Opportunities for extra-solar planet observations with the telescopes of the Rozhen NAO

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Abstract. On the basis of a review of different methods for detecting and study of extra-solar planets a program for tests of Rozhen's telescopes was completed. The results are leading to a conclusion that several tasks can be realized using the available facilities.
Key words: extra-solar planets, transit method, photometry

Възможности за наблюдения на извън-слънчеви планети с телескопите на НАО Рожен

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На базата на обзор на различни методи за откриване и изследване на извънслънчеви планети беше осъществена програма за тестване на роженските телескопи. Резултатите водят до извода, че някои от изследователските задачи могат да се реализират с наличната апаратура.

Introduction

The discovery of planets orbiting around other stars always attracted the interest of the people. This interest is prompted by the search for the answer to the eternal question "Are we alone in the Universe?". This explains the increased interest of researchers to "see" Earth-like planets orbiting around other suns, which have suitable conditions for life.

Just 20 – 30 years ago the possibility to observe exoplanets from the Earth was pure speculation for astronomers. But now several hundred such objects have been found, and their number is constantly increased. Some specialist in this field predict that using the new ground-based and space technologies to detect extra-solar planets, the number of newly detected planets will increase by hundreds every month.

International Astronomical Union has established working definition for extra-solar planets in 2001 (and last modified in 2003) with the following criteria:

1. Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metalicity), that orbit stars or stellar remnants are "planets" (no matter how they formed). The minimum mass/size required for an extra-solar object to be considered a planet should be the same as that used in our Solar System.
2. Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are "brown dwarfs", no matter how they formed nor where they are located.

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3. Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not “planets”, but are “sub-brown dwarfs” (or whatever name is most appropriate).

There have also been reports of free-floating planetary-mass objects (i.e. ones not orbiting any star), sometimes called “rogue planets” or “interstellar planets”.

1 Methods for detecting extra-solar planets.

Detection methods for extra-solar planets can be classified into several groups (Perryman 2000; Perryman et al. 2005; Schneider 1995; http://www.transitsearch.org):

1.1 Dynamical effects

- Radial Velocity or Doppler Spectroscopy is the most effective method for locating extra-solar planets. Doppler Spectroscopy relies on the fact that a star does not remain completely stationary when it is orbited by a planet, it moves in a small circle or ellipse. When viewed from a distance, these slight movements affect the star’s normal spectrum, shifted towards the blue or the red. The success of this method was made possible by the development in recent years of highly sensitive spectrographs, which can detect even very slight movements of a star, very close to the practical accuracy limit for ground-based RV measurements of ~ 1 meters per second, implying mass detection limits only down to $0.01 - 0.1\ M_{Jup}$. As of December 2008, 309 extra-solar planets have been discovered from their RV, comprising 265 systems.

- Astrometry is the oldest method used to detect extra-solar planets. It is the science of precision measurement of star’s location in the sky. If a periodic shift is detected, it is almost certain that the star is being orbited by a companion planet. Astrometry is one of the most sensitive methods for detection of extra-solar planets. The largest ground-based telescopes are currently being fitted for accuracy of 20 micro arcsec. NASA’s Space Interferometry Mission will be able to make angle measurements of single stars as accurate as 2 micro arcsec, ie it has the potential of detecting a planet of 6.6 M_{Earth} orbiting its star at the 1 AU distance.

- Timing method - A pulsar emits radio waves extremely regularly as it rotates. Slight anomalies in the timing of its observed radio pulses can be used to track changes in the pulsar’s motion caused by the presence of planets. The first milestone in the discovery of extrasolar planets was in 1992, when Wolszczan and Frail (1992) published results indicating that pulsar planets existed around PSR B1257+12. (Three pulsar planets: PSR B1257+12 B , PSR B1257+12 C and PSR B1257+12 A). Four planetary systems with 7 planets were discovered around pulsars by this method.

1.2 Gravitational microlensing effects:

Microlensing occurs when the gravitational field of a star acts like a lens, magnifying the light of a distant background star. Possible planets orbiting the foreground star can cause detectable anomalies in the lensing event light curve. Microlensing is the only known method capable of discovering planets at truly great distances from the Earth. Whereas spectroscopy searches for planets in our immediate galactic neighborhood, up to 100 light-years from Earth, and photometry can potentially detect planets at a distance of hundreds of light-years, microlensing can find planets orbiting stars near the center of the Galaxy, thousands of light-years away. This method is capable of finding the smallest planets of any currently available method (Earth-like planets). The drawback of the method is that planets detected by microlensing will never be observed again. Microlensing events are unique and hardly ever repeat themselves. Seven planetary systems with 8 planets were found applying microlensing method.

1.3 Photometric effects:

- Transit method - If a planet crosses (or transits) in front of its parent star's disk, then the observed brightness of the star drops by a small amount. The amount by which the star dims depends on its size and on the size of the planet. Photometric limits below the Earth's atmosphere are typically a little below the 1% photometric precision, limited by variations in extinction, scintillation and background noise (depending on telescope aperture size), corresponding to masses of about 1 $M_{\rm Jup}$ for solar type stars. If differential photometry is used, then the accuracy of around 1 mmag over a wide field of view, is reached. The situation improves above the atmosphere and a number of space mission are planed to reach the 0.01% limits required for the detection of Earth-size planets orbiting at an Earth-like distance from their star.

Photometry transit is one of the most sensitive methods for detecting extra-solar planets. This is the unique and the most easy method to observe the extra-solar planets with smaller telescopes, so easy, in fact, that it can often be accomplished by amateurs using commercially available equipment. Several exoplanets already were discovered in the XO project (McCullough et al. 2005) – collaboration between professional and amateur astronomers. Method of transits is one of the most effective – so far 55 extra-solar planets were found by this method.

- Reflected light - Additional phase-dependent effect, such as the modulation of light reflected from a planet, should also be detectable by accurate photometric satellites.

- Black-body emission of a close planet. If the planet rotation is synchronized with the orbital motion, one side of the planet faces the parent star all the time, resulting in different temperatures (up to 1500K or more) of the two sides of the planet. The hot side of the planet can contribute some fraction of the light of the system, with a sinusoidal modulation. The effect can be seen only in the infrared.

1.4 Direct imaging: (from ground or space, in optical or infrared)

The light coming from an extra-solar planet is much fainter (in order of 10^9 in the optical, and 10^7 in the infrared) than the signal from the star. Therefore the challenge is to build instruments that are able to provide extremely high contrast and spatial resolution. A number of programme are using, or planning to use, interferometry to achieve high spatial resolution. A Jupiter-like planet in a Jupiter-like orbit around a very nearby star should be detectable. The first direct detections are proposed in the literature (9 planetary systems with 11 planets).

1.5 Miscellaneous detections:

There have also been reports of two free-floating planets in young star clusters, and one interstellar planet.

Up to now, 393 extra-solar planets have been discovered and confirmed.

2 Extra-solar planet transit search projects

Some of the ongoing and future projects for transit search of extra-solar planets are listed below:

Space Orbital Missions

- MOST (Microvariability and Oscillations of STars)
- CoRoT (COnvection ROtation and planetary Transits)
- Kepler Mission

Ground-based telescopes

- WASP, Super-WASP (Wide Angle Search for Planets)
- ASAS-3 (All Sky Automated Survey)
- TrES (Trans-atlantic Exoplanet Survey)
- HATnet (Hungarian Automated Telescope Network)
- RAPTOR-P
- Vulcan
- BEST, BEST-II (Berlin Exoplanet Search Telescope)
- OGLE-III (Optical Gravitational Lensing Experiment)

A detailed description of one of these projects (TrES) is given below, because we maintain close collaboration with the colleagues at Lowell Observatory, and we observe the suspected stars of this project. The Trans-atlantic Exoplanet Survey has three small wide-field fully-automated small-aperture telescopes:

– PSST (Planet Search Survey Telescope) located at Lowell Observatory, Arizona, USA
– Sleuth located at Palomar Observatory, USA
– STARE (Stellar Astrophysics and Research on Exoplanets) located at Tenerife, Canary Islands, Spain

PSST telescope, for example (Dunham, et al. 2004), includes Canon FD 300 mm, F/2.8 optical system, 2K × 2K back-illuminated Loral CCD with 15 μm pixel, and BVR_C filters. Cooling is provided by CryoTiger system, cooling CCD camera to its regulated operating temperature of about −110°C. The telescope forms images with a FWHM of $\sim$ 1.6 pixels (scale of $10''.0$ pixel^{-1}). The telescope simultaneously observes thousands of stars with apparent R magnitude between 10 and 13 in a field approximately $6^\circ \times 6^\circ$. Every light curve consists of $\sim$ 2000 measurements in R. The light curves of all stars are searched for transit events using the box-fitting least squares algorithm (Kovács et al. 2002). The light curves of the transit candidates are examined visually to eliminate possible false detections, such as stars with deep eclipses or with signs of a secondary eclipse.

Four extra-solar planets of "Hot Jupiter"-type has already been discovered and published by TrES Project, the last one TrES-4b is the largest known exoplanet so far – about 70% bigger than Jupiter, but less massive, making it a planet of extremely low density (Mandushev et al. 2007).

3 Stages in the study of extra-solar planets

The process of searching for new transiting extra-solar planets and their follow-up study may be divided into several main stages:

1. **Wide-field observations**. The observations are carried out by small wide-field telescopes (TrES telescopes for example) that monitor tens of thousands of stars simultaneously, greatly increasing the probability of the precense of planets in the observed area. The light curves of all stars are analyzed and a list of suspected stars for follow-up observations is prepared.
2. **Photometric observations** to reject unsuitable candidates. Most of the candidates are actually eclipsing binary systems or pulsating stars, but additional observations are needed to understand their real nature. Telescopes with aperture of range 0.5 – 1.0 meters are appropriate for this purpose, whose resolution is large enough to separate blended objects.
3. **High-precision CCD photometry** to specify the parameters of the transit event. Accurate multi-colour observations at the moment of transit are needed to determine the parameters of the transit event – phases of the eclipses of the stellar disk, the shape of the transit, the orbital period and others. This step can be implemented with greater telescopes – 1.0m aperture or bigger. (for example FLWO 1.2m telescope or LCOGT 2.0m telescope, O'Donovan et al. 2007)
4. **Spectral observations** to determine the parameters of the parent star. The stellar parameters as effective temperature $T_{\rm eff}$, surface gravity $\log g$,

projected rotational velocity $v \sin i$ are derived using high resolution spectral observations of the parent star. If the scatter of the observed RV curve is less than 1 – 2 kms^{-1} it is possible to set an upper limit for the mass of the companion. Otherwise the candidate is rejected as eclipsing binary. The TrES team uses to this purpose CfA Digital Speedometer (Latham 1992).

5. **High-precision spectral observations** to complete the Radial Velocity curve with typical internal errors 1 – 10 ms^{-1}. Because the transit planets are relatively faint, observations with a large telescope are needed in order to reach the required precision – for example 10m Keck I telescope equipped with HIRES echelle spectrograph (O'Donovan et al. 2007).

The final model of the planetary system can be constructed as a last step after all these observations. One of the critical steps in this process is point 2, where follow-up CCD observations of hundreds suspected stars are necessary.

4 Rozhen observations

The first test observations of transiting extra-solar planets at Rozhen NAO were made during 2007 and 2008, followed by systematic monitoring of TrES planet candidates. Tests were carried out using the available observational equipment:

– **60cm Cassegrain telescope** equipped with a CCD camera SBIG STL 11000M, 4008 × 2672 array, 9 μm pixel, and Johnson BVR filters. In 2008 tests and regular observations was made with the new CCD camera FLI PL09000, 3056 × 3056 array, 12 μm pixel, and Bessell $UBVRI$ filters.
– **50/70cm Shmidt telescope** equipped with a CCD camera SBIG ST-8, 1530 × 1020 array, 9 μm pixel, and Johnson $UBVRI$ filters.
– **2m RCC telescope – main focus**, equipped with a VersArray 1330B CCD camera, 1340 × 1300 array, 20 μm pixel, and Johnson $UBVRI$ filters.
– **2m RCC telescope – Coude spectrograph**, Photometrics CCD camera, 1024 × 1024 array, 24 μm pixel, BL 628/14.7 diffraction grating.

The first transit phenomenon for a planet TrES-3b was recorded by 60cm telescope in August 24, 2007 (Fig. 1, left panel). The basic data for the parent star and the planet itself are systematized in a Table 1:

100 individual two-minute measurements in V were made with the total duration of observations of about 4.5 hours. The duration of transit event was $T_D \simeq 105$ minutes, the depth of the transit was $D = 2.5\%$, and the scatter of the light curve is about 0.015 mag. The observation of the TrES-3b event on the next night with 50/70cm Shmidt telescope was unsuccessful, because wrong ephemeris and bad weather conditions.

Test observations of extra-solar planets with 2m RCC telescope were carried out on October 01, 2008. The planet XO-2b (Burke et al. 2007) was selected for monitoring as the only appropriate, although it was not possible to cover the entire event. The basic data for the parent star and the planet are listed in a Table 2, and the resulting light curve is shown in Fig. 1 (right

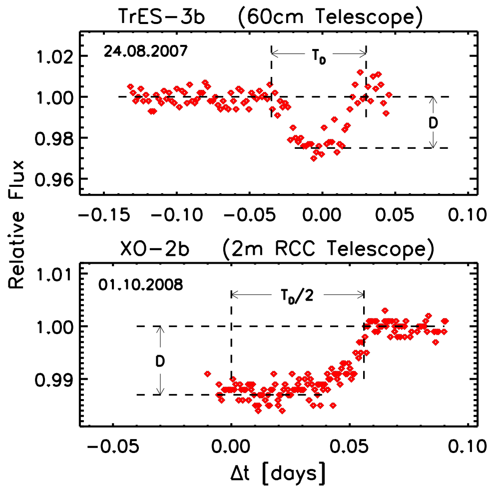

Fig. 1. The first observations of extra-solar transit planets with 60cm and 2m RCC telescopes at Rozhen NAO.

Table 1. TrES-3b transit extra-solar planet and it's parent star data (O'Donovan et al. 2007).

Parent star's data			Planet's data		
ID		GSC 3089 0929	$P_{\rm orb}$	[days]	= 1.30619
V	[mag]	= 12.402	a	[AU]	= 0.0226
$B-V$	[mag]	= 0.712	i	[deg]	= 82.15
$M_{\rm star}$	$[M_{\rm Sun}]$	= 0.9	K	[ms^{-1}]	= 378
$R_{\rm star}$	$[R_{\rm Sun}]$	= 0.802	$M_{\rm P}$	$[M_{\rm Jup}]$	= 1.92
$T_{\rm eff}$	[K]	= 5720	$R_{\rm P}$	$[R_{\rm Jup}]$	= 1.295
$\log g$		= 4.6	$R_{\rm P}/R_{\rm star}$		= 0.166
$v \sin i$		< 2 kms^{-1}			

panel). A total of 150 thirty-second data points in V filter, were carried out for total duration of 2.4 hours. The depth of the transit $D = 1.3\%$ is smaller than in TrES-3b, but the scatter is quite good – only 0.006 mag.

The test observations of extra-solar planet 51 Peg b (Mayor and Queloz 1995) with the Coude spectrograph were carried out on October, 2008 (Table 3 and Fig. 2) and the basic data for the planet and parent star are listed in Table 4. Radial velocities were measured by cross-correlation technique, choosing one of the stellar spectrum as a template, and all radial velocities were compared to the its radial velocity. It is evident that in spite of the relatively small internal errors of the individual measurements, comparable to the amplitude of the theoretical RV curve, the scatter of the observations completely prevents the detection of the RV changes generated by planets.

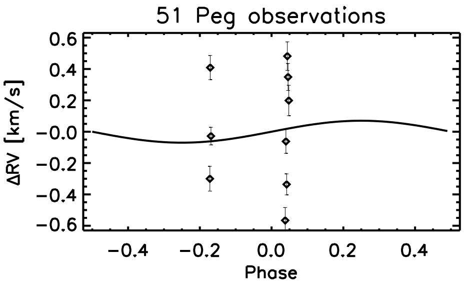

Fig. 2. RV curve of 51 Peg b extra-solar planet: diamonds present observational data, the solid line is the model ($P = 4.23$ days, $K = 55$ ms^{-1}, $e = 0.00$).

Table 2. XO-2b transit extra-solar planet and it's parent star data (Burke et al. 2007).

Parent star's data			Planet's data		
ID		GSC 3413 0005	P_{orb}	[days]	= 2.615857
V	[mag]	= 11.18	a	[AU]	= 0.0369
$B-V$	[mag]	= 0.82	i	[deg]	= 88.9
M_{star}	[M_{Sun}]	= 0.98	K	[ms^{-1}]	= 85
R_{star}	[R_{Sun}]	= 0.97	M_{P}	[M_{Jup}]	= 0.57
T_{eff}	[K]	= 5340	R_{P}	[R_{Jup}]	= 0.98
$\log g$		= 4.48			
$v \sin i$		= 1.4 kms^{-1}			

The scatter of observations probably occurs as a consequence of instabilities in the parameters of the spectrograph construction.

Table 3. 51 Peg b extra-solar planet observations.

Date	HJD	RV [kms^{-1}]	Phase
15.10.2008	2454755.502170	-0.316 ± 0.079	0.828
	2454755.509480	0.393 ± 0.077	0.829
	2454755.516695	-0.044 ± 0.056	0.831
16.10.2008	2454756.393210	-0.582 ± 0.082	0.038
	2454756.400453	-0.078 ± 0.076	0.040
	2454756.407692	-0.352 ± 0.067	0.042
	2454756.418745	0.466 ± 0.091	0.044
	2454756.425956	0.333 ± 0.086	0.046
	2454756.433164	0.183 ± 0.097	0.048

After the successful test carried out on 60cm telescope, a systematic monitoring began for TrES suspected stars. More than 30 candidates were ob-

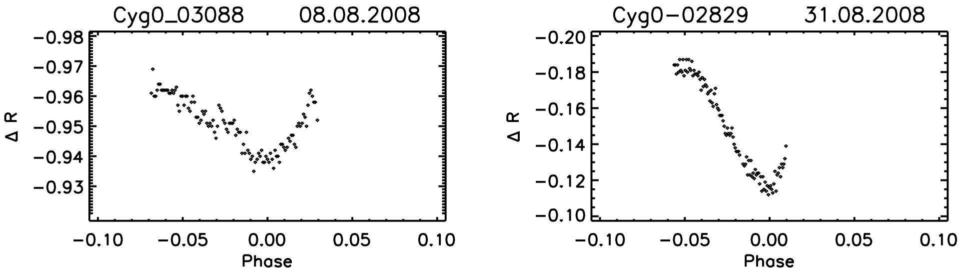

Fig. 3. Light curves of still suspected candidates, which need additional observations.

Table 4. 51 Peg b extra-solar planet and it's parent star data (Schneider 1995).

Parent star's data			Planet's data		
Spectra		G2IV	$P_{\rm orb}$	[days]	= 4.23077
V	[mag]	= 5.49	a	[AU]	= 0.052
$M_{\rm star}$	[$M_{\rm Sun}$]	= 1.11	K	[ms^{-1}]	= 54.99
$R_{\rm star}$	[$R_{\rm Sun}$]	= 1.266	$M_{\rm P}$	[$M_{\rm Jup}$]	= 0.468
$T_{\rm eff}$	[K]	= 5793	$R_{\rm P}$	[$R_{\rm Jup}$]	= 0.98
Metalicity	[Fe/H]	= 0.2			

served during last 1.5 years, and eclipse events for a part of them were registered. Figure 3 shows the light curves of the candidates who still need additional observations. If they are not exoplanets, there is a great chance for them to be brown dwarfs – objects also interesting to astrophysics.

Other cases of rejected candidates are presented in Fig. 4 and 5. The amplitude of the minimum is quite large – several tenths of magnitude, so the stars are classified as eclipsing binary systems. As it was mentioned in section 2 the resolution of the wide-field telescope is insufficient and the close objects may be blended, leading to misinterpretation of the data. The shift in the time of the minimum can be seen on those figures, due to incorrectly estimated period. The shift can reach up to several hours and this is the reason not to register an event for some of the observed stars.

Conclusion

The following conclusions can be derived using the tests and regular observations of suspected transiting extra-solar planets:

1. **60cm telescope** at Rozhen NAO is suitable for the task of monitoring of the suspected stars and rejection of inappropriate candidates – a task No 2 (in section 3). The observations with this telescope are also useful for specifying the orbital period of the system.

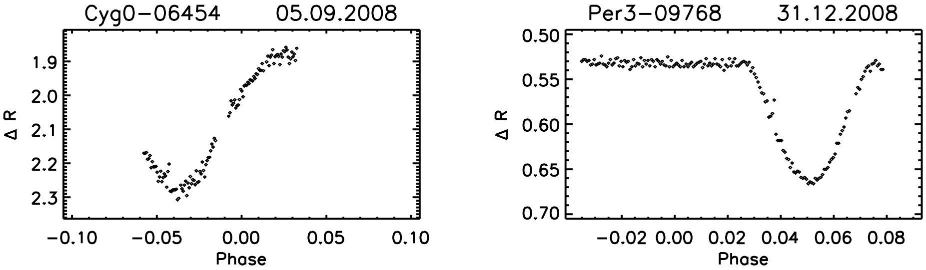

Fig. 4. Light curves of rejected candidates - actually eclipsing binary systems.

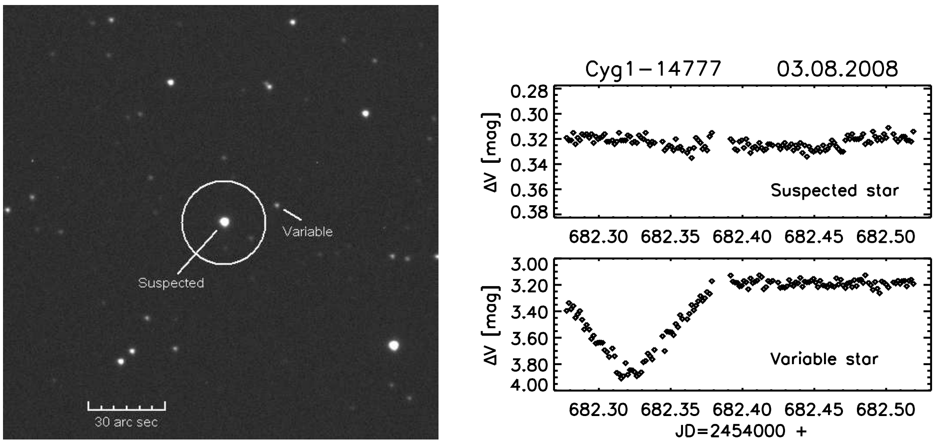

Fig. 5. The chart and light curves of suspected star Cyg1-14777 and nearby true eclipsing binary, observed with 60cm telescope at Rozhen NAO. The circle indicates the resolution of wide-field TrES telescopes.

2. **2m telescope, in its main focus**, can be used for high-precision multicolour observations of the transit event of the suspected extra-solar planet – a task No 3.
3. **2m telescope, in the Coude regime**, can be used to fulfill task No 4., but only for relatively bright stars (brighter than 9 mag in V). The situation will not improve significantly, if the 2m telescope is equipped with high-resolution echelle spectrograph – the fainter stars will be still unavailable again. The advantage of a new spectrograph is the ability to apply the other basic method of searching for extra-solar planets – the Radial Velocity method (for the brightest stars only).
4. **50/70cm Shmidt telescope**, equipped with a new wide-area CCD camera can be used along with the 60cm telescope for a task No 2.

There are existing possibilities to perform several stages of the discovery and research of extra-solar planets at Rozhen NAO but the absence of an wide-field automatic telescope for preliminary extraction of candidates prevents the completion of the full cycle of extra-solar planets study.

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