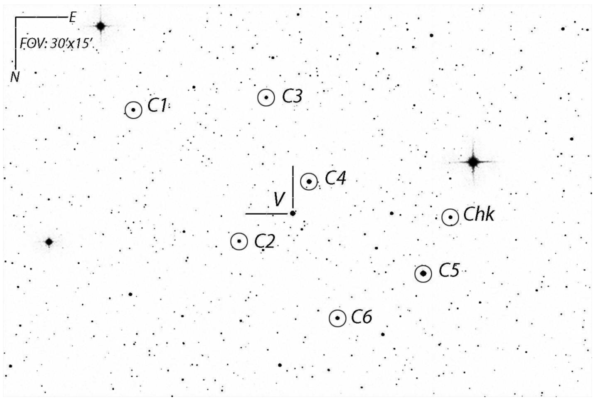

Fig. 1. The field of WASP 4

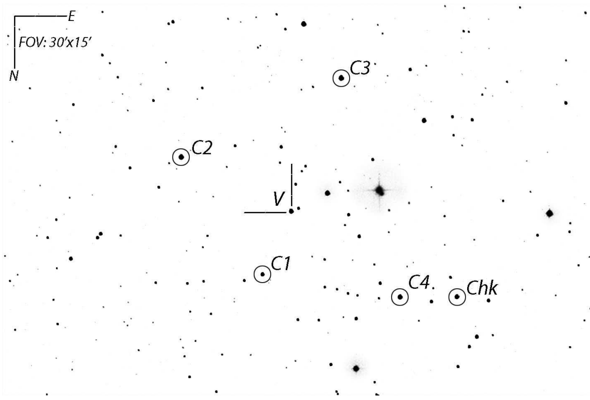

Fig. 2. The field of WASP 46

The standard procedures were used for reduction of the photometric data by *AIP4WIN2.0*. We tested several sets of reduction parameters and

Table 1. Journal of observations

Target	Date	exposures	number
WASP 4b	Aug 22 2014	60	150
WASP 46b	Aug 28 2014	60	125

chose the set that gave the most precise photometry for the stars of similar brightness to targets. After carefully selecting of reference stars (Table 2, Figs. 1–2) we performed differential aperture photometry by the software *VPHOT*.

Table 2. Coordinates and magnitudes of the targets (V), check (Chk) and comparison (C) stars

Label	Star/GSC1ID	RA (2000)	DEC (2000)	V
V	WASP 4	23 34 15.06	-42 03 41.10	12.5
Chk	UCAC4-240-183713	23 34 45.99	-42 03 28.25	14.188
C1	UCAC4-240-183695	23 33 44.15	-42 07 33.25	14.193
C2	UCAC4-240-183699	23 34 04.54	-42 02 43.52	14.524
C3	UCAC4-240-183701	23 34 10.27	-42 07 55.98	14.465
C4	UCAC4-240-183706	23 34 18.40	-42 04 51.10	12.933
	2MASS J23341836-4204509			
C5	UCAC4-240-183711	23 34 40.49	-42 01 26.63	11.999
C6	UCAC4-241-188385	23 34 23.53	-41 59 52.32	13.984
V	WASP 46	21 14 56.86	-55 52 18.10	12.9
Chk	UCAC4-171-208082	21 14 14.14	-55 55 29.75	13.035
C1	UCAC4-171-208121	21 15 04.57	-55 54 35.62	13.733
C2	UCAC4-171-208133	21 15 25.24	-55 50 16.71	12.592
	TYC 8797-506-1			
C3	UCAC4-172-203754	21 14 43.47	-55 47 28.94	12.448
	2MASS J21145329-5545281			
C4	UCAC4-172-208090	21 14 28.90	-55 55 28.79	12.797

The average photometric precision per data point was around 0.003 mag (the atmospheric conditions during the observations were not perfect).

The newly-observed transits are shown in Figs 3–4. The comparison with the previous ones led to two conclusions.

(1) The depth of the newly-observed transit of WASP 4b is around 35.5 mmag while the most of the earlier transits are with depth 30–32 mmag. We assume that the reason for the bigger transit depth is the specific filter we used rather than the lack of the ending points of our light curve or its precision. The passband of the filter *TriG* is 490–580 nm, i.e. it corresponds to shorter wavelengths than the filters R or I used as a rule for planet observations. This means bigger limb-darkening coefficient and thus deeper transit.

(2) The depth of the newly-observed transit of WASP 46b is around 22.5 mmag, well within the range 21–24 mmag of the observed earlier transits.

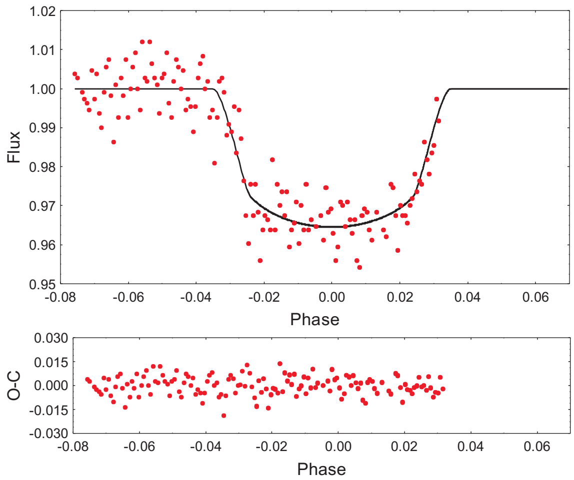

Fig. 3. The observed transit of WASP 4b and our fit (top) and the corresponding residuals (down)

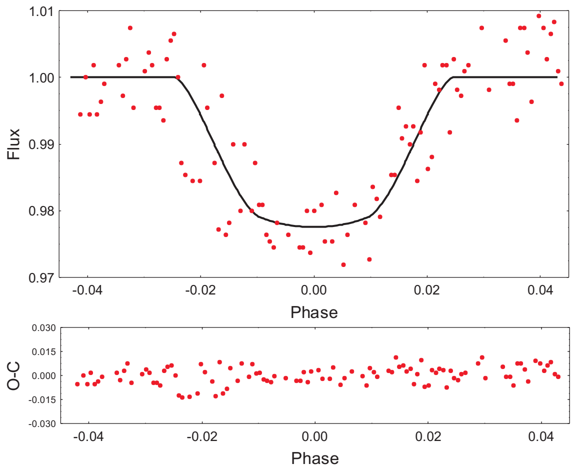

Fig. 4. The observed transit of WASP 46b and our fit (top) and the corresponding residuals (down)

Models of the observed transits

Our observations were modelled using the method of Kjurkchieva et al. (2011) by the code *TAC maker 1.1.0* (Kjurkchieva et al. 2014).

We fixed the stellar temperatures as T_s(WASP 4) = 5500 K (Paper I) and T_s(WASP 46) = 5620 K (Paper II), and varied relative radii R_s/a, R_p/a and orbital inclination i, as well as the period and the initial epoch T_0. Initially we adopted linear limb-darkening law. After obtaining of a satisfactory fit, we tried quadratic, logarithmic and square root limb-darkening laws with coefficients of limb-darkening from the tables of Van Hamme (1993) corresponding to the stellar temperatures. It turned out that the best fits corresponded to linear limb-darkening law.

The results of our transit solutions are given in Table 3. The synthetic curves corresponding to the best fit parameters are shown in Figs. 3-4 as continuous lines.

Table 3. Parameters of WASP 4

Target	Period	T_0	R_s/a	R_p/a	i	references
WASP 4b	1.3382282	2454697.797562	0.1894	0.02848	88.6	Paper I
	1.3382290	2454697.797565	0.1880	0.0326	87.85	this paper
	±0.0000001	±0.000001	±0.0001	±0.0001	±0.05	
WASP 46b	1.430370	2455392.31553	0.174	0.02774	82.63	Paper II
	1.430368	2455392.31553	0.179	0.02725	82.015	this paper
	±0.000001	±0.00001	±0.001	±0.00005	±0.005	

Note: Refined value of T_0 for WASP 4b is taken from ETD data base (not from Paper I).

The comparison of our results with the previous solutions of the targets (Table 3) allows us to make several conclusions.

(1) The coincidence of the solution of the newly-observed transit of WASP 46b and that of Paper II is excellent. The difference between them is 0.6 % for the inclination, around 2 % for the relative planet radius and below 3 % for the relative star radius.

(2) The coincidence of the solution of the newly-observed transit of WASP 4b and that of Paper I is good. The difference between them is around 1 % for the inclination, below 1 % for the relative star radius and around 12 % for the relative planet radius. The bigger value of the planet radius we obtained was expected taking into account the bigger depth of our transit.

(3) The transits observed by the 40 cm telescope have good time resolution and may be used for refinement of the ephemerides of WASP 4b and WASP 46b.

The small errors in Table 3 are the formal ones of the code *TAC maker* (similar to the formal errors of the *PHOEBE* software for eclipsing stars).

Conclusions

We obtained new sets of parameters of WASP 4b and WASP 46b by modelling of their transits observed with a 40 cm telescope.

The study supported the expectation about the successful detection of exoplanet candidates by observations with 30-40 cm telescopes taking into account that about 100 stars monitored photometrically with a 2% or better precision over 2 months could yield 1-2 transiting exoplanets.

Acknowledgments

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