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High precision defocused observations of planetary transits

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Abstract. It is only possible to measure physical properties of extrasolar planets, if they transit their host stars. One can determine the masses and the radii of this kind of objects, and hence, have constraints on their chemical composition, internal structure, formation and evolution. The availability of high quality light curves of planetary transits is essential in determining these properties within a few percent. In order to obtain high-quality transit light curves, we apply the well-established defocus technique on meter and sub-meter class telescopes in our project. This technique allows longer integration times, and hence collecting more photons to build up a higher S/N ratio. In this study, we present our first photometric results with the 1m Turkish telescope (T100) located at TÜBİTAK National Observatory (TUG) of Turkey, which proved to be a well suited instrument to these observations with its large field of view.

Key words: photometry – defocusing – exoplanets

1. Introduction

One of the greatest achievements of observational astronomy in the 20^{th} century was the detection of extrasolar planets (Wolszczan & Frail 1992, Mayor & Queloz 1995). The number of exoplanets, discovered so far, has exceeded 1000 (http://exoplanet.eu), most of which were detected with the radial velocity method. Although this method has been very successful in the detection of planets, it yields little information about an individual one, only its orbital parameters and a lower limit on its mass (Marcy & Butler 1998). In order to derive absolute parameters of an exoplanetary system, and thereby to study it in more detail, we need to analyze also their light curves recorded in their transits. The morphology of a transit light curve depends on the relative size

Table 1. The log of the observations presented in this work

Planet	Date	Start Time (UT)	End Time (UT)	Exp. Time (s)	Filter	Scatter (mmags)
XO-3b	2012-12-13	22:55	03:43	120	R_c	1.30
XO-3b	2013-01-14	17:12	01:19	150	R_c	0.56
HAT-P-10b	2013-01-15	16:28	20:21	120	R_c	0.96
XO-3b	2013-09-07	20:58	02:35	120	R_c	1.10
WASP-33b	2013-09-08	20:46	22:49	60	R_c	1.73

of the planet with respect to that of its host star(s). With some dependence on a stellar theory, and the velocity variation of the parent star, it is possible to compute the mass of the planet to an accuracy of 1-3% (Torres *et al.* 2008; Southworth *et al.* 2009).

In the framework of an observational project we pursue at TÜBİTAK National Observatory (TUG) of Turkey, we aim to measure the radii of known transiting exoplanets to 5 % or even better precision from observations of transit events with the 1 m Turkish telescope T100. In order to reach the required photometric precision over a 2-4 hour duration of a typical transit, one needs a high S/N ratio. This is only possible by collecting more photons and carefully controlling the systematic effects, which arise mainly from detector imperfections (e.g. variations in pixel response) and atmospheric conditions (e.g. seeing).

Our observational strategy to reach high S/N in our transit observations with the T100 telescope is to defocus it heavily in order to distribute the point spread function (PSF) over thousands of pixels so that it is possible to expose the CCD for longer durations in the observations of bright stars, hence, diminish Poisson noise because the large PSFs are insensitive to focus or seeing changes (Southworth *et al.* 2009). Then the main source of systematic errors, flat-fielding, is decreased by two orders of magnitude, as well. We present here the first defocused observations of exoplanet transits with the T100 telescope and summarize our experiences with the technique and the instrument.

2. Observations and Data Reduction

The Turkish telescope T100 is a 1 meter, Ritchey-Chrétien telescope. Its wide field of view ($21'.5$ x $21'.5$) makes it very easy to find comparison stars for differential photometry. The CCD chip serves the system perfectly with its size and quality. We were able to observe only 5 transits in 24 nights allocated to our project in nine months of time. A log of our successful observations is given in Table 1. In each observation, several images were taken with the telescope properly focused in order to find the target, to verify that there were no faint stars nearby that would interfere the defocused PSF of the target, and to choose the center of the field of view so that there would be as many comparison stars as

Table 2. Information for targets in Figures 1, 2, and 3

Planet	Period (days)	Epoch	V (mag)	Depth (mag)	Duration (min)
XO-3b	3.1915289	2454864.76684	9.86	0.0080	173
WASP-11b	3.722469	2454729.90631	11.89	0.0254	159
WASP-33b	1.2198669	2454163.22373	8.3	0.0151	163

possible, similar to the target in brightness and colour. In order to determine the exposure time, the mutual effects of the transit duration, sizes of the defocused star images in pixels, linear regime of the CCD, and the brightness of the target have been taken into account. In order to achieve the desired precision in radius determination, at least 30 to 50 exposures in and out of the transit profiles were aimed to avoid undersampling in the modeling. The ideal median count rate was determined to be ∼25000 ADUs. The sizes of the defocused star images were determined accordingly, covering an average area of 100 pixels by 100 pixels in most of the observations. Since the observed targets in successful runs were bright (brighter than 12 magnitudes), no binning was used and there were no problems related to tracking thanks to the autoguiding system.

For data reduction, we used the pipeline written by Southworth et al. (2009) in the IDL programming language and the DAOPHOT photometry package (Stetson 1987), distributed as part of the ASTROLIB library to perform aperture photometry. We experimented with different aperture radii and used the ones giving the least scatter. The differential-magnitude of the potential comparison stars were checked for a short-time scale variability and those with similar brightness and colour, and showing no indication of such a variability, were selected. All good comparison stars were combined by weighted flux summation into one ensemble. Then the differential magnitudes were computed in the sense that the magnitude was subtracted from that of the ensemble. The transit observations of the planets XO-3b (Johns-Krull *et al.* 2007), WASP-11b / HAT-P-10b (West *et al.* 2009; Bakos *et al.* 2019), and WASP-33b (Herrero *et al.* 2011) with T100 are phased with the ephemeris information from the Extrasolar Transit Database (hereafter ETD, http://http://var2.astro.cz/ETD/), given in Table 2 for three successful runs. The transit depth, given for XO-3b in the ETD (0.0048) is far different from the values given in the literature (Johns-Krull *et al.* 2007, Winn *et al.* 2008) and from what we observed. The ETD value can only be half of the transit depth according to our observations. Hence, we gave its transit depth value in Table 2 as it was given in the discovery paper (Johns-Krull *et al.* 2007) as 0.008. The light curves obtained in these runs are presented in Figures 1, 2, and 3. We obtained the most precise transit light curve on January 14, 2013, when we observed the transit of the exoplanet XO-3b. The biggest scatter presented here was observed for WASP-33b, which is the brightest star in our sample. WASP-33 is a variable star of δ Sct type for which various distortions, and a central hump feature, have been observed in many of its light curves (Sada *et al.* 2012, Kovács *et al.* 2013). Although the weather conditions at the time might have an effect, we think that the correlated noise has an astrophysical origin mostly, discussion of which is beyond the scope of this paper.

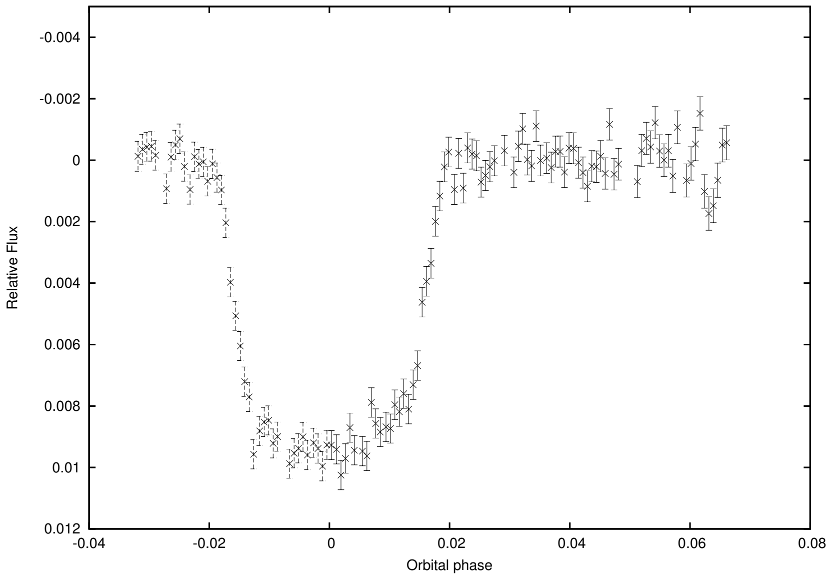

Figure 1. Transit observation of XO-3b in a defocused mode by T100, 2013-01-14.

3. Conclusion

We have presented our first transit light curves obtained with the 1 meter Turkish telescope, T100, located at TÜBİTAK National Observatory (TUG), which proved to have a decent potential for transit observations with the defocusing method giving high photometric precision. We aim to accumulate additional data in the future and provide a full analysis of all T100 data in future publications.

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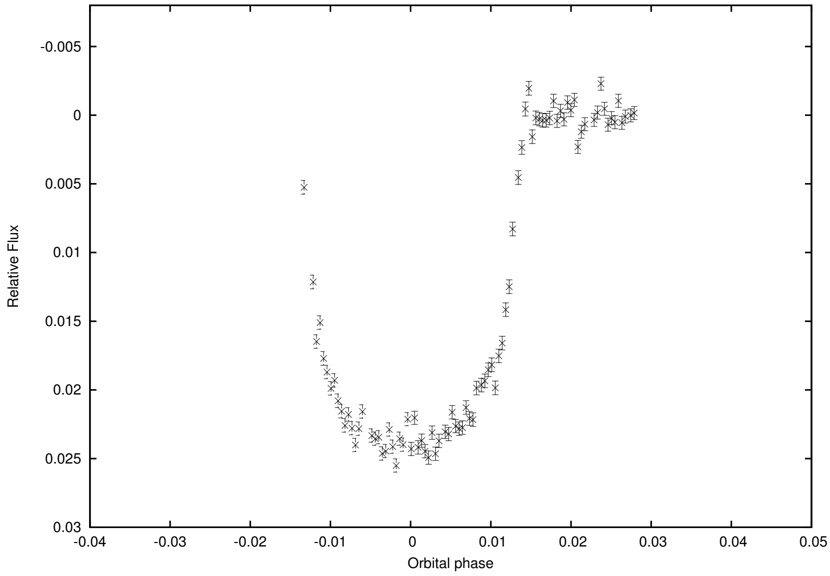

Figure 2. Transit observation of WASP-11b / HAT-P-10b in a defocused mode by T100, 2013-01-15.

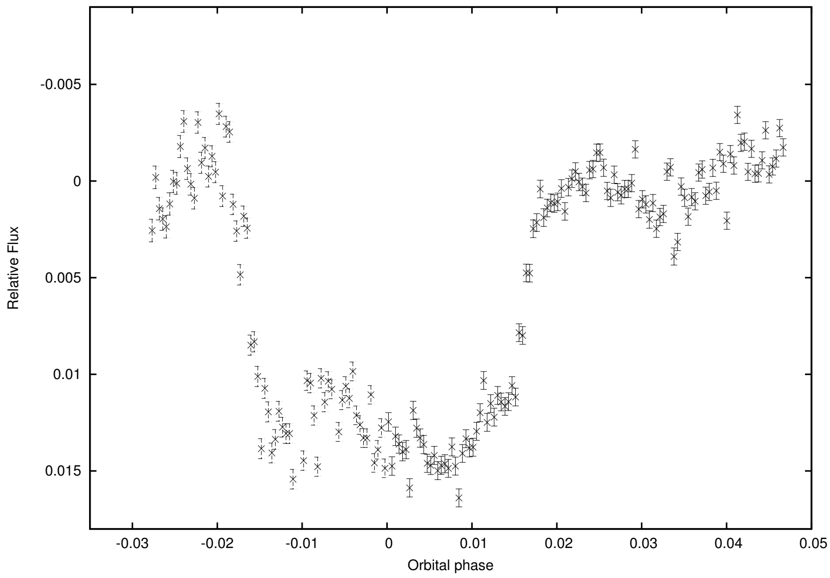

Figure 3. Transit observation of WASP-33b in a defocused mode by T100, 2013-09-08.

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