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Extrasolar worlds: a review of the current state of exoplanet research in Russia and the world

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Abstract. The history of the discovery and the main results of the study of extrasolar planets (exoplanets) in the world and in Russia are presented. The main emphasis is on describing the methods and results of the most successful space and ground-based research projects. The most striking examples among the studies of exoplanets discovered around stars of different types are given. The Russian projects over the past few years for the search and study of exoplanets, their results, and immediate prospects are described.

Keywords: planets and satellites: detection; methods: observational; techniques: photometric, spectroscopic

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1 Introduction

The theme of the plurality of worlds in the Universe has occupied the minds of thikers and nations of all times for thousands of years. In attempts to understand the structure of our world and the place of humanity in it, some thinkers of the past, long before the advent of modern observational means, even expressed the opinion that the stars are distant suns, around which planets like Earth and other planets of the Solar system can revolve. In particular, Giordano Bruno, who lived in the 16th century, suggested that life is not only on Earth, that it is distributed in an infinite Universe on planets with diverse conditions, and that the forms it takes are infinitely diverse (Bruno 1584). He also believed that life inevitably gives rise to intelligence. Currently, the truth of many of Bruno's amazing statements is confirmed by modern science. Meanwhile, despite such interest, systematic studies of extrasolar planets began only recently.

In fact, the first confidently confirmed extrasolar planets (hereinafter referred to as "exoplanets", or simply "planets") date back to the nineties of the 20th century (Wright and Gaudi 2013), although such research could have begun much earlier and been successful. Apparently, such a historical delay was associated with pessimistic expectations regarding the detectability of exoplanets. In particular, the existence of hot Jupiters—exoplanets with a mass close to the mass of Jupiter but orbiting in orbits close to the stars with periods of less than 10 days—turned out to be a surprise for astronomers (Bryant et al. 2023). Massive planets orbiting red dwarf stars exhibit very deep transits (Kanodia et al. 2023), which could once be detected even by photoelectric methods. They also demonstrate amplitudes of variability in the radial velocities of stars up to several hundred $\mathrm{m\,s^{-1}}$, which could easily be detected within the framework of classical high-spectral resolution spectrographs of the generation of the 60–70s of the 20th century.

The history of the systematic search and study of exoplanets started in the 80s of the last century. However, most reports of positive detections of planetary mass objects before 1995 turned out to be erroneous. Only two of them have been confirmed and recognized by the world scientific community. In particular, in 1988, Canadian astronomers B. Campbell, G. Walker, and S. Young (Campbell et al. 1988) reported the discovery of a massive planet around the main component of the binary star γ Cephei, which was finally confirmed in 2003 by Hatzes et al. (2003). Also, in 1992, Polish astronomer A. Wolszczan, using the Arecibo radio telescope, discovered two super-Earth-mass planets near the millisecond pulsar PSR B1257+12 (Wolszczan and Frail 1992).

Meanwhile, the first unequivocal discovery of a planetary mass object orbiting a normal main sequence star was announced by Swiss astronomers M. Mayor and

D. Queloz in October 1995 (Mayor and Queloz 1995). Using the ELODIE spectrograph mounted on the 1.93-m telescope at the Haute–Provence Observatory in France, Queloz et al. (1998) detected sinusoidal Doppler oscillations of the Sun-like star 51 Pegasi, located 50 light-years from Earth. The short period (4.2 days) and significant amplitude of oscillations indicated that the planet should have of about 0.5 mass of Jupiter. Thus began a triumphant march of massive discoveries and detailed studies of the physical properties of new extrasolar worlds.

2 The most important results in the history of exoplanet observations

From the mid-nineties of the last century until the present day, a number of dozens of ground and space missions have successfully added to the list of more and more extrasolar worlds. Among the most successful, it is necessary to note the work of the space observatories Kepler (Dupree 2009), CoRoT (Baglin et al. 2007), and TESS (Ricker et al. 2014) as well as the work of ground-based photometric surveys of exoplanets such as the famous SuperWASP (Street et al. 2003) or the lesser-known domestic “Kourovka Exoplanet Survey” (Burdanov et al. 2016). Thanks to all these missions, we now have a list of over ten thousand extrasolar planets and candidates. Based on these studies, the physical properties of a significant part of the confirmed planets became known, which turned out to be much more diverse than the characteristics of the planets of the Solar system. Without being able to present all this amazing diversity within the framework of this work, we will dwell only on the most significant, in our opinion, discoveries in the world of extrasolar worlds of the last few years.

February 2017. Discovery of a very compact system of seven transiting Earth-sized planets orbiting the nearby ultra-cool red dwarf TRAPPIST-1 (Gillon et al. 2017). At least three of the seven planets are in the habitable zone of their parent star.

February 2021. Direct observations with the upgraded VISIR instrument on the VLT of the stars α Centauri A and α Centauri B in the mid-IR range led to the discovery of a candidate exoplanet with a radius of 3–11 $\mathrm{R}_\oplus$ orbiting in the habitable zone of star A at a distance of about 1.1 AU (Wagner et al. 2021). This image artifact, however, may be the exozodiacal disk of α Centauri A.

January 2022. A study of transits of the gas giant Kepler-1708 b, orbiting in the habitable zone of a Sun-like star, revealed signs of the presence of a natural satellite in the orbit of the parent planet (Kipping et al. 2022). The exomoon’s radius can be 2.6 times greater than Earth’s, and its orbital period can be 4.6 days.

July 2022. The beginning of the scientific program of the infrared James Webb Space Telescope (JWST) marked a new stage in the development of astronomy in general, and exoplanetary research in particular (Pontoppidan et al. 2022). The observatory was designed and developed by the National Aeronautics and Space Administration (NASA) in collaboration with the European and Canadian Space Agencies (ESA and CSA), and has a segmented mirror with a total diameter of 6.5 meters. The beginning of a massive study of the atmospheres of exoplanets with a wide variety of sizes, both in direct light (Lustig-Yaeger et al. 2023) and in reflected light.

March–September 2023. Using JWST, several emission and transmission spectra of two inner planets of the TRAPPIST-1 system, b and c, were obtained (Lim et al. 2023). Due to their proximity to the star, both are tidally locked. The high brightness temperature and lack of heat redistribution from the day side to the night side suggest the absence of noticeable atmospheres—both planets probably resemble Mercury with a bare surface.

September 2023. Using JWST, the transmission spectrum of mini-Neptune K2-18 b was obtained at wavelengths of 0.9–5.2 μm (Madhusudhan et al. 2023). The presence of methane and carbon dioxide as well as the absence of ammonia was detected. This may indicate the existence of an ocean of liquid water under a temperate, hydrogen-rich atmosphere. The water probably forms clouds in deeper layers of the atmosphere than was accessible to James Webb.

March–June 2024. Using JWST, transmission spectra of LHS 1140 b, a planet with a radius of $1.73\,\mathrm{R}_\oplus$ orbiting in the habitable zone of a red dwarf, were obtained at wavelengths of 0.65–5.18 μm (Cadieux et al. 2024). A hydrogen-rich atmosphere was excluded, but the spectrum showed evidence of Rayleigh scattering in a nitrogen-dominated atmosphere. The water clouds likely form deep enough to remain undetected.

3 Basic methods for detecting and studying exoplanets

Today, there is a significant collection of methods for diagnosing the exoplanetary environment of stars of various types. Among them, probably the only direct one is the method of obtaining images of exoplanets using coronagraphs and adaptive cameras in the case of ground-based observations. Using this method, the presence of entire families of outer planets in the surroundings of several bright stars was discovered (see, e.g., Marois et al. 2010). The advantages of the method are obvious, so they are not discussed here.

The disadvantages include the limited application of the method under ground-based observations. All other methods are indirect in one way or another. Let us consider only those of them that, in our opinion, are the main ones and the combination of which provides unambiguous information about the presence and physical properties of exoplanets in the orbits of their parent stars.

3.1 Photometric transit method

This is one of the most productive methods of searching for the planets the orientation of whose orbits makes it possible to observe the events of their passage against the background of the disks of their parent stars. For ground-based instruments, the method makes it possible to detect exoplanets that are capable of causing a drop in the light flux from the parent star from several percent ("Jupiters" against the background of small stars) to 0.1% ("super-Earths" and even "Earths" against the background of red dwarfs). Figure 1 shows an example of a comprehensive observation of super-Earth transits in the star system HD 219134 (Valyavin et al. 2018). These results, obtained using the 1-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS), clearly illustrate the precision capabilities of ground-based astronomy in the study of exoplanets. In this case, the transit depth obtained in total from five events is determined at the level of $0.13 \pm 0.027\%$ (Valyavin et al. 2018).

Often within the framework of the method, depending on the forms of transits, it is possible to speak with a high degree of probability about a transit event of a planetary nature even without the involvement of additional research. Figures 2 and 3 show different examples of the shapes of transit curves obtained using the robotic 0.5-m telescopes of SAO RAS (Valyavin et al. 2022a,b). The observed data are taken from Yakovlev et al. (2022, 2023).

As you can see, the registered forms of transits can be different. The example in Fig. 2 represents the so-called sliding transit. In this case, as a rule, there is great uncertainty in establishing the size of the eclipsing body relative to the disk of the parent star. Such transits are quite often diagnosed as false. Meanwhile, examples of central transits (Fig. 3) immediately give an idea of the size of the eclipsing body. Such transits, as a rule, require minimal additional diagnostics to confirm their planetary nature.

Among these methods, the main one is the radial velocity method.

3.2 Radial velocity method

Along with the photometric transit method, the radial velocity method based on Doppler spectroscopy is traditionally one of the most popular and effective methods

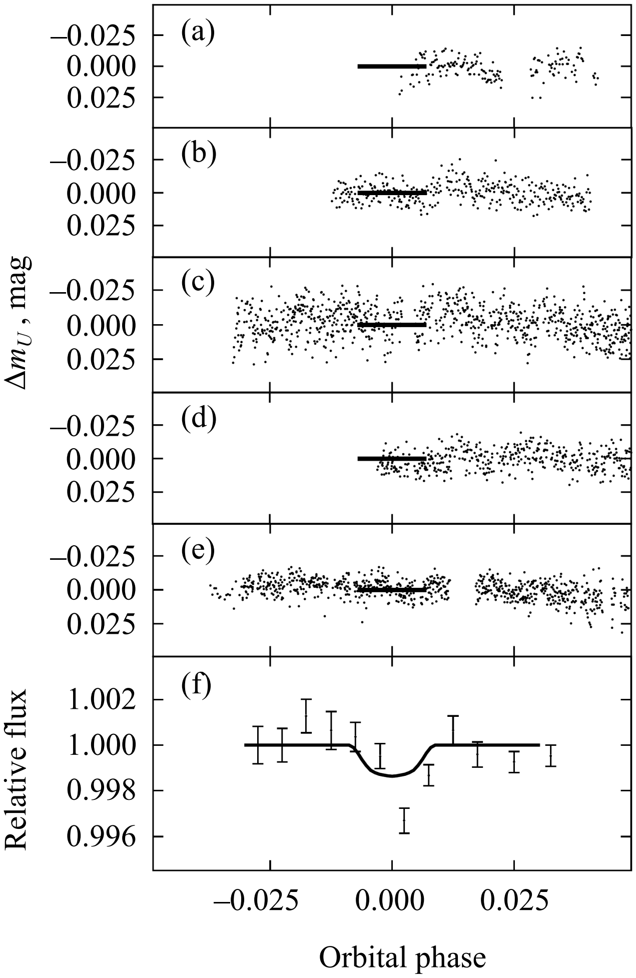

Fig. 1. Phased time series of flux in the Johnson system U band from the star HD 219134 in units of residual magnitudes for different dates (a, b, c, d, e) and their average (f). For details, see Valyavin et al. (2018).

for searching and studying the physical characteristics of exoplanets. Despite this, just like the transit method, Doppler diagnostics is not self-sufficient. There are a number of effects that mimic the Doppler variability of the radial velocities of stars. In particular, the presence of global magnetic fields with secular stability can cause rotationally modulated variability of radial velocities in such stars. For example (see Lee et al. 2018), the star χ Dra A exhibited signs of the presence of a global magnetic field, the variability of which coincided with the rotation of the star. Detected

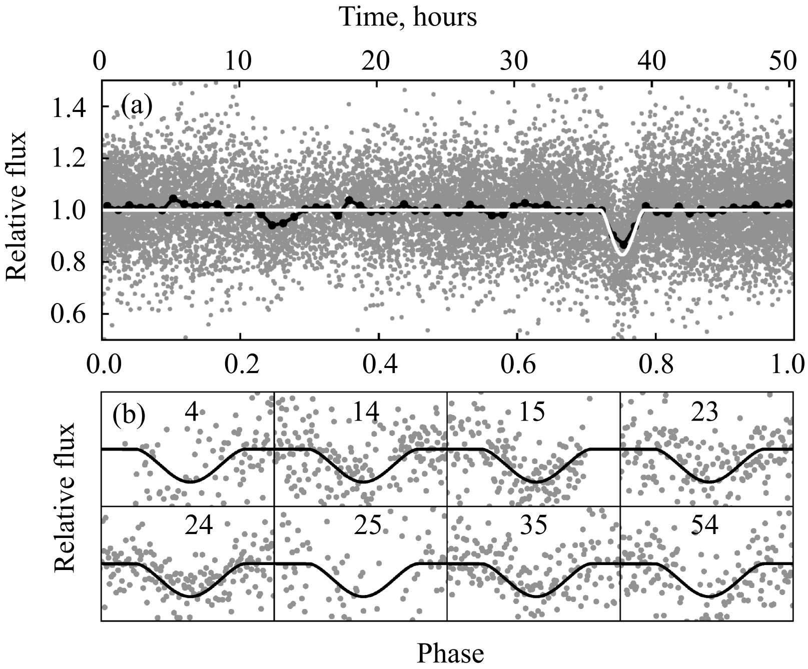

Fig. 2. Light curve of SOI-2 (Yakovlev et al. 2022, 2023). Top: phase convolution with the rotation period (dots), median values (black line), and the model curve (white line). Bottom: fragments of individual transits with the same model curve (black line).

variability of the radial velocities of the star (Lee et al. 2018) folded with the found rotation period is shown in Fig. 4. The arguments presented in Han et al. (2018) indicate that the desired variability in the radial velocity of the star is caused not by an exoplanet but by a rotationally modulated magnetic field.

Of course, the found change in the star's radial velocity may also be associated with a synchronously rotating planet, but uncertainty of this kind in this particular case cannot be resolved unambiguously. Meanwhile, for systems whose planetary orbits are visible "edge-on" to an observer on Earth, the radial velocity method in combination with the transit method in the vast majority of cases provides an accurate diagnosis of the planetary nature of the registered transit event. In this regard, let us dwell on the spectroscopic technique of testing the variability of the radial velocities of stars in a little more detail.

It is known (Valenti et al. 1995) that the observed spectra of stars are presented by the convolution of their true spectra with the instrumental profile (IP) of the spectrograph. In the general case, the IP is a multiparameter function depending on

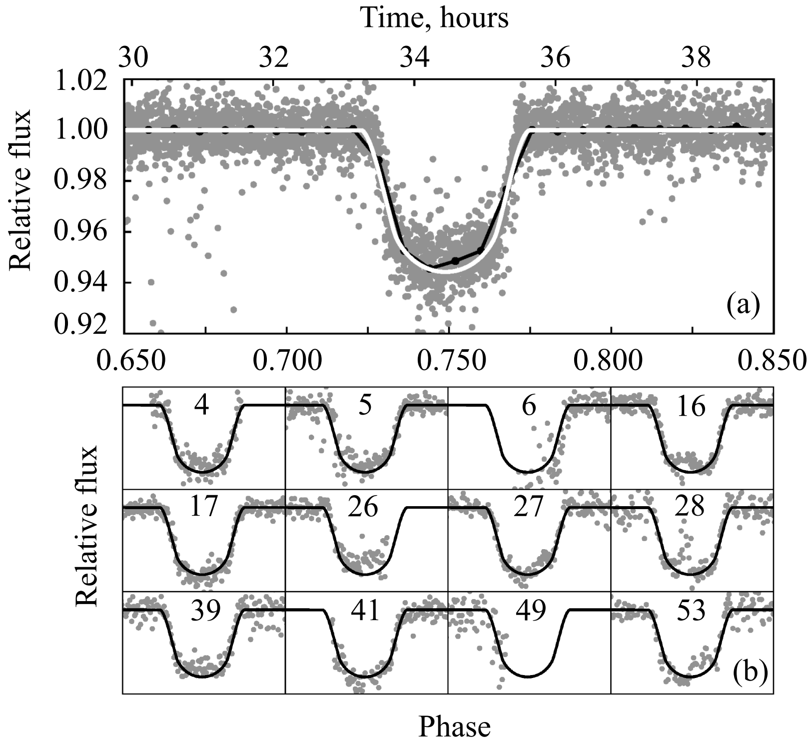

Fig. 3. Light curve of SOI-3 (Yakovlev et al. 2022, 2023), explanations are given in the caption to Fig. 2.

the slit width, the quality of the instrument optics, etc. For classical spectrographs, which do not provide uniform illumination of the slit by the light of the star being studied and/or stabilization of its image on the slit, the IP is also a function of the position of the star (object) on the slit and weather conditions. For this reason (lack of sufficient optical stabilization), also in the absence of thermal and mechanical stabilization of the spectrograph, the IP is a variable function depending on time. The presence of this variability can introduce distortions in the position of spectral lines in the observed spectra of stars up to several $\mathrm{km\,s^{-1}}$. Thus, in the matter of achieving the accuracy of measurements of stellar radial velocities necessary for detecting exoplanets, there are two methods. The first is associated with the technique of wavelength calibration, which allows determining the IP in each observation and taking into account its variability when calculating the Doppler shift in the spectra of stars. To date, the most proven method for determining the IP uses the so-called absorption iodine cell (Valenti et al. 1995). The iodine cell is a transparent, sealed flask

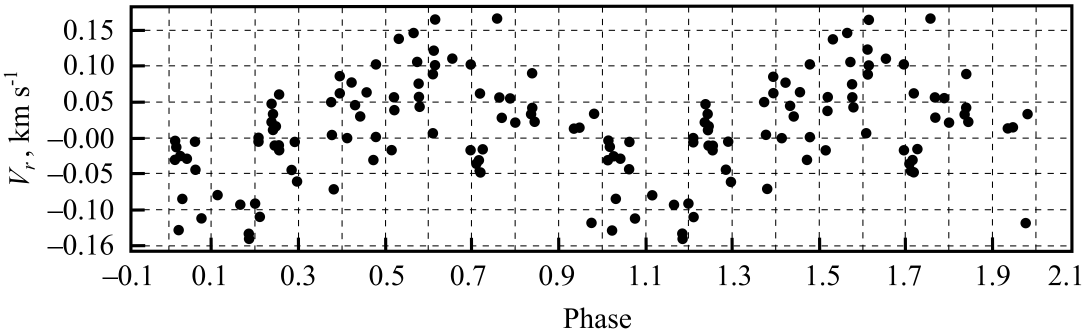

Fig. 4. Residual curve of variation in the radial velocity of χ Dra A convolved with the star rotation period $P = 22\overset{\mathrm{d}}{.}2$.

filled with molecular iodine gas I 2. When light from a star passes through the cell, a system of molecular lines of I 2 is generated in the resulting spectrum between wavelengths of 500 nm and 600 nm in addition to the spectrum of the star. The shapes and residual intensities of these lines are weakly sensitive to changes in pressure and temperature of the environment. And, since they are recorded under conditions absolutely identical to recording the stellar spectrum, precise knowledge of the shapes of their profiles allows one for each wavelength in the range of 500–600 nm to obtain the IP shape directly at the moment of observing the star. In turn, this allows correction almost all distortions related to spectrograph instability. Thus, the use of iodine cells in combination with slit spectrographs, even without expensive optical-mechanical stabilization, is capable of demonstrating the accuracy of measuring the variability of radial velocities of stars sufficient for searching for exoplanets near them. This is the main advantage of the method. The disadvantages include a limited spectral range and significant loss of light due to absorption by iodine in the working range of 500–600 nm.

The second method involves the maximum possible optical-mechanical stabilization of the spectrograph. The use of a fiber-optic input instead of a slit has revolutionized this type of spectrograph. For a long time, the world leader in this concept was the HARPS fiber-optic input spectrograph (Mayor et al. 2003). This instrument took all possible measures for its optical, mechanical and thermal protection. In addition, the entire spectral part of HARPS is placed in a vacuum chamber, which, among other things, eliminates the instability of the resulting spectrograms due to fluctuations in air refraction in the optical path of the spectrograph. With the help of this instrument, over the past two decades, probably the most accurate Doppler studies of exoplanets have been obtained, up to 20 cm s^{-1} and even higher.

As our practice has shown (Burlakova et al. 2020; Gadelshin et al. 2020; Valyavin et al. 2022a,b; Galazutdinov et al. 2023) with the BTA FFOREST fiber-optic spectrograph (Valyavin et al. 2014, 2015, 2020; Galazutdinov et al. 2023), this path has significantly greater prospects compared to the previous method, although it is more financially expensive.

3.3 Transmission spectroscopy

Transmission spectroscopy methods, which can detect changes in the radii of transiting exoplanets with wavelength, provide a unique opportunity to study the physical and chemical properties of their atmospheres. The transmission spectrum is the dependence of the exoplanet radius, obtained by observing a planet transit in a number of bands over the spectral range, on the wavelength. To construct broadband and midband transmission spectra, multicolor photometric and spectrophotometric observations are carried out on telescopes of different apertures. Analysis of such spectra helps draw conclusions about the vertical structure and internal structure of the planet's atmospheric layers and study their evolution. Transmission spectroscopy also allows us to reconstruct absorption and scattering lines in the exoplanet's atmosphere. More details on the method can be found in Valyavin et al. (2018) and references therein.

4 Russian ground-based projects for the study of exoplanets and their future prospects

Unfortunately, in Russia, for various reasons, this area lags far behind the level of world science, especially in terms of observational astronomy. Meanwhile, over the past 10 years, several domestic working groups on the study of exoplanets have been formed from astronomers of the Kourovka and Pulkovo Observatories, SAO RAS, and Kazan Federal University. Through their efforts, together with groups from other countries, almost ten exoplanets have already been discovered. Also, several scientific groups from INASAN, SAI MSU, IKI RAS, and others are known for their strong theoretical studies of exoplanets.

Since the creation of the Russian Science Foundation in 2014, financial support for instrumental scientific projects on a competitive and private basis has created a stable trend in Russia in the direction of experimental research of exoplanets by ground-based observational means. In particular, the efforts of young enthusiastic scientists united around the photometric project MASTER (for the results from the part of it at the Kourovka Observatory, see Burdanov et al. 2016) allowed the first, Kourovka survey of exoplanet candidates to begin and the first exoplanet in Russia to be discovered based on additional diagnostics of these candidates by different methods at SAO RAS and other observatories.

Another successful working project, which allowed systematic observations of exoplanets by the Doppler method and which at about the same time began to give positive detections (Yılmaz et al. 2017), is the Russian-Turkish project, headed on the Russian side by Kazan University, the owner of a 1.5-m telescope on an equal basis with the Turkish side. This telescope has a high spectral resolution spectrograph, which allowed achieving the accuracy necessary for discovery with an iodine cell.

Young Russian astronomers have also achieved some success in the search for exoplanets using the TTV (Transit Time Variation) method. As part of their research (Sokov et al. 2018), a second exoplanet TrES-5c was discovered in the TrES-5 system.

Finally, the EXPLANATION (EXoPLANet And Transient Events InvestigatiON) project has been running since 2022. The goal of the project is a mass search for non-stationary events in the Universe using photometric, speckle interferometric, spectral, and radiobolometric observing methods as well as the study of exoplanets. The core of the project is all optical telescopes of SAO RAS and a number of other observatories. The philosophy of the project and the first results of its work are presented in Valyavin et al. (2022a,b); Yakovlev et al. (2022, 2023). We associate further prospects for the development of exoplanet research in Russia with this project as well as with the upcoming launch and operation of the Russian space mission WSO-UV (Sachkov et al. 2022).

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