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First results of the Kourovka Planet Search: discovery of transiting exoplanet candidates in the first three target fields

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ABSTRACT

We present the first results of our search for transiting exoplanet candidates as part of the Kourovka Planet Search (KPS) project. The primary objective of the project is to search for new hot Jupiters which transit their host stars, mainly in the Galactic plane, in the R_c magnitude range of 11–14 mag. Our observations were performed with the telescope of the MASTER robotic network, installed at the Kourovka astronomical observatory of the Ural Federal University (Russia), and the Rowe-Ackermann Schmidt Astrograph, installed at the private Acton Sky Portal Observatory (USA). As test observations, we observed three celestial fields of size $2 \times 2\,\mathrm{deg}^2$ during the period from 2012 to 2015. As a result, we discovered four transiting exoplanet candidates among the 39 000 stars of the input catalogue. In this paper, we provide the description of the project and analyse additional photometric, spectral, and speckle interferometric observations of the discovered transiting exoplanet candidates. Three of the four transiting exoplanet candidates are most likely astrophysical false positives, while the nature of the fourth (most promising) candidate remains to be ascertained. Also, we propose an alternative observing strategy that could increase the project's exoplanet haul.

Key words: techniques: photometric – planetary systems.

1 INTRODUCTION

As of the end of 2015, the existence of more than 1500 extrasolar planets in the vicinity of stars of different types has been reliably confirmed (Schneider et al. 2011; Wright et al. 2011). Most of the newly found exoplanets were discovered through photometric observations of their transits or by analysing the radial velocity variations of the host stars [for a review of the history of the search for exoplanets and the main techniques of the discovery, see Perryman (2012) and Wright & Gaudi (2013)]. Furthermore, most of the 4000 exoplanet candidates from the *Kepler* mission are, in all likelihood, planets, too (Mullally et al. 2015).

The anticipated number of exoplanets in our Galaxy is significantly larger than the number of already discovered extrasolar planets, which renders their primary distribution similar to the 'tip of the iceberg'. In addition, the available distribution of exoplanets is

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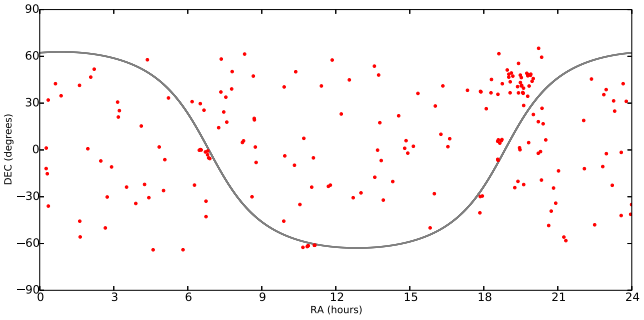


Figure 1. Spatial distribution of the known transiting hot Jupiters, i.e. exoplanets with orbital periods less than 10 d and with the minimum mass greater than $0.5M_J$ (Wright et al. 2011). The Galactic plane is shown by the grey solid curve.

distorted by the selection effects of each of the search methods. Therefore, each newly discovered exoplanet with reliably determined characteristics will increase the population of the known exoplanets and contribute to the further development of the planet population synthesis, this being the method by which the synthetic populations of exoplanets are compared with the observed ones (Mordasini et al. 2015). The advancement of this method will shed light on some of the aspects related to the formation and evolution of extrasolar planets. On the other hand, the search for new transiting exoplanets is also necessary for determining a more accurate boundary between late M dwarfs, brown dwarfs, and gaseous giant exoplanets due to the similar size of these objects.

Ground-based photometric surveys, such as HATNet (Bakos et al. 2004), HATSouth (Bakos et al. 2013), KELT (Pepper et al. 2007), OGLE (Udalski 2003), QES (Alsubai et al. 2013), TrES (Alonso et al. 2004), WASP (Pollacco et al. 2006), and XO (McCullough et al. 2005), along with space projects such as *Kepler* (Borucki et al. 2010) and *CoRoT* (Auvergne et al. 2009), have discovered more than half of the known exoplanets through observations of a significant portion of the celestial sphere. However, the sky has not yet been covered in its entirety by such observations (see Fig. 1). Most ground-based photometric surveys that focus on the search for transiting hot Jupiters are incapable of reliably recording transits for host stars fainter than 13 mag in the R_c band and, most importantly, avoid observing dense fields in the Galactic plane. Thus, a large number of hot Jupiters transiting relatively bright stars are waiting to be discovered there.

The Kourovka Planet Search (KPS) project was organized at the Kourovka astronomical observatory of the Ural Federal University (Yekaterinburg, Russia). One of the observatory's photoelectric telescopes with a two-star photometer had already participated in one of the first attempts to find exoplanets within the framework of the 1994–1999 TEP project [see Doyle et al. (2000) and Deeg et al. (2008)]. Our observations were made with the robotic MASTER-II-Ural telescope. This instrument forms part of the network of MASTER telescopes (Lipunov et al. 2010). The primary mission of the MASTER project is to carry out synoptic surveys of the sky, searching for various optical transients (supernovae, optical afterglow of gamma-ray bursts, and asteroids). A synoptic sky survey does not require high precision photometry, but the technical characteristics of the system make it possible to perform photometric observations of 11–14 mag stars with 1 per cent precision in the R_c band. For that reason, we used the MASTER-II-Ural telescope to study open clusters (Popov et al. 2013) as well as to observe the transits of other known exoplanets (Gorbovskoy et al. 2013; Baluev et al. 2015).

When testing the technique of high precision photometry with the MASTER-II-Ural telescope, we decided to carry out a pilot photometric survey in search for transiting exoplanets. In 2012, we observed with the MASTER-II-Ural telescope a region of the sky in the constellation of Cygnus. During 2013–2014, we carried out a survey of another region of the celestial sphere in the Cassiopeia constellation, which was also observed with the Celestron Rowe-Ackermann Schmidt Astrograph (RASA) telescope installed at the private Acton Sky Portal Observatory (Massachusetts, USA). A third region of the celestial sphere, in the Ursa Major constellation, was observed with the RASA telescope only.

The MASTER and RASA telescopes provide the optimal parameters for searching such exoplanets transiting their host stars, with magnitudes ranging from 11 to 14 mag. The expected transit depth in this case is about 0.01–0.02 mag, and can be detected with 0.001 mag precision. The 1.8 arcsec pixel^{-1} image scale allows one to observe with high photometric precision the celestial regions of the Galactic plane with large concentrations of stars. Current ground-based wide-field surveys usually stay clear of dense portions of the Galactic plane to avoid the blending of stars and associated problems of photometric processing. The KPS survey is similar in image scale to the ongoing exoplanet photometric surveys BEST II (Kabath et al. 2009; Fruth et al. 2014) and ASTEP 400 (Fressin et al. 2006; Crouzet et al. 2010; Daban et al. 2010).

This paper is organized as follows: Section 2 is devoted to the description of the instruments used and observations made; Section 3 presents the observed data processing technique; Section 4 deals with the detected transiting exoplanet candidates and with their additional photometric, spectroscopic, and speckle interferometric observations; in conclusion we discuss the main results and the future of the project.

2 INSTRUMENTS AND OBSERVATIONS

Observations of the first field of the KPS survey were made with the MASTER-II-Ural telescope only, installed at the Kourovka astronomical observatory ($\varphi = 57^\circ$ N, $\lambda = 59^\circ$ E). The telescope consists of a pair of Hamilton catadioptric tubes (400 mm, f/2.5) installed on one equatorial Astelco NTM-500 mount. Each tube is equipped with a 4098 × 4098 pixel Apogee Alta U16M CCD yielding an image scale of 1.8 arcsec pixel^{-1} in a 2 × 2 deg^2 field. The average full width at half-maximum (FWHM) of the stellar profiles is 3–4 arcsec. Each tube of the telescope has four filters: *V*, I_c, P, and the 'red continuum' on the east tube and R_c, B, P, and Hα on the west tube. Filters BVR_cI_c constitute a Johnson–Cousins system, and the P filters are polarized with perpendicular orientation. The 'red continuum' is a narrowband filter 5 nm wide transmitting radiation in the 645 nm wavelength region. The Hα filter also has a width of 5 nm and is centred on the wavelength 656 nm.

For our pilot observations we selected a Milky Way field in the Cygnus constellation with a high density of stars which does not overlap with the *Kepler* field of view (FOV). The field was named TF1 (Target Field #1). The coordinates of the TF1 centre are α_{J2000} = 20:30:00 δ_{J2000} = +50:30:00. The choice of TF1 was based on two main factors: favourable observing conditions during the summer at the Kourovka observatory, and the absence of known exoplanets there.

The main TF1 observation set was completed during the short and bright summer nights from May to August 2012. We obtained 3600 frames with 50 s exposure times, but only in the R_c band, because

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Table 1. Parameters of observations made with the MASTER-II-Ural and RASA telescopes.

Field	Coordinates of centre (J2000)	Telescope	Year of observation	Number of images	Exposures *s*	Filter
TF1	20:30:00 +50:30:00	MASTER-II-Ural	2012	3600	50	R_c
TF1	20:30:00 +50:30:00	MASTER-II-Ural	2012	1000	120	BV
TF2	02:47:00 +63:00:00	MASTER-II-Ural	2013–2014	4400	50	VR_c
TF2	02:47:00 +63:00:00	MASTER-II-Ural	2014	500	120	BI_c
sub-TF2	02:47:00 +63:00:00	RASA	2014	8000	50	R_c
sub-TF2	02:47:00 +63:00:00	RASA	2014	485	50	V
TF3	11:00:00 +65:48:00	RASA	2015	7000	50	R_c
TF3	11:00:00 +65:48:00	MASTER-II-Ural	2015	50	120	$BV\,R_cI_c$

only one of the CCD cameras of the telescope was operable at the time. The time interval between consequent frames was about 1.5 min.

After the initial data reduction, we performed follow-up observations of TF1: we acquired R_c-band data with 50 s exposure times, and B- and V-band frames with 120 s exposure times, to determine the colour indices of the stars from the input catalogue (description of the catalogue is provided in Section 3.1). All in all, TF1 was observed for 90 h in the R_c band (36 nights) with a 2.5 h average duration of an observing night.

The second target field (TF2) is located in a less dense zone of the Milky Way in the Cassiopeia constellation. The coordinates of the centre are $\alpha_{J2000} = 02{:}47{:}00$ $\delta_{J2000} = +63{:}00{:}00$. The choice of TF2 was based on the same principles as TF1.

The TF2 field was observed with the MASTER-II-Ural telescope for 100 h (43 nights) in 2013 and 2014. The major portion of the observed data consists of 4400 frames obtained simultaneously with the two tubes of the telescope in the V and R_c bands with 50 s exposure times. Likewise, we conducted B- and I_c-band observations to determine the colour indices of the stars from our input catalogue. As in the case of TF1, the average observing night lasted for only 2.5 h due to the weather conditions at the telescope site.

All observations with the MASTER-II-Ural telescope were made in automatic mode. Prior to each observation night, dark frames were obtained with the necessary CCD temperature; under good weather conditions, every morning the telescope obtained twilight sky flat-field frames in the appropriate filter.

In September 2014, a second telescope was involved in the KPS project. The RASA (Celestron Inc., Torrance, CA, USA) is operated at the private observatory Acton Sky Portal, Massachusetts, USA ($\varphi = 43^\circ$ N, $\lambda = 71^\circ$ W). The telescope consists of a 279 mm diameter mirror with a focal length of 620 mm. Initially, a Celestron CGEM mount was used; it was later replaced by a Losmandy Titan mount (Hollywood General Machining, Los Angeles, CA, USA) to provide new observing regimes. The installed CCD camera is a 3352 × 2532 pixel SBIG ST-8300M (SBIG, Santa Barbara, CA, USA) which provides an image scale of 1.8 arcsec pixel^{-1} in a 1.2 × 1.6 deg^2 field. This FOV is almost twice smaller than the MASTER-II-Ural telescope FOV. Typical PSF FWHM values for stars are 2–3 arcsec. Despite the smaller FOV, this telescope benefits from clearer observing nights than those at the Kourovka observatory site.

The RASA telescope obtained 8000 frames containing the inner subregion of the TF2 field. The observations were carried out from early September 2014 to late November 2014, in the R_c filter, with 50 s exposure times. The time interval between the frames was 1 min. Also, V-band frames were obtained on one night. All in all, the TF2 field was observed with the RASA telescope in the R filter for 130 h (18 nights), averaging 7.2 h per night.

The third field, TF3, is located in the Ursa Major constellation and contains the smallest number of stars of all the observed fields. This field is not part of the Milky Way, but was none the less observed as part of the test observation with the RASA telescope. TF3 was observed with the RASA telescope only in the R_c band, from January to April 2015. The TF3 field was observed for 115 h (21 nights), averaging 5.5 h per night. The MASTER-II-Ural telescope obtained BVR_cI_c band frames of TF3 for determining the colour indices of the stars.

The information about the obtained observation sets is summarized in Table 1.

The volume of the obtained data amounted to several terabytes, which is not very large by modern astronomical standards, yet it required automated flow processing. The description of the data processing and analysis procedures is provided in the next section.

3 DATA REDUCTION AND SEARCH FOR VARIABLE STARS AND EXOPLANET TRANSITS

All obtained FITS files were transferred to the IT cluster of the Ural Federal University where they were processed using a computer with a Debian operating system.

Prior to data processing, we had to filter some of the FITS files. Not all observations were made in optimal weather conditions due to operational instability of the Boltwood Cloud Sensor II at the Kourovka observatory. To this end, we analysed the standard deviation of the pixel counts σ_{pix} for each image. The value of σ_{pix} varies smoothly from image to image on the photometric nights. In the presence of clouds, σ_{pix} varies significantly, making it possible to discard the images obtained in poor weather conditions.

3.1 From FITS files to light curves

For automated processing of the FITS files, we developed a K-PIPE script using the BASH programming language. The script combines the procedures of photometric calibrations of frames in the IRAF package (Tody 1986), creation of the WCS header in the ASTROMETRY.NET application (Lang et al. 2010), aperture photometry in the IRAF package, and differential photometry in the ASTROKIT application (Burdanov, Krushinsky & Popov 2014).

Initially, the IRAF package was used for the photometric reduction of each frame, i.e. to subtract the master dark frame and divide by the master flat-field frame.

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The physical CCD coordinates of the stars change from image to image, so we created the correct parameters that are responsible for referencing the image coordinate system to the WCS (World Coordinate System). We used the console version of the ASTROMETRY.NET application for this.

Then, using the *PHOT* task in the IRAF package on each frame, we carried out aperture photometry with individual values of the aperture and sky background for each frame. To do this, we used a catalogue of objects generated by means of 2MASS (Skrutskie et al. 2006) catalogue and containing equatorial coordinates of stars and their ordinal numbers. Objects were selected basing only on the limiting magnitude $J = 14.5$ mag. For the TF1 field the input catalogue contains 23 000 stars, for the TF2 field, 15 000 stars, for the sub-TF2 field, 8500 stars. For the TF3 field the catalogue contains 1000 stars.

The radius of the aperture that was used for a particular frame is determined as $0.8 \times$ FWHM for the data from the MASTER-II-Ural telescope, and $0.7 \times$ FWHM for the RASA telescope. Here FWHM is the mean FWHM of the stars' PSF in the frame. The resulting ratio for an optimal radius of the aperture is obtained empirically from a set of test data for each telescope.

Next, the obtained data are transferred to the ASTROKIT software. It corrects brightness variations of the stars caused by the variations of atmospheric transparency: for this purpose, for each star in the FOV the software generates an individual ensemble of reference comparison stars which are similar in brightness and position on the frame. Also, ASTROKIT searches for variable stars based on the Robust Median Statistics (RoMS) criterion (Rose & Hintz 2007) which makes it possible to select variable star candidates with more confidence than in the case of analysing the standard deviation of stellar brightness. A more detailed description of the operation of ASTROKIT is provided in Burdanov et al. (2014).

The K-PIPE script is used separately for the data from each of the target fields in each filter. The output of the script consist of light curves for all the stars of our input catalogue in instrumental stellar magnitudes and variable star candidates.

The best photometric precision of the MASTER-II-Ural telescope was attained in the R_c band. For the TF1 field it varied from 0.005 to 0.05 mag for stars with stellar magnitudes from 11 to 16, respectively. For the TF2 field the precision varied from 0.005 to 0.06 mag for stars with stellar magnitudes from 11 to 16, respectively.

The RASA telescope achieved its highest precision in the R_c band for the TF2 field. The precision varied from 0.006 to 0.08 mag for stars with magnitudes ranging between 11 and 16, respectively. The precision of the data for the TF3 field varied from 0.008 to 0.05 mag for stars with stellar magnitudes from 11 to 16, respectively. The precision as a function of magnitude for each field and telescope is presented in Fig. 2.

For each data set we calculated the total number of low-noise stars, i.e. stars whose standard brightness deviation for the entire series of observations was less than 0.02 mag (see Table 2).

Due to the highest quantity and accuracy, the data referring to the R_c filter were used to search for transiting hot Jupiter candidates. The frames in the other filters were used to determine the colour indices of the stars.

3.2 Search for variable stars and exoplanet transits

The search for variable stars was carried out by using the algorithm described in Rose & Hintz (2007). For each star the RoMS criterion

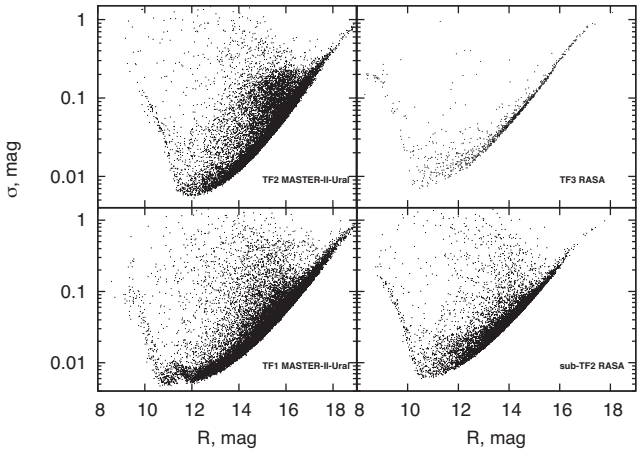


Figure 2. Standard deviations of the stars' magnitudes for the entire series of observations versus their magnitudes in the R_c band.

Table 2. Photometric precision of observations in the R_c band obtained with the MASTER-II-Ural and RASA telescopes.

Field	Telescope	Total number of stars	Low-noise stars
TF1	MASTER-II-Ural	23 500	25.5 per cent
TF2	MASTER-II-Ural	15 000	18.0 per cent
sub-TF2	RASA	8500	18.2 per cent
TF3	RASA	1000	20.9 per cent

η_n was calculated:

$$\eta_n = \frac{\sum_i \frac{|\, m_i - m_{\rm med} \,|}{\sigma_{\rm rms}}}{N-1}, \quad (1)$$

where n is the ordinal number of a star; m_i is the ith measurement of the magnitude; $m_{\rm med}$ is the median of magnitude measurements for star n; N is the total number of magnitude measurements for star n; $\sigma_{\rm rms}$ is the estimated standard deviation of star n, determined by the least-squares method from the dependence of standard deviation of magnitude on stellar magnitude for the stars in the frame.

The RoMS criterion makes it possible to estimate the magnitude variations of an object. If it exceeds 1, then the star is suspected of variability and is subsequently investigated in greater detail. Based on the results of a visual inspection of the light curves of variable star candidates from the TF1, TF2, and TF3 fields, we were able to find about 500 previously unknown variable stars which are discussed in the following article by Popov et al. (2015).

In our search for transiting exoplanets, we selected stars with standard deviations of magnitude for the entire series of observations of less than 0.02 mag (i.e. those for which there is a possibility of detecting a transit of a hot Jupiter with a depth of about 0.01 mag). Prior to searching for transit signals in the light curves, we used the Trend Filtering Algorithm (Kovács et al. 2005) in order to remove systematic brightness variations for low-noise stars. The algorithm is used to approximate the light curve for each star in the field by a linear combination of basis vectors (usually, the data for the vectors are provided by the light curves of the stars selected in the FOV). Next, the approximated curve is subtracted from each light curve thus resulting in a photometric time series partially corrected for common systematic effects.

The search for specific transit-like signals was carried out by the BLS method (Box-fitting Least Squares) widely used in exoplanet

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Table 3. Data on the detected transiting exoplanet candidates.

Internal ID	R_c (mag)	V (mag)	Period (d)	Depth (mag)	Duration (h)
KPS-TF1-3154	12.4	12.7	0.846 74	0.02	1.6
KPS-TF1-19251	13.9	14.3	0.983 41	0.025	1.7
KPS-TF2-11789	14.2	14.4	1.346 52	0.02	2
KPS-TF3-663	12.6	13.0	1.706 30	0.01	1.5

astronomy (Kovács, Zucker & Mazeh 2002). This method, as well as the Trend Filtering Algorithm, is implemented in the publicly available VARTOOLS Light Curve Analysis Program (Hartman et al. 2008). The detected periods of variability with a high signal-to-noise ratio in the periodogram were used to construct phase-folded light curves in the VARTOOLS software which were subsequently analysed visually.

Based on the results derived from analysing the MASTER-II-Ural telescope data, we were able to find two transiting exoplanet candidates with periods less than 1 d in the TF1 field, which subsequently turned out to be astrophysical false positives. The data obtained with the RASA telescope for the TF2 area were analysed separately first, and then together with the data from the MASTER-II-Ural telescope. This way we detected one transiting exoplanet candidate with a period of 1.34 d which is also most likely an astrophysical false positive. In spite of the small number of stars in the TF3 field, we detected a transiting exoplanet candidate with a period of 1.7 d and a transit depth of about 0.01 mag. The nature of this object still remains to be ascertained.

The information about the detected transiting exoplanet candidates is provided in more detail in the next section.

4 TRANSITING EXOPLANET CANDIDATES

In our search for transit signals by the BLS method, we found four transiting exoplanet candidates among the low-noise stars; relevant information about the candidates is provided in Table 3.

We carried out additional photometric observations in order to confirm the reality of the visible transits from our initial data. We intended to make sure that the visible decreases in brightness were not caused by systematic errors of observations and/or data processing. By using telescopes with a larger resolving power than that of the wide-field MASTER-II-Ural and RASA telescopes, it was possible to establish whether an exoplanet candidate is a visual binary (multiple) system. The next stage consisted of photometric monitoring of the phase 0.5 to detect possible secondary eclipses, which would reveal the eclipsing binary nature of the candidates.

The campaign of additional photometric observations involved telescopes with apertures of up to 60 cm, and one 1-m class telescope [T100 of the TUBITAK National Observatory (TUG)]. The 6-m BTA telescope of the Special Astrophysical Observatory of RAS was used for spectroscopic and speckle interferometric observations of the candidates. The Kourovka 1.2-m telescope was used for low-resolution spectroscopic observations. The information regarding the telescopes is provided in Table 4.

The observed data confirmed the detection of actual transits, as well as helped specify the periods of the transits. After that, we carried out spectroscopic and speckle interferometric observations of some of the candidates. The analysis of the data for each of the candidates is reported below.

Table 4. Information about the telescopes that took part in follow-up observations of transiting exoplanet candidates.

Telescope	Observatory
Celestron EdgeHD 11 SCT	Acton Sky Portal
MTM-500	Kislovodsk Mountain Astronomical Station
MASTER-II-Tunka	Irkutsk State University Astrophysical Centre
ZA-320M	Pulkovo Observatory
Kreiken	Ankara University Kreiken Observatory
T100	TUG
0.6-m Cassegrain	Torun Centre for Astronomy Observatory
BTA, 6-m	Special Astrophysical Observatory of RAS
KAO-1.2-m	Kourovka Observatory
0.43-m Cassegrain	Baronnies Provençales Observatory
0.3-m Smith-Cassegrain	Observatori Montcabrer
Meade LX200 12 arcsec and 14 arcsec	University of Saskatchewan
0.3-m Maksutov-Cassegrain	University of Siena

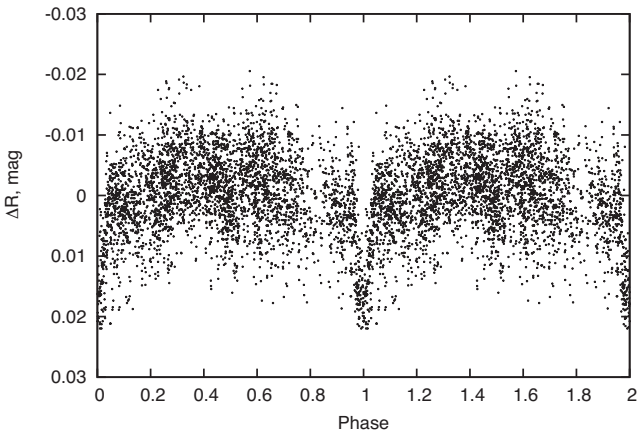


Figure 3. Phase-folded light curve of transiting exoplanet candidate KPS-TF1-3154 as obtained using the data from the MASTER-II-Ural telescope.

4.1 KPS-TF1-3154

The transits of exoplanet candidate KPS-TF1-3154 [labelled as MASTER-1 b in Burdanov et al. (2013)] were observed with the MASTER-II-Ural telescope four times, and three of them were full transits. The BLS method revealed in the periodogram a powerful peak corresponding to a period of 0.846 74 d. The light curve folded with the determined period is presented in Fig. 3. The 2MASS catalogue gives the following magnitudes for the host star 2MASS 20260213+5006032: $J = 11.40$ mag, $H = 11.05$ mag, and $K_s = 10.88$ mag. The initial epoch of the transit minima is $T_0(\mathrm{HJD_{TT}}) = 2456062.826678$.

Additional photometric observations made with the T100 telescope showed a clear V-shape form of the light curve, which is shown in Fig. 4.

On the night of 2013 May 17/18, high angular resolution images and spectra of the KPS-TF1-3154 candidate were obtained with the multimode focal reducer SCORPIO-2 (Afanasiev & Moiseev 2011) at the prime focus of the SAO RAS 6-m BTA telescope. The FWHM of the image in the SDSS r band is 1.8 arcsec. It was determined

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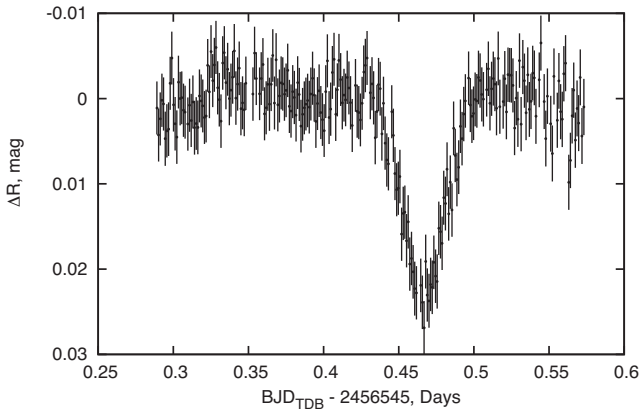


Figure 4. Single transit of the exoplanet candidate KPS-TF1-3154 as obtained with the T100 telescope of TUG.

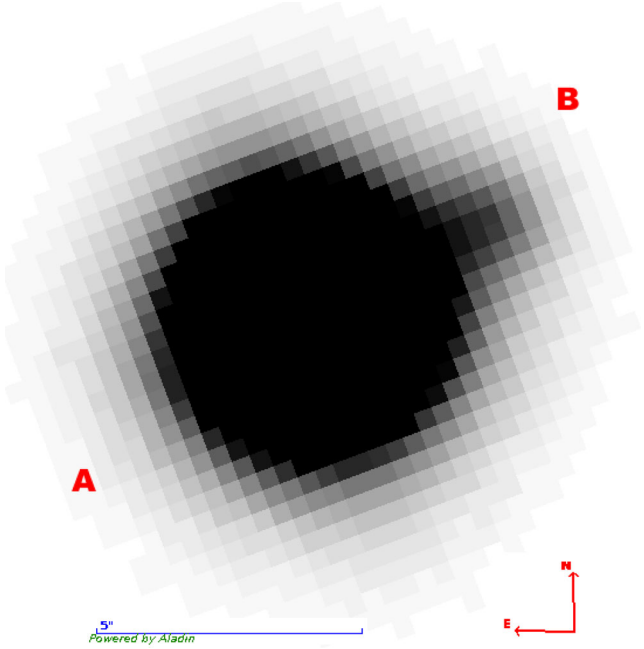


Figure 5. Image of transiting exoplanet candidate KPS-TF1-3154 as obtained with the SAO RAS 6-m telescope. The candidate represents a visual binary system.

that the KPS-TF1-3154 candidate is a visual binary system with the brighter component A and a less bright component B (see Fig. 5).

To obtain spectra we used the VPHG1200@540 grating and a slit 1 arcsec wide. The image scale along the slit was 0.36 arcsec pixel^{-1}. The spectral resolution of the resulting spectra is about 5 Å, and the spectral range is 3850 − 7200 Å. The slit was oriented along $PA = 110^{\circ}$ to obtain spectra from the two components simultaneously. To separate the spectra of a pair of closely related sources we used the following technique. For each column of pixels along the direction across the dispersion, the spectra were approximated by a sum of two Moffat functions and a constant component describing the background. The amplitudes of the functions were represented by the intensity value in the spectrum of the component. The bright component A is a G8V type star as is the fainter component B.

Subsequent photometric observations at the expected time of secondary minimum revealed a 0.009 mag decrease in brightness lasting for 1.7 h. The observations were made with the EdgeHD 11

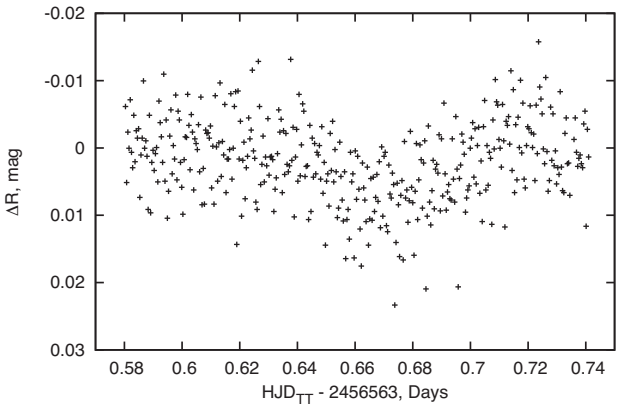


Figure 6. Secondary minimum of transiting exoplanet candidate KPS-TF1-3154 as obtained with the EdgeHD 11 SCT telescope (279 mm, f/7) installed at the Acton Sky Portal.

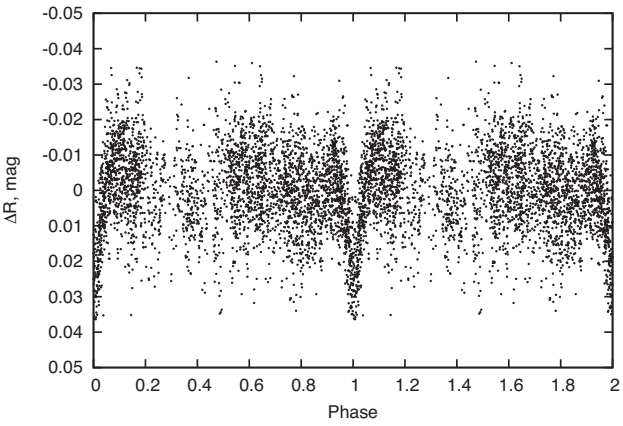


Figure 7. Phase-folded light curve of transiting exoplanet candidate KPS-TF1-19251 as obtained with the MASTER-II-Ural telescope.

SCT telescope (279 mm, f/7) (Celestron Inc., Torrance, CA, USA), installed at the Acton Sky Portal. One of the secondary minima is presented in Fig. 6. Thus the KPS-TF1-3154 candidate is an astrophysical false positive – an eclipsing binary system.

4.2 KPS-TF1-19251

Four transits of the exoplanet candidate KPS-TF1-19251 were observed with the MASTER-II-Ural telescope; two of them were full transits. The BLS method revealed in the periodogram a powerful peak corresponding to a period of 0.983 41 d. The resulting light curve folded with the determined period is presented in Fig 7. The magnitudes of the host star 2MASS 20341625+5015427 are $J = 12.60$ mag, $H = 12.21$ mag, and $K_s = 12.10$ mag. The initial epoch of the transit minima is $T_0(\mathrm{HJD_{TT}}) = 2456062.956109$.

Additional photometric observations revealed a V-shape form of the light curve with the transit depth 0.025 mag and duration 2.5 h. One such transit, obtained with the 60-cm telescope of the Centre for Astronomy of the Nicolaus Copernicus University, is presented in Fig. 8.

Decreases in brightness at the times corresponding to secondary eclipses were not revealed (from photometric observations with 0.003 mag precision).

On the same observation night as for the KPS-TF1-3154 candidate, we obtained high angular resolution images and spectra

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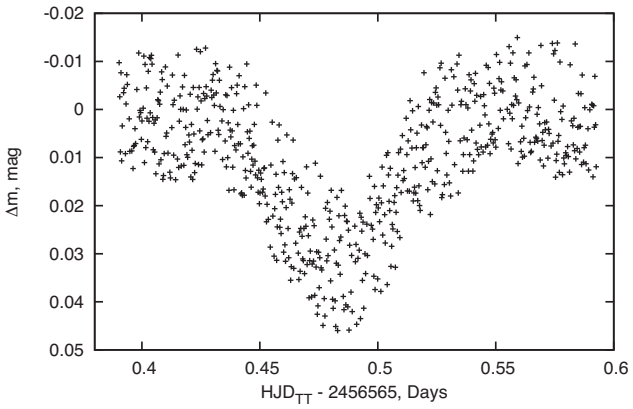


Figure 8. Single transit of the exoplanet candidate KPS-TF1-19251 as obtained with the 0.6-m Cassegrain telescope at the Centre for Astronomy of the Nicolaus Copernicus University in Torun (Poland).

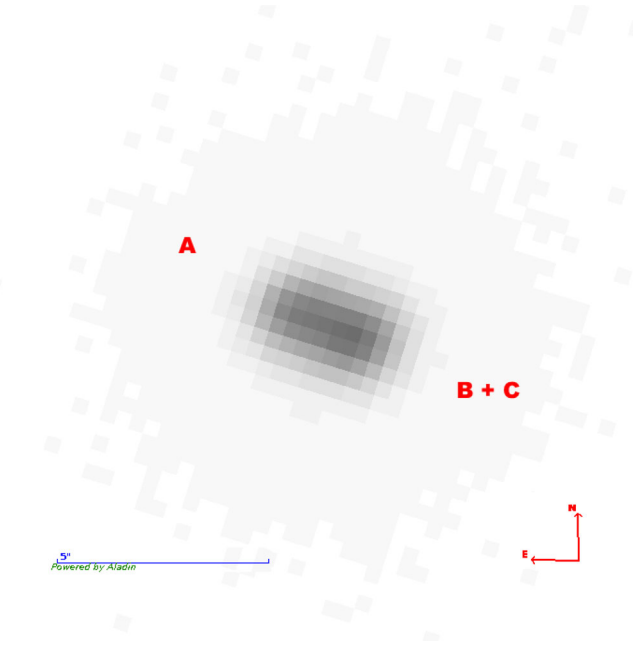


Figure 9. High angular resolution image of transiting exoplanet candidate KPS-TF1-19251 as obtained with the SAO RAS 6-metre telescope. According to these data, the candidate represents a visual binary system. Actually, it is a triple system (see Fig. 10).

of KPS-TF1-19251 with SCORPIO-2 at the SAO RAS 6-m BTA telescope. The seeing was about 1.2 arcsec. We found that the KPS-TF1-19251 candidate is also a visual binary system consisting of two components of almost identical brightness and separated by 1.3 arcsec (see Fig. 9). Based on spectral data, we found that the brighter component A is a dwarf of class G2 and the weaker component B is a dwarf of class K0.

On 2014 September 05, the SAO RAS 6-m BTA telescope carried out speckle interferometric observations of transiting exoplanet candidate KPS-TF1-19251. The speckle interferometer acquired six series of short-exposure images with x 10 and x 16 micro-objective lenses in the 600/40, 800/100, and 900/80 nm bands (Maksimov et al. 2009). The entire system was observed in a single FOV. It was discovered that the system's faint component B is a speckle binary system and contains another component, C. The position parameters of the system were determined from the image series obtained in

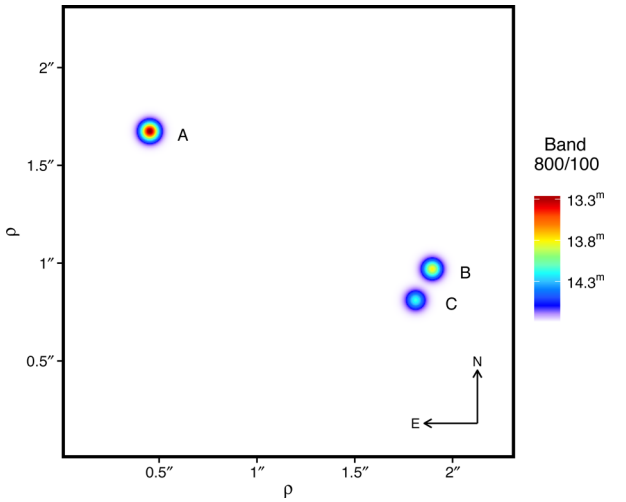


Figure 10. Model of transiting exoplanet candidate KPS-TF1-19251 based on speckle interferometric images obtained with the SAO RAS 6-metre BTA telescope.

the 800/100 nm band. The angular distances between the system's components are: $\rho_{AB} = 1317 \pm 14$ mas and $\rho_{BC} = 148 \pm 12$ mas; the position angles are $\Theta_{AB} = 244^\circ \pm 1\overset{\circ}{.}5$ and $\Theta_{BC} = 152^\circ \pm 2^\circ$. Because of the low signal-to-noise ratio, we were unable to determine the parameters from the series in the 600/40 and 900/80 nm filters. The brightness differences in the 800/100 nm band are: $\Delta m_{(A-(B+C))} = 0.01 \pm 0.05$ mag and $\Delta m_{(B-C)} = 0.5 \pm 0.5$ mag. The obtained image is presented in Fig. 10. Based on these data, we estimate the spectral class of component C as K5.

The available data are insufficient to determine which component of this triple system has periodic transits. But sequential estimates were made of the 'true' depths of the eclipses for each of the components of this visual triple system. The 'true' depth of an eclipse is defined as the decrease in brightness of one of the components which would be observable in the absence of other stars in the aperture. If eclipses occur for star A, then the true depth of an eclipse would be about 0.05 mag. Such decreases in brightness are not typical for transits of extrasolar planets, even for the most inflated exoplanet orbiting a main sequence star known to date [WASP-17 b, see Anderson et al. (2010)]. If we assume that a 0.05 mag decrease in brightness is caused by a planet orbiting a G2V star, then its radius would be equal to 2.2 radii of Jupiter. If eclipses occur for star B or C, then the true depths of the eclipses would be equal to 0.08 or 0.14 mag, respectively. Such a depth is also too large for the eclipsing object to be an exoplanet. Taking into account the V-shaped form of the light curve, the system is most likely an eclipsing binary star. Although the discrepancy between the hot Jupiters' predicted radii and observed radii (known as 'radius anomaly') has not yet been solved, there still might be a chance of an exoplanet companion orbiting star A. Of course, the nature of the eclipsing body can be ascertained conclusively by using radial velocity observations, i.e. by estimating its mass.

4.3 KPS-TF2-11789

Transiting exoplanet candidate KPS-TF2-11789 was discovered in the TF2 field of the KPS survey. The transits were observed with the MASTER-II-Ural telescope and the RASA telescope. In the combined data set, the BLS method revealed a powerful peak in the periodogram, but now corresponding to a longer period of

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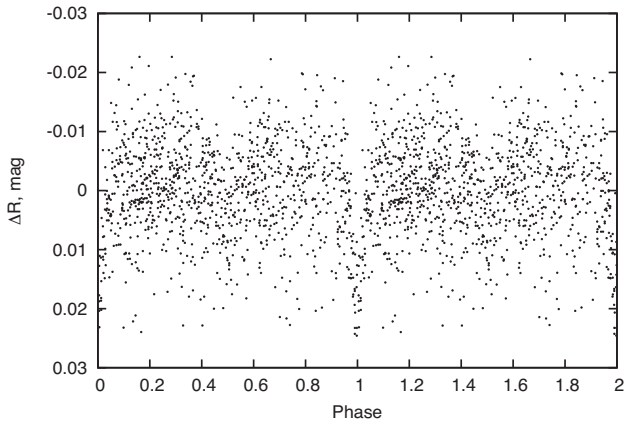


Figure 11. Phase-folded light curve of transiting exoplanet candidate KPS-TF2-11789 as obtained from the combined data of the MASTER-II-Ural and RASA telescopes. The main minimum is clearly evident, and a hint of a secondary minimum is also visible.

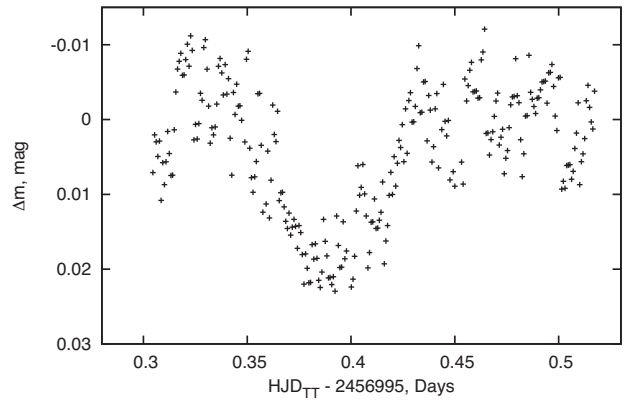


Figure 12. Single transit of the KPS-TF2-11789 exoplanet candidate as obtained with the MTM-500 telescope.

1.346 52 d. The resulting phase curve folded with the period thus determined is presented in Fig. 11. According to the 2MASS catalogue, the magnitudes of the host star 2MASS 02472435+6324230 are $J = 13.04$ mag, $H = 12.84$ mag, and $K_s = 12.74$ mag. The initial epoch of the transit minima is $T_0(\mathrm{HJD_{TT}}) = 2456365.223054$.

As in the case with the previous candidates, additional photometric observations were made in order to specify the shape of the light curve, as well as to check for the presence of a secondary minimum. The MTM-500 telescope (500 mm, f/8.2) of the Kislovodsk Mountain Astronomical Station was used to obtain several transit light curves (one of them is plotted in Fig. 12). It is a U-shaped curve, the transit depth is 0.02 mag, and the duration of the transit is about 1.8 h. It was not possible to detect any visual companions of the KPS-TF2-11789 candidate from the images available (see Fig. 13).

However, it was possible to detect a secondary minimum with a depth of about 0.006 mag and a duration of about 2 h at the predicted time. One such light curve with a secondary minimum, obtained with the MTM-500 telescope, is plotted in Fig. 14. Thus, in all likelihood, this candidate is also an astrophysical false positive, namely an eclipsing variable star.

The spectral class of the system was determined as F0 through the use of low-resolution spectra obtained with the ANNA spectrograph of the 1.2-m telescope at the Kourovka astronomical observatory.

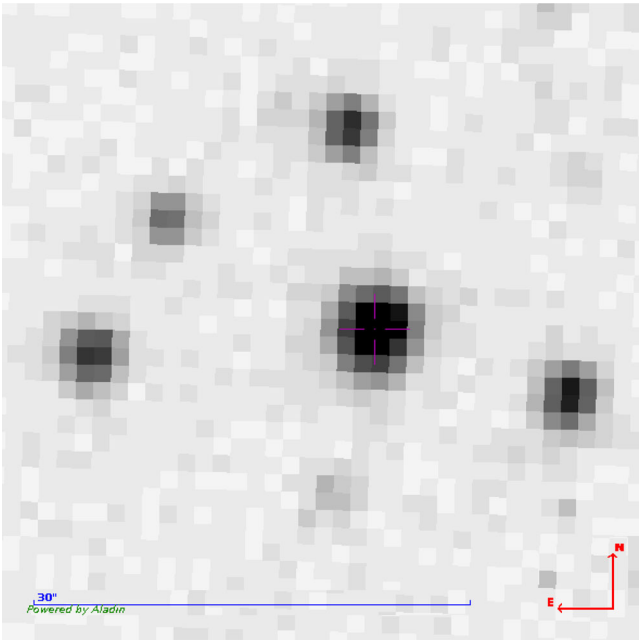


Figure 13. Image of transiting exoplanet candidate KPS-TF2-11789 as obtained with the MTM-500 telescope.

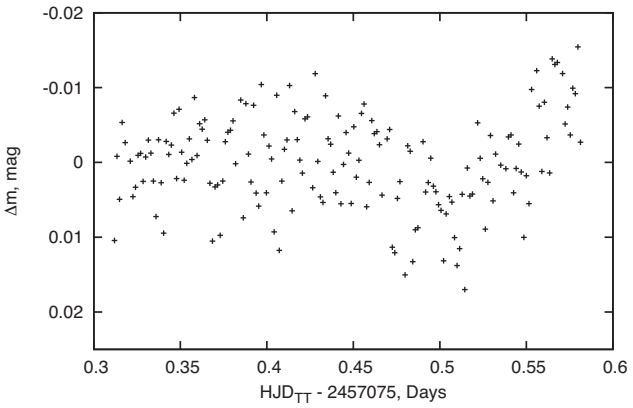


Figure 14. Secondary minimum of transiting exoplanet candidate KPS-TF2-11789 as obtained with the MTM-500 telescope. The theoretical time of the minimum (JD 2457075.51293) coincides with the minimum on the light curve.

4.4 KPS-TF3-663

Initially, the transits of the exoplanet candidate KPS-TF3-663 were observed only with the RASA telescope. We detected five transits, and two of them were full transits. The BLS method revealed in the periodogram a peak corresponding to a period of 1.706 30 d. The resulting light curve folded with the determined period is presented in Fig 15.

One of the best transits of the KPS-TF3-663 candidate in terms of precision, shown in Fig. 16, was acquired by the 0.43-m Cassegrain telescope located at the Baronnies Provençales Observatory. It is a U-shaped curve, the transit depth is 0.01 mag, and the duration of the transit is about 1.5 h. Decreases in brightness at the predicted times corresponding to a secondary minimum were not detected (from photometric observations with 0.003 mag precision).

On 2015 June 08, the SAO RAS 6-m BTA telescope carried out speckle interferometric observations of the KPS-TF3-663

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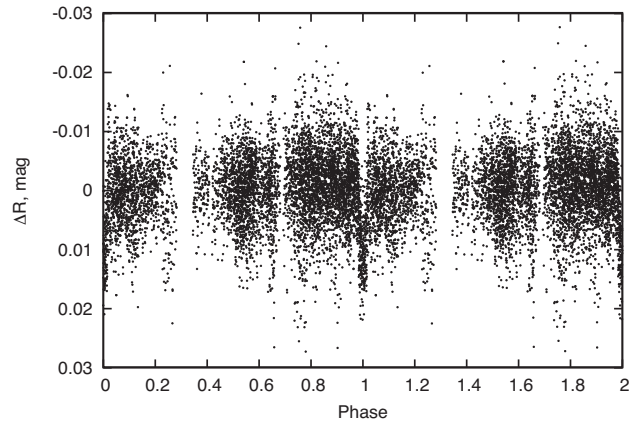


Figure 15. Phase-folded light curve of transiting exoplanet candidate KPS-TF3-663 as obtained from the RASA telescope data.

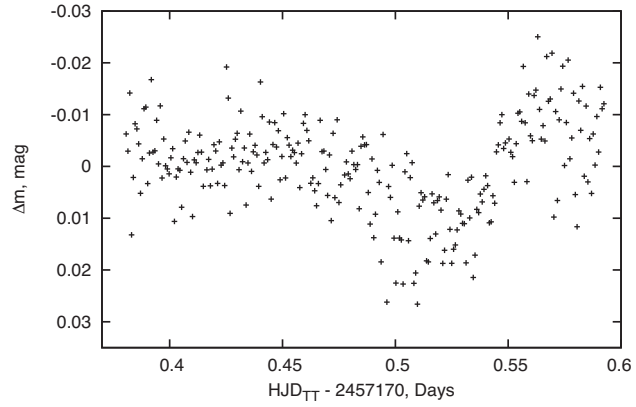


Figure 16. Single transit of the exoplanet candidate KPS-TF3-663 as obtained by the Baronnies Provençales Observatory telescope.

candidate. We were unable to detect a visual companion of the candidate from these data.

According to the MASTER-II-Ural telescope observations, the magnitudes of the candidate are: $B = 14.1$, $V = 13.0$, $R = 12.6$, and $I = 12.8$ mag. Taking into account JHK photometry from the 2MASS catalogue ($J = 11.4$, $H = 11.0$, and $K_s = 10.9$ mag), we suggest that the spectral type of the star is G8–K1.

KPS-TF3-663 is the most promising exoplanet candidate, and spectral observations are needed to clarify the nature of the eclipsing body.

5 CONCLUSIONS

We have presented the first results of the Kourovka Planet Search project. Over a period of two years, the MASTER-II-Ural telescope observed two fields of size $2 \times 2\,\mathrm{deg}^2$ (TF1 and TF2), and the RASA telescope made observations of the TF2 subregion of size $1.2 \times 1.6\,\mathrm{deg}^2$ as well as of the TF3 field.

As a result, four transiting exoplanet candidates and about 500 new variable stars were discovered among the 39 000 stars of the input catalogue. The transiting exoplanet candidates thus discovered were all identified reliably by the BLS method. Three of the four candidates represent one of the most widespread types of astrophysical false positives. The nature of the fourth candidate, which is the most promising one, can be ascertained by further spectral observations. We would like to conclude that amateur wide field observations, such as the RASA setup at Acton Sky Portal, can provide high-quality data for discovering exoplanet candidates.

We associate the lack of discovered transiting hot Jupiters with a low duty cycle of observations made by a single instrument and with the small number of observed fields. Unfortunately, poor astroclimatic conditions at the Kourovka astronomical observatory result in only ≈3 h (on average) of observations a night. Also, in the course of our observations, the TF2 field was first observed with the MASTER-II-Ural telescope, and then with the RASA telescope only. The estimates of our exoplanet survey yield (with the real duty cycle and number of low-noise stars) the detection of less than 0.5 hot Jupiters. In the future, we would like to relocate the MASTER-II-Ural telescope to a site with a better astroclimate, and observe identical fields of the sky with the two telescopes separated in longitude.

We assume that the relatively small number of discovered transiting exoplanet candidates, compared to the wider-field surveys, might be due to the fact that our observations encompassed a smaller number of fields in the sky and that the image scale was different (1.8 arcsec pixel^{-1} versus 14 arcsec pixel^{-1} in the case of the WASP and HATNet surveys). This smaller image scale results in a smaller number of blending stars and, as a consequence, a smaller number of astrophysical false positives.

Another way of improving the probability of detecting transiting exoplanets involves observing a larger number of fields in the sky. Both telescopes were used to make trial observations in an alternative (cyclic) mode: during a single night, observations of three to five adjacent image fields of the celestial sphere were made, one of which included a known transiting exoplanet. The transit light curve obtained in such a mode of observation has a lower time resolution, but the transit phase is clearly evident and the BLS method allows confident discovery of the transit signal. In future observation campaigns, we plan to observe three to five fields with the two telescopes every night.

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