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SEARCH FOR EXOPLANETS: STATUS 2020

V. G. Surdin[*]

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An overview of the history, status by mid-2020, and the nearest prospects for the search and study of planets outside the solar system — exoplanets, is given.

1. TERMINOLOGY AND DESIGNATIONS

The term "exoplanet" is currently used in two meanings. In a broad sense, it is any planet outside the Solar System, i. e., an extrasolar planet, regardless of whether it is associated with any particular star or not. In this sense, all the planets in the Universe, except for the eight known planets of the Solar System, are exoplanets. However, this contradicts the definition accepted by the International Astronomical Union (IAU) in 2006. A planet was considered as a celestial body orbiting a star or stellar remnant with a mass less than that at which fusion reactions with deuterium can occur (more than 13 Jupiter masses for objects of solar metallicity), but sufficient for the gravity to shape the body as a sphere and to clear the neighborhood of its orbit from the objects of a smaller mass.

The term "exoplanet" is often interpreted in a narrow sense, as "a planet belonging to a different, non-Solar, planetary system" in order to avoid contradiction. This definition does not include planetary bodies that are not gravitationally bound to any star, but are free-floating in interstellar or intergalactic space. It is necessary to introduce separate terms for them: an orphan planet, a rogue planet, a nomad planet, a planemo (planetary mass object), a wandering planet, an interstellar planet, a free-floating planet, an unbound planet, a starless planet, a sunless planet, a quasi-planet, a single planet, a sub-brown dwarf, etc. The IAU has not made an unambiguous decision about the naming of such planets so far. Further, we will refer to all bodies of planetary mass outside the Solar System as exoplanets, i. e., they are not bound to the Sun by gravity.

The designation of an exoplanet belonging to a star consists of the naming of that star followed by a Latin letter starting with "b". The letter "a" is reserved for the star itself. For example, YZ Cet b, YZ Cet c, and YZ Cet d are the first, second, and third (in order of discovery) planets of the YZ Ceti star, respectively.

In 2014, the IAU invited everyone to invent names for exoplanets, followed by a national vote, to attract public interest in science. Thus, several dozen exoplanets got their own names, e. g., Orbitar (42 Dragon b), Poltergeist (PSR B1257+12 c), etc. The names of some planets are historically linked. For example, the four planets near the Mu Altar star (μ Arae) are named Quixote (μ Ara b), Dulcinea (μ Ara c), Rocinante (μ Ara d), and Sancho (μ Ara e). And the five planets near the 55 Cancri star (55 Cnc) are named Galileo (55 Cnc b), Brahe (55 Cnc c), Lippersgey (55 Cnc d), Jansen (55 Cnc e), and Herriot (55 Cnc f).

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[*] vsurdin@gmail.com

M. V. Lomonosov Moscow State University, P. K. Sternberg State Astronomical Institute, A. A. Kharkevich Institute for Information Transmission Problems of the Russian Academy of Sciences, Moscow, Russia. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Radiofizika, Vol. 63, Nos. 9–10, pp. 730–748, September–October 2020. Original article submitted May 6, 2020; accepted June 9, 2020.

2. INDIRECT EVIDENCE

Indirect signs of the existence of exoplanets were frequently recorded during the XX century. In 1917, the lines of heavy elements were detected in the spectrum of the nearest single white dwarf van Maanen 2, which, taking the high gravity at the surface of this star into account, could not stay in its upper atmosphere for a long time, and it was the first indication, correctly understood only today. Nowadays, an infrared excess was found in the radiation of this star, indicating a debris disk around it. Most likely, heavy elements fall on the star together with dust and larger bodies (asteroids, comet nuclei, etc.), whose orbital motion is disturbed by at least one massive planet [1].

The morphology of planetary nebulae, which are the precursors of white dwarfs, also implies the presence of planets. Planetary nebulae often have mirror symmetry, indirectly indicating that the plane of symmetry is determined by the orbital plane of the planetary system. Such "bipolar" nebulae make up 14% of all classified objects [2], which, in view of their arbitrary spatial orientation, can be considered a fairly high fraction.

The presence of gas and dust protoplanetary disks in the forming stellar objects and young stars of the T Tauri type has long indicated the possibility of the birth of planetary systems [3]. Recent detailed studies using the ALMA telescope have revealed "dust-free" orbits in these disks, which is indirect evidence for the presence of massive bodies in these orbits. The assumption was confirmed in 2018: two planets were found in the protoplanetary disk of the T-type Tau PDS 70 star (V1032 Centauri). At the same time, one of them even has a protosatellite disk [4].

Thus, indirect signs of the formation and presence of planets near different types of stars had been detected even before the discovery of the exoplanets themselves.

3. FIRST ASTROMETRIC SEARCH

The practical search for exoplanets was started in the middle of the XX century using the methods of optical astronomy. Table 1 shows what the Solar System would look like when observed from the nearest Alpha Centauri star (α Cen). Generally speaking, our planets themselves would be detectable by the most advanced modern telescopes if they were located away from the bright stars. But in reality, the Sun with its apparent brightness of 0.5^m is next to them at a very small angular distance. It is hundreds of millions of times brighter than any of the planets, and its diffused light obscures completely their images. It was impossible to detect such dim objects next to such a bright star without any special equipment, which began to appear only in the XXI century.

TABLE 1. The Solar System when observed from α Cen.

Planet	Maximum angular distance from the Sun, seconds	Apparent brightness, m
Mercury	0.3	27
Venus	0.5	24
Earth	0.8	25
Mars	1.1	27
Jupiter	3.9	22
Saturn	7.2	23
Uranus	14.0	27
Neptune	23.0	28

Therefore, the search was conducted only with the help of astrometric measurements from 1938 to 1990: attempts were made to detect periodic displacements of the stars themselves in the picture plane (i. e., in the sky plane perpendicular to the observer's line of sight) under the influence of the planets orbiting around them. Although these oscillations usually do not exceed $0.01''$ even for nearby stars, which is lower than the practical precision of ground-based astrometric measurements, it was hoped to distinguish them from errors, taking into account the periodic nature of the star's displacement related to the orbital motion of the planet.

The astrometric method did not bring any reliable results for several decades, although, since 1942, reports on the discovery of exoplanets have been published several times, but each time they were not confirmed. The greatest interest of astronomers was attracted by "Barnard's Flying Star" in the constellation

Ophiuchus (BD+04°3 561a, Gliese 699, HIP 87937). Its visual apparent magnitude is 9.5^m, and its distance from the Sun is 1.83 pc. It is the fourth star after the three components of the Alpha Centauri system (α Cen) in its proximity to us.

Since the mass of Barnard's star is almost 6 times less than the mass of the Sun, the influence of its neighbor planets (if any) should be very pronounced. The movement of this star was being studied by the American astronomer Peter van de Kamp (1901–1995) for more than half a century, since 1938. He measured its position on thousands of photographic plates and stated that the star had a wavy trajectory with a swinging amplitude of about $0.02''$, which meant that an invisible satellite orbited around it. It followed from van de Kamp's calculations that the mass of the satellite is slightly greater than the mass of Jupiter (M_{Jup}), and the radius of its orbit is 4.4 a. u. In the early 1960s, this message spread around the world and received a wide response. Continuing his observations, van de Kamp later insisted on the existence of two or even three planets near Barnard's star. Confidence in the existence of planets near Barnard's star was so great that in the mid-1970s a detailed project of launching a nuclear starship Daedalus to the star to search for a habitable planet was developed.

However, not all astronomers agreed with van de Kamp's conclusions. Continuing observations and increasing measurement accuracy, the American astronomer George Gatewood and his colleagues found out by 1973 that Barnard's star moves smoothly, without oscillations, which meant that it does not have any massive planets as satellites. However, these works brought a new discovery in 1996: zigzags in the motion of the sixth star from the Sun, Lalande 21185, were observed, which is 2.5 pc away from us (van de Kamp himself pointed out its undulatory motion back in 1951). According to Gatewood, two planets orbit the star Lalande 21185: one with a period of 30 years (mass $1.6M_{\text{Jup}}$ and orbit radius 10 a. u.) and the second with a period of 6 years ($0.9M_{\text{Jup}}$ and 2.5 a. u.). But this discovery is still not only unconfirmed, but also raises more and more doubts. However, in 2017, a planet with a mass of about $0.01M_{\text{Jup}}$ was detected near the star Laland 21185 by the Doppler method (see the text below) in an orbit with a semi-major axis of 0.07 a. u. and a period of about 10 days. But this is not at all what the astrometrists used to assume.

The search for planets near Barnard's star using the Doppler method also brought a positive result: a body with a mass of about 3 Earth masses ($0.01M_{\text{Jup}}$) and an orbital period of 233 days was found near it in 2018. But this is not at all what van de Kamp reported.

The astrometric method had yielded only two reliable results by 2020: the binary star HD 176051 was found to have a planet with a mass of $1.5M_{\text{Jup}}$ in 2010, and in 2018, the binary star 2MASS J0249-0557 was found to have a "super-Jupiter" with a mass of $12M_{\text{Jup}}$, close to the boundary mass with brown dwarfs ($13M_{\text{Jup}}$). However, there is a prospect for this method, and it is connected with the work of the Gaia Space Observatory (ESA), which has been measuring the positions of 1 billion stars with an accuracy of 7 to 300 microseconds of arc (depending on their brightness) since 2014.

4. DISCOVERY OF EXOPLANETS

Back in 1952, Otto Struve in the United States wrote that there is no good reason why planets cannot be much closer to their parent star than in the Solar System, and suggested that Doppler spectroscopy and transit photometry (transit method) could be used to detect super-Jupiters in compact orbits. He turned out to be right: it is these two methods that are now bearing the greatest results in the search and study of exoplanets. But these methods were technically impossible to apply in the middle of the XX century.

In the late 1980s, the precision of optical spectroscopy of stars began to increase, and astronomers began to search for periodic Doppler line displacements caused by the influence of orbiting planets on the star. There were hints of such a displacement in the HD 114762 and Gamma Cepheus (γ Cep A) stars in 1987–1989, but then they were not confirmed and the discovery did not take place. Later, in 2003, a planet near γ Cep A was discovered.

The first system of three exoplanets was discovered in 1991 around a neutron PSR B1257+12 radio pulsar. Their masses were comparable to the mass of the Earth (M_{E}): 3.8 M_{E}, 4.1 M_{E}, and 0.02 M_{E}. Although the latter body is more similar in mass to the Moon, it has the physical features of a planet, since, based on its mass, it should have a spherical shape. The discovery was made by the Polish radio astronomer Aleksander Wolszczan working in the United States at the 305-meter telescope in Arecibo, who noticed a periodic variation in the frequency of arrival of pulses from the pulsar. Although this technique is usually called the timing, it is essentially close to the Doppler methods.

Later, a search for planets near several thousand other pulsars led to the discovery of planet-like objects near 13 of them, and they turned out to be real planets with masses less than the lower limit of the mass of brown dwarfs near half of the pulsars. The multi-planet system, except for PSR B1257+12, was found only near the PSR B0943+10 pulsar; it consists of two planets with masses of about $3M_{\text{Jup}}$ each. The orbital periods of some near-pulsar planets are extremely short: from 40 min to 2 h.

Although the bodies found near pulsars are similar in mass to planets, their origin seems to be secondary. It is known that the birth of a neutron star is preceded by a supernova explosion, which causes a large mass loss (in the form of an ejected star shell). Therefore, the initial planetary system would not be able to survive: having high orbital speeds, the planets would fly away from a light neutron star. But if the exploded star was part of a binary system with a more massive (by the time of the explosion) component, then the matter of the second star, which flowed to the pulsar after the explosion, could possibly form planet-like bodies. Several variants of such a scenario are now being discussed, but such bodies are not recognized as fully featured planets. Thus, planets near neutron stars are a rare and not fully understood phenomenon.

The existence of a “real” exoplanet near a normal star was first reliably proven in 1995. This was done by astronomers at the Geneva Observatory in Switzerland, Michel Mayor and Didier Queloz, who created a stellar spectrograph capable of measuring the Doppler shift of lines to an accuracy of up to 13 m/s in 1993. The best accuracy of measuring the radial velocities of stars was 1 km/s before the appearance of this device, i. e., the new device increased it by two orders of magnitude at once.

Mayor and Queloz started regular measurements of the radial velocities of 142 sun-like stars from the close surrounding of the Sun at the Haute-Provence Observatory (France) in 1994, and in 1995 they discovered the “swinging” of the 51 Pegasus star (51 Peg) with a period of 4.23 days, caused by the influence of a planet with a mass close to Jupiter. Several teams of astronomers were involved in a similar research in those years, but the first success, partly by chance, came to Major’s team. In the future, this team remained among the leaders in the number of discovered exoplanets, but the first place was taken by the American team led by Geoffrey Marcy, which started similar observations earlier, but they failed to make the first discovery. The discovery of extrasolar planetary systems is considered one of the greatest scientific achievements of the XX century. Michel Mayor and Didier Queloz were awarded a Nobel Prize in Physics for this discovery in 2019.

TABLE 2. Sample statistics on the discovery of exoplanets [5].

Date	Number of reliably discovered exoplanets
October 5, 2003	117
December 14, 2006	210
March 23, 2009	344
November 7, 2012	843
December 1, 2016	3 544
March 11, 2019	4 000
January 11, 2020	4 168
March 5, 2020	4 692

About 20 planetary systems had been discovered near close stars by the end of the XX century. Then the growth in the number of discoveries accelerated (see Table 2). More than 270 planets had been observed in 230 systems (up to 5 planets in the system) by the beginning of 2008. And more than 760 planets (up to 6, possibly 7, planets in the system) had been discovered by 2012. Most of them were detected by the Doppler method, namely, by the periodic variation in the radial velocity of the star, but a significant part was found by the transit method (see the text below), which is becoming more and more productive.

At first, only relatively massive giant planets close to the star were discovered, but the lower mass limit decreases and the maximum distance increases from year to year. By 2012, the masses of the exoplanets observed by the Doppler method were in the range from $25M_{\text{Jup}}$ to $1M_{\text{E}}$ ($M_{\text{E}} = 0.003M_{\text{Jup}}$) and the orbital semi-major axes, from 0.006 to 30 a. u.; however, the orbital eccentricities were usually quite large. Note that

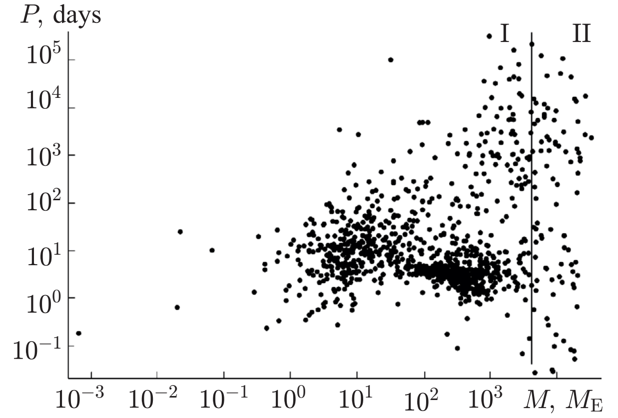

Fig. 1. Distribution of objects of the network "Encyclopedia of Exoplanets" [5] as of May 5, 2020. Here, M is the mass of the planet and P is the orbital period. The boundary mass ($13M_{\mathrm{Jup}} = 4130M_{\mathrm{E}}$) between the planets (I) and the brown dwarfs (II) is marked.

for physical reasons, the boundary between planets and brown dwarfs runs over a value of about $13M_{\mathrm{Jup}}$, but objects with a mass reserve are included in the catalog of exoplanets, since old brown dwarfs differ only slightly from extremely massive giant planets, i. e., super-Jupiters (see Fig. 1).

By 2020, the lower limit of the mass of detected exoplanets had decreased to $6.7 \cdot 10^{-4} M_{\mathrm{E}}$, i. e., to 5% of the mass of the Moon. This record belongs to the white WD 1145+017 dwarf planet, which has a diameter of about 1900 km and an orbit radius of 0.005 a. u. with an orbital period of 4.5 h. This planet is twice larger and four times more massive than the dwarf Ceres planet, which is considered dwarf only because its gravitational influence on the surrounding bodies of the Solar System is not able to compete with large planets. Otherwise, Ceres is a fully featured planet, since it has a hydrostatic spheroidal shape and its interior has undergone gravitational matter differentiation.

Calculations show that ice bodies take a rounded shape for a diameter of more than 400 km and icy-rocky bodies like Ceres, for a diameter of more than 900 km. Therefore, WD 1145+017 b can undoubtedly be considered a planet, although it is extremely peculiar. Its star, a white dwarf, has a surface temperature of about 16000 K, and the calculated surface temperature of the planet is about 4000 K. It is clear that intense ablation occurs at such a small mass and high temperature, and the estimated lifetime of the planet is from 100 to 200 million years. However, the estimated cooling time of the star is 175 million years [6], so it is not obvious that the planet will have time to completely evaporate.

5. METHODS FOR DETECTING EXOPLANETS

The existing and promising methods for detecting exoplanets are diverse, but there are two absolute leaders in the number of discoveries, namely, the spectroscopic method of radial velocities (Doppler method) and the transit photometry method [7].

5.1. The radial velocity method

This method consists in recording the periodic motion of a star along the observer's line of sight under the influence of the gravity of the planets orbiting around it. Since the masses of the planets are hundreds or even hundreds of thousands of times smaller than the masses of the stars, the oscillation rates of the stars are extremely small. For example, the maximum oscillation amplitude of the speed of the Sun is 12.4 m/s under the influence of Jupiter and 0.1 m/s under the influence of the Earth.

Even if the spectrograph makes measurements with such precision, we must remember that we do not see the center of mass, but the surface of the star which experiences eigen-oscillations, being heavy (gravity) waves, under the action of acoustic waves coming from below, from the convective zone. They contain useful information about the internal structure of the star, which is now being studied within the framework of helioseismology for the Sun and astroseismology for other stars. But these oscillations are harmful noise for the detection of exoplanets.

For example, oscillations with a period of about 5 min and a radial velocity amplitude of about 0.5 km/s on a scale of thousands of kilometers are observed in the solar photosphere, while the Sun is one of the most quiet stars. When observing a star from a distance, we see the total light from its full disk, so the oscillations are averaged, but still create noise with a velocity amplitude of 0.1 to 1 m/s and a relative brightness amplitude of the order of 10^{-3}–10^{-4}. Such measurement precision is required in spectral and photometric methods of detecting exoplanets. Therefore, it is no coincidence that solar-type pulsations of another star (η Herdsman) were first reliably recorded in 1995 — almost simultaneously with the discovery of the first exoplanet.

The best accuracy for measuring the radial velocities of stars, as was already mentioned, was 1 km/s before the advent of modern high-precision spectrographs. In 1993, Andre Baran, Michel Mayor, and Didier Queloz built ELODIE, a stellar echelon spectrograph with a resolution of 45000, which is capable of measuring the Doppler displacements of lines with an accuracy of 13 m/s (later the accuracy was increased up to 7 m/s) for the two-meter telescope. Among the features of its design, we mention fiber-optic transmission of light from the telescope to a separate temperature-controlled room, imaging of the spectrum up to the 67th order of interference, recording with a CCD matrix, and numerical cross-correlation with a digital mask.

The SOPHIE device (Spectrographe pour l'Observation des Phenomenes des Interieurs stellaires et des Exoplanetes, a spectrograph for observing phenomena in the stellar interior and exoplanets), with a resolution of 75000 and a cooled receiver was the development of the scheme. Its precision is 1.3 m/s for a single measurement and 2 m/s for long series.

In 2002, the HARPS (High Accuracy Radial Velocity Planet Searcher) spectrograph was installed on the 3.6-meter telescope at the La Silla Observatory (ESO, Chile), in which the temperature was stabilized with an accuracy of 0.01 K. Its internal velocity measurement accuracy is 30 cm/s and could be brought down to 1 cm/s, but for real long series of measurements, it gives an accuracy of 0.97 m/s, which is reduced mainly due to the intrinsic noise of the stellar surface (for astroseismology, this is not noise, but useful data). The HARPS spectrograph had been the most productive tool for detecting exoplanets before the Kepler Space Telescope was launched in 2012.

A similar HIRES device (High Resolution Echelle Spectrometer) with a precision of 1 m/s operates on the 10-meter telescopes of the W. M. Keck Observatory on the Hawaii islands. But this device can explore less bright stars due to the larger diameter of the feeding optics.

The Doppler method makes it possible to measure the mass of an exoplanet with uncertainty caused by the lack of data on the inclination of its orbit to the line of sight. The current precision of recording the radial velocity of stars at 1 m/s seems to be close to the limit related to the instability of stellar atmospheres. This precludes detecting the Earth's analogs near the Sun's analogs, which requires a precision of about a few centimeters per second. However, this already provides an opportunity to detect the presence of planets several times more massive than the Earth (the so-called "super-Earths") near stars several times less massive than the Sun. Such planets have indeed been detected, and some of them are located in those areas of their planetary systems where, according to the temperature conditions on their surface, the presence of liquid water is possible (the so-called "habitable zones").

5.2. Transit photometry method

This method consists in accurately measuring the brightness of a star to record its decrease when the exoplanet passes against the background of the star disk (see Fig. 2). Let us estimate the depth of such a "micro-eclipse" taking the Solar System as an example: Jupiter's and Earth's diameters are 10 and 109 times smaller than the diameter of the Sun, respectively. Therefore, the passage of Jupiter will weaken the brightness of the Sun by 1%, while the passage of the Earth, only by 0.008%. The first phenomenon is easy to notice when observing a fairly bright star from the Earth's surface, and the second one is almost impossible to detect from the Earth.

Figure 2, although being schematic, reflects some fine details in the brightness variation of the "star + exoplanet" system, e. g., when a planet passes in front of a star, the brightness changes symmetrically with a minimum in the middle. This is due to the fact that after crossing the limb, the planet first approaches the disk center and then moves away from it. The star disk in the optical range has a maximum brightness

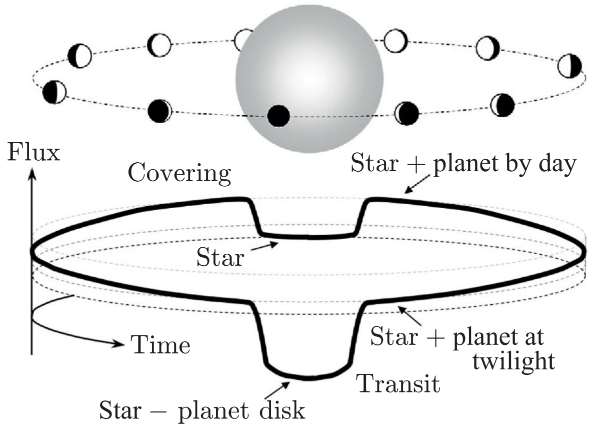

Fig. 2. Brightness variation of the "star + planet" system in the orbital period. The star radiance is considered unchanged.

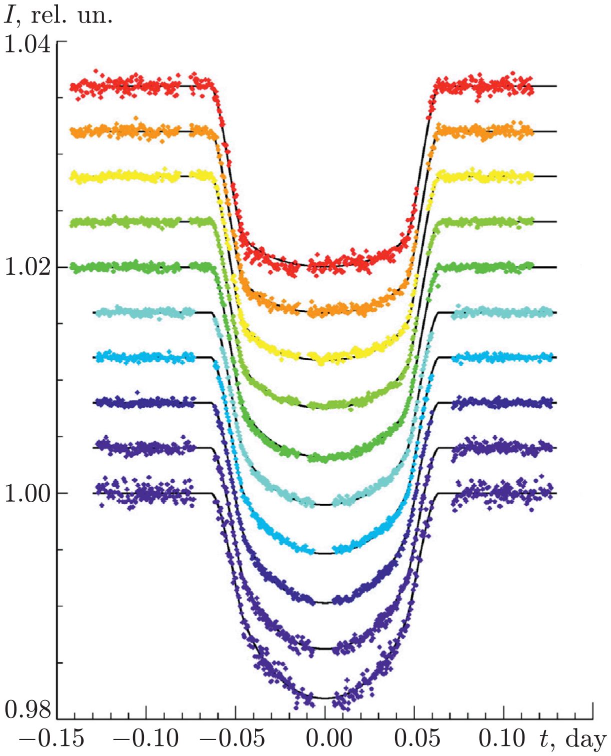

Fig. 3. The brightness curves of the HD 209458 star during the passage [8] (I is the relative radiation flux, t is the time from the middle of the passage). The measurements were obtained with the Hubble Space Telescope in ten bands of the spectrum (from bottom to top) between 320.1 and 970.8 nm.

in the center because of the limb darkening effect (see Fig. 3). When passing, the planet almost does not change in brightness, but just scans the star, covering different parts of the star disk with its dark disk. This makes it possible to measure the limb darkening effect in different regions of the spectrum and thus examine the structure of the star's photosphere.

The planet is covered with a star disk after half of the orbital period. This phenomenon is more difficult to observe, since the surface brightness of the planet is much lower than that of the stars. But if this is possible, the albedo and even the spectrum of the planet can be measured (the planet lines rapidly disappear from the total spectrum and are recovered at the end of the coating) and the data on the presence and even the structure of its atmosphere can be obtained. However, such measurements require very high photometry and spectrophotometry precision.

Figure 3 shows the brightness curves of the HD 209458 star in different colors at the instant its only planet HD 209458 b passes in front of it. It can be seen that the limb darkening effect is much stronger in blue rays. This star is almost a copy of the Sun (mass $1.15M_{\odot}$, radius $1.2R_{\odot}$, and surface temperature 6100 K), and the planet is a "hot Jupiter" (mass $0.69M_{\text{Jup}}$ and radius $1.4R_{\text{Jup}}$), moving very close to the star (the orbital semi-major axis is $a = 0.0475$ a. u.) with a period of 3.5 days in the tidal trapping state. The temperature of its daytime surface ranges from 1250 to 1400 K.

The first planet (HD 209458 b) was discovered from Earth in 2000 by David Charbonneau and Timothy Brown, as well as other teams of astronomers made this discovery almost simultaneously with them. The eclipse depth of this star is 1.7%. It is a bright Sun-type star, and its planet is one-third greater than Jupiter in size and has an orbital period of only 3.5 days. The discovery was inevitable, but the passage of smaller exoplanets is not so easy to detect. Therefore, this method proved its high efficiency only after the launch of space observatories, from which very precise photometric observations of the stars are conducted in the absence of atmospheric interference.

The first attempt to find exoplanets from space was made by the famous and still the largest space telescope "Hubble" (NASA/ESA) with a lens of 2.4 m in diameter. The telescope implemented the SWEEPS program in 2006 (Sagittarius Window Eclipsing Extrasolar Planet Search): it observed 180000 stars of the galactic bulge for a week in a field with a size of a few arc minutes through a relatively transparent region of the Milky Way — the Sagittarius "window." Sixteen candidates for exoplanets with orbital periods from 0.4 to 4 days were found. Only two of the brightest systems among them have been confirmed so far, possibly because it

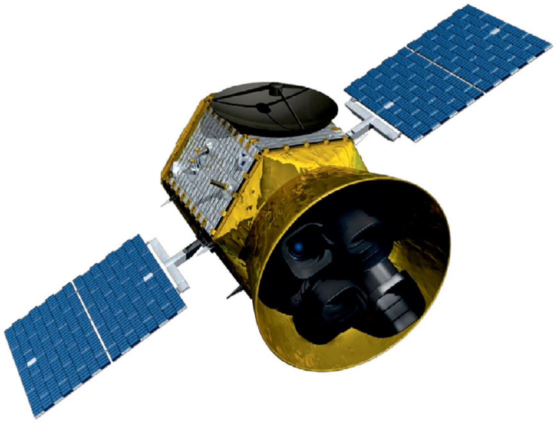

Fig. 4. The TESS Space Observatory (NASA/MIT) [9].

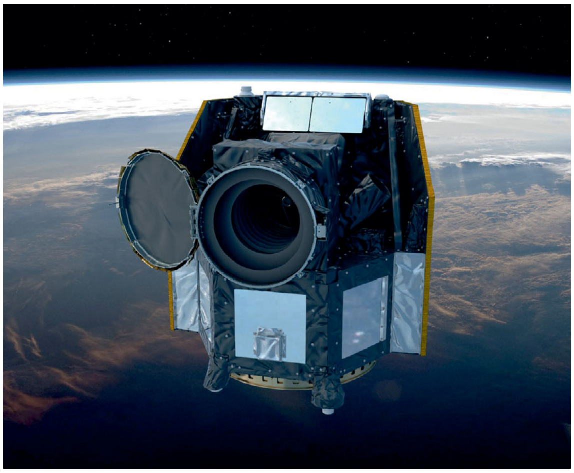

Fig. 5. CHEOPS (ESA) Space Observatory [11].

is impossible to obtain a result using ground-based methods for the others with a brightness of 22^m to 26^m. However, this experience has shown that specialized tools with a large field of view are required for seeking exoplanets by the transit method.

The French CoRoT (Convection, Rotation, and Planetary Transits) was the first such tool, which worked in near-Earth orbit from 2006 to 2014. It discovered 34 exoplanets and studied the acoustic oscillations of thousands of stars using a telescope with a lens of only 27 cm in diameter.

The Kepler space telescope (NASA) with a lens of 0.95 m was much more effective. From 2009 to 2018, it operated far from the Earth, in a near-solar orbit with semi-major axis $a = 1.0133$ a. u. and a period of 372.5 days, gradually lagging behind the Earth as it moved. Its wide-angle Schmidt camera with a large CCD mosaic had a field of view of $10^\circ \times 10^\circ$ and from 2009 to 2013 was constantly focused on the same area of the sky near the border of the Cygnus and Lyra constellations, providing high-precision photometry of 150000 stars. Then, due to the failure of the gyrodines, the telescope lost its stability, but continued to observe different areas of the sky near the ecliptic.

In total, Kepler measured the brightness of more than half a million stars, reliably detected 2670 exoplanets and 3600 more yet unconfirmed candidates. According to Kepler's data, 2165 eclipsing binary stars and a huge number of variable stars of other types have been discovered. Kepler remains an absolute leader in the number of discovered exoplanets in 2020, which has proven the high efficiency of the transit photometry method, despite the fact that Kepler studied (before the failure) about 100 square degrees of the sky in detail, while the area of the entire celestial sphere is 41253 square degrees.

A new generation of similar tools for studying exoplanets has been created after the CoRoT and Kepler space telescopes. In 2018, the TESS (Transiting Exoplanet Survey Satellite) was launched into a high-altitude orbit with a period of 13.7 days. Its 4 wide-angle cameras with lenses 10 cm in diameter and a field of view of $24^\circ \times 24^\circ$ each cover simultaneously $24^\circ \times 96^\circ = 2300$ square degrees, i. e., more than 5% of the celestial sphere (see Fig. 4). TESS was expected to make a repeated survey of the entire celestial sphere and find more than 20000 exoplanets in 2 years of operation. However, the catalog of reliably detected exoplanets [5] lists only 58 finds from TESS by June 2020; in addition, the TESS team's website reports about 1913 dubious stars, the presence of which has not yet been confirmed [10]. Nevertheless, the data from this satellite are very useful in preparing the program of observations of the future large space telescope "James Webb" with a lens of 6.6 m. Since TESS studies only bright stars up to 12^m in the wavelength range of 600 to 1000 nm, the exoplanets it finds will be an ideal target for detailed study by the Webb telescope, which will operate in the range 600–28300 nm.

The European CHEOPS (CHaracterising ExOPlanets Satellite) satellite with a Ritchey–Chretien telescope having a diameter of 30 cm was launched into a sun-synchronous orbit with an altitude of 700 km

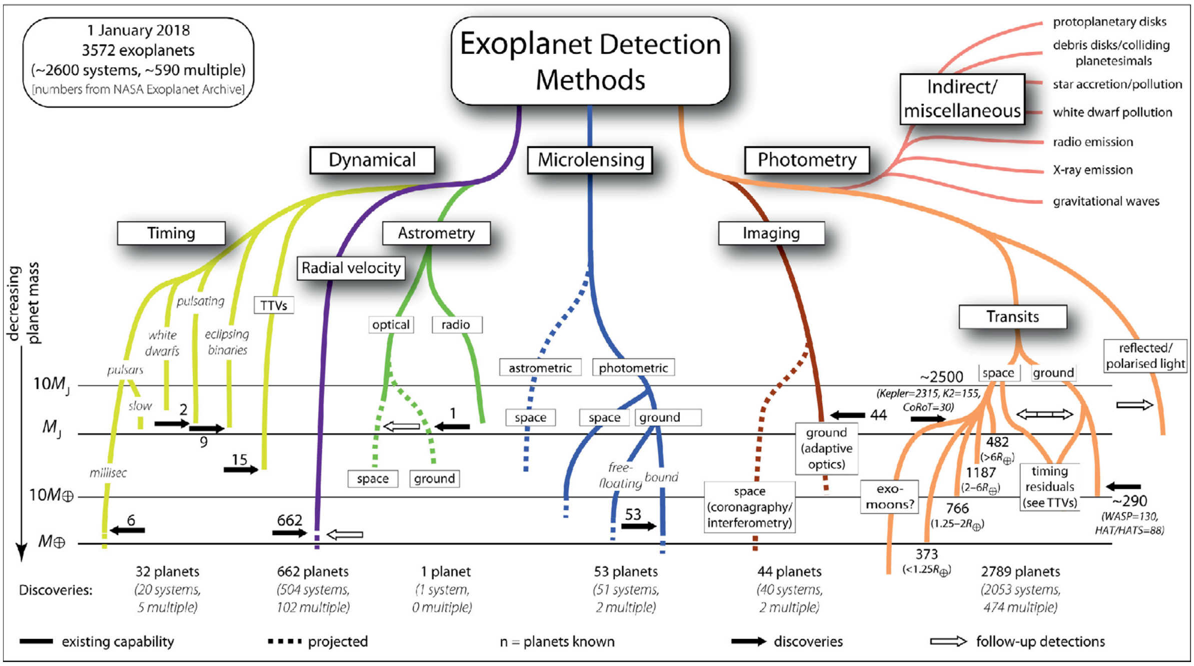

Fig. 6. Methods for detecting exoplanets by Perryman [7].

at the end of 2019 (see Fig. 5). Its task is to measure accurately the size of relatively small Earth-type planets (super-Earths) by the transit photometry method. Both TESS and CHEOPS should identify promising objects for future spaceborne and ground-based giant telescopes.

Other space telescopes are also being prepared for launch in the coming years. "PLATO" (PLAnetary Transits and Oscillations of stars, ESA) will be equipped with 26 refractor telescopes with a diameter of 12 cm each to search for Earth-like planets in the habitable zones (see the text below) and research on astroseismology. Their total field of view will be 2250 square degrees. The launch is scheduled for 2026 at the L2 Lagrange point of the Sun–Earth system. The expected operating time is at least 4 years, with a possible extension for another 4 years. During this time, at least a million stars will be explored.

The ARIEL satellite (Atmospheric Remote-sensing Infrared Exoplanet Large-survey, ESA) with a visible and near-infrared telescope is expected to be launched at the same Lagrange point in 2028. This is a Cassegrain reflector with an oval main mirror with dimensions of 1.1×0.7 m. Its infrared spectrometer will operate at a temperature of 55 K in the wavelength range 1.95–7.8 μm. This device is assumed to study the atmospheres of at least 1000 exoplanets by the transit photometry method in 4 years.

5.3. Other methods

All other methods, in addition to the Doppler and transit photometry methods, have made a small contribution to the number of exoplanets discovered. This contribution can be seen in Fig. 6, which reflects the situation at the beginning of 2018, and in Table 3. At that time, the contribution of other methods was about 3%, but by 2020 it had increased to 5%, which indicates their enhanced effectiveness.

Despite the small number of discoveries, each of the "secondary" methods has its own advantages. For example, the method of gravitational microlensing is good for detecting low-mass exoplanets far from the star, as well as satellites of planets. The method of direct image record provides an opportunity to study the radiation of these bodies (but the most massive so far).

The gravitational lens effect increases the brightness of a distant radiation source (e. g., a galaxy or quasar) when a massive object (another galaxy or a cluster of galaxies) passes in front of it. If a star is the

TABLE 3. Statistics on the discovery of exoplanets by methods as of June 2020 [18].

Discovery method	Number of planets
Astrometric (star coordinate fluctuations)	1
Planet image recording	49
Doppler method (star's radial velocity fluctuations)	802
Photometry of planet transits in front of a star (transit photometry method)	3164
Planet passage time variations	21
Star eclipse time variations	16
Gravity microlensing of background stars	89
Radio pulsar period variations	7
Star's pulsation period variations	2
Orbital modulation of the total brightness of a star and a planet	6
Protoplanetary disk kinematics	1

source, and an object of stellar or planetary mass is the lens, then this is called gravitational microlensing. Sometimes they speak of "nanolensing" if the lens has a planetary mass. The first gravitational microlens was discovered in 1989. In the 1990s, experiments were started for seeking invisible mass (dark matter) carriers using the gravitational microlensing effect, including the Polish–American OGLE (Optical Gravitational Lensing Experiment), the American–Australian MACHO (Massive Compact Halo Objects), the French EROS (Experience de Recherche d'objets Sombres), the Japanese–New Zealand MOA (Microlensing Observations in Astrophysics), and other experiments. The brightness of thousands of stars is almost constantly measured in each experiment using telescopes with a diameter of 1 to 4 m, hoping that an invisible object passing between the Earth and the observed star will distort the star image and change the star brightness by its gravitational field.

It is quite easy to distinguish this variation from brightness fluctuations of a variable star: if a massive dark body passes between the star and the Earth, then the star has a single symmetrical change in the brightness of the characteristic shape (Fig. 7), which is not repeated in the future, since this is an extremely unlikely event for each particular star. In order to notice such an event in a reasonable time, it is necessary to measure simultaneously the brightness of tens of millions of stars. For this, star-rich fields are observed in the Magellanic Clouds, the Andromeda Nebula, or the bulge of the Galaxy.

When seeking dark matter carriers, the gravitational microlensing experiments gave only an upper limit, showing that such objects in the mass range from 10^{-7} to 30 $M_\odot$ cannot be the dominant component of the dark halo of the Galaxy. But these observations also brought a positive result: by June 2020, 121 exoplanets had been detected by microlensing based on the presence of small secondary brightness peaks on the brightness curve of a background star. Therefore, most researchers who were looking for dark matter have now switched to seek exoplanets using the same equipment. The OGLE and MOA teams are leading in this work.

The essence of the method is to detect secondary short peaks on the brightness curve, indicating the presence of caustics in the lensed image, caused by the combined action of the gravitational fields of a star and the planets orbiting around it.

Figure 8 shows, as the example, the brightness curve of the gravitational microlensing event that was observed by the OGLE, MOA, and KMTC telescopes in May 2019 and revealed the KMT-2019-BLG-0842L lens star (as indicated by the letter L in its designation), as well as its planet KMT-2019-BLG-0842Lb. The mass of the lens star is $0.8M_\odot$, and the mass of its planet is $10M_\mathrm{E}$. Their mutual distance is about 3 a. u., and they are about 3 kpc away from us. Theoretically, the source of the second (smaller) brightness peak might be not the planet near the lens star, but the second component of the binary star as the light source if the latter is indeed binary. However, the analysis shows [13] that the probability of this is low.

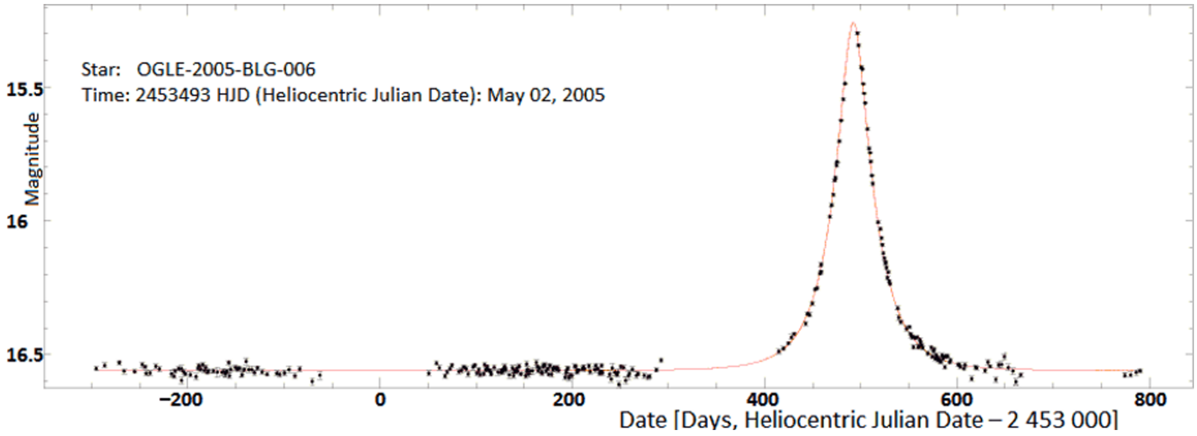

Fig. 7. The brightness curve of a star under gravitational microlensing [12]. The event lasted about 300 days. The star brightness at the maximum increased by 1.3^m, i. e., 3.3 times. The dots are the observational data; the line is a theoretical curve within the framework of general relativity, which approximates observations.

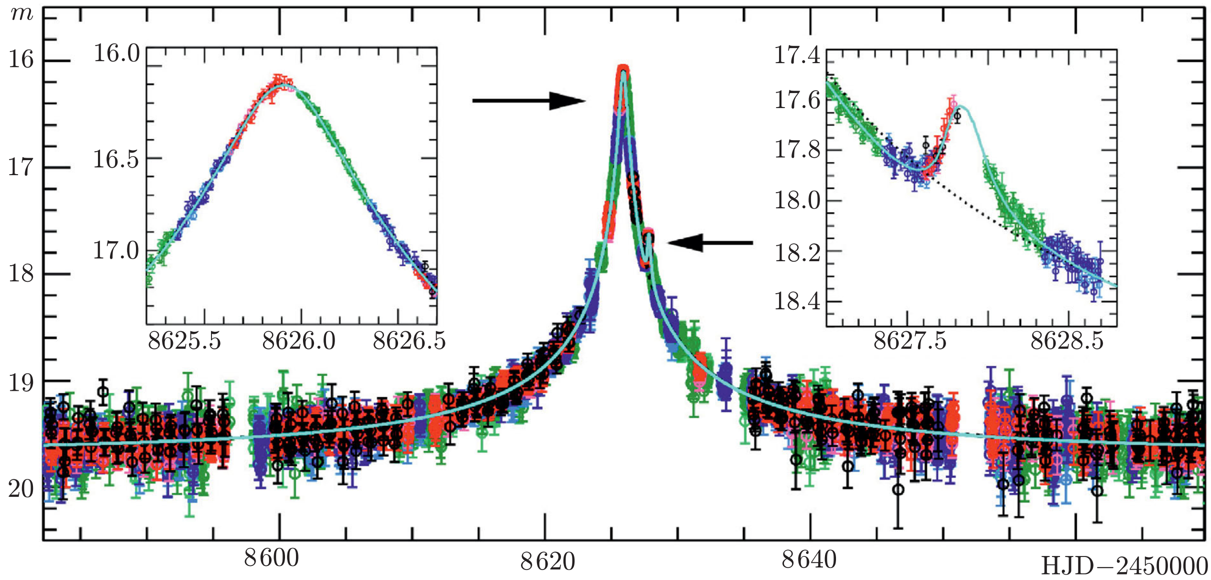

Fig 8. The KMT-2019-BLG-0842 microlensing event. Here, m is the apparent stellar magnitude and HJD is the heliocentric Julian date. The insets show on an enlarged scale the brightness peaks caused by the lens star (left) and its planet (right). Based on Ref. [13].

Imaging of exoplanets faces greater difficulties due to the weak brightness of the planet itself and its proximity to the bright parent star. The imaging technique is constantly being improved, mainly by creating stellar coronographs, in which the mask covers or otherwise extinguishes the star image. But up to date, it has been possible to get an image of an exoplanet in exceptional cases: if the parent star is very dim (a white dwarf) or if the planet is located very far from the star and at the same time is so massive and young that it glows by itself in the infrared range. In this case, either a spaceborne or a ground-based telescope with adaptive optics is used.

In the recent past, the best telescopes with adaptive optics obtained near-infrared images and spectra of exoplanets at angular distances of $0.25''$, $0.5''$, and $1.0''$ from the star with a planet/star brightness contrast of at least 10^{-3}, 10^{-4}, and 10^{-5}, respectively. At the same time, the masses of most of the studied exoplanets were at least 10–15M_{Jup}, and the distances from the star exceeded $0.5''$ (this is about 30–100 a. u. for the nearest stars). However, more advanced systems with adaptive optics have recently been created, such as the GPI (Gemini Planet Imager) on the Gemini-South telescope, as well as the SPHERE (Spectro-Polarimetric

High-contrast Exoplanet REsearch instrument) on the VLT (Very Large Telescope) telescope, capable of detecting planets at a distance of $0.25''$–$1.0''$ even if their brightness in the near-infrared range is 10–100 times weaker. This will be used to study planets with a lower mass (down to $2M_{\rm Jup}$), as well as massive planets located closer to the star (down to $0.1''$–$0.4''$, i. e., 10–15 a. u.). Integrated field spectrographs in combination with GPI and SPHERE provide an opportunity to explore the atmospheres of young planets, including their cloud cover, temperature, and gravity. But this program has not been implemented yet.

An example of direct imaging is shown in Fig. 9: this is an image of the Kappa Andromedae star (κ And) and its satellite κ And b, obtained by the SCExAO device (Subaru Coronagraphic Extreme Adaptive Optics) and the CHARIS integrated field spectrograph in the near-infrared wavelength range on the Japanese 8.2-meter Subaru telescope (Mauna Kea, Hawaii) with an adaptive optics system. The mass of the satellite is from 13 to $50M_{\rm Jup}$, i. e., it is a brown dwarf or an extremely massive planet. In any case, the temperature of the satellite is about 2000 K; therefore, being at a distance of about 100 a. u. from the star, it glows by itself.

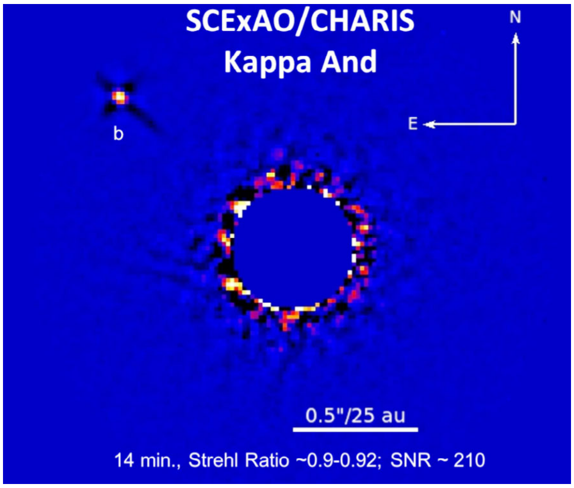

Fig. 9. Image of the κ And star (in the center, covered with a mask) and its satellite in the wavelength range 1.1–2.4 μm [14].

91 of the 137 objects in the catalog [5] marked as photographed in May 2020 have a mass above the boundary between planets and brown dwarfs, and all the others are super-Jupiters with a mass of more than $2.5M_{\rm Jup}$. Ground-based telescopes with adaptive optics and stellar coronographs are exceptionally able to capture images of very massive and young planets at a distance of about $0.1''$ from an extremely low-mass star or a brown dwarf. The extremely small age of the planet is exactly the reason why it glows not so much with reflected as with its own infrared radiation, which is comparable in brightness to that of a star.

The astrometric method has already been discussed above. It has not brought any notable results in the field of exoplanets so far, since only two of the 12 objects marked in the catalog [5] as “astrometric” are considered as planets in mass, and the rest are brown dwarfs. However, the Gaia space observatory is expected to finish measuring the positions of the stars with the required accuracy in a few years, and then the astrometric method will bear fruit.

6. PROPERTIES OF EXOPLANETS

This review is mainly dedicated to the methods of seeking exoplanets; therefore, we will describe their main properties only briefly. Astronomers had known the Solar System as the only planetary system until 1995. Its properties seemed generally understandable and were tacitly extended to still undiscovered systems, but this was a mistake: the properties of the discovered exoplanetary systems appeared to be diverse and unexpected.

Probably, the only discovery expected from general considerations was the detection of super-Jupiters that fill the gap in the mass distribution from the giant planets of the Solar System to brown dwarfs, i. e., from $1M_{\rm Jup}$ to $13M_{\rm Jup}$. But the discovery of super-Earths with masses from 1 to 15 Earth masses, i. e., from Earth-like planets to planets with the masses of Uranus or Neptune, was unexpected; there are no such planets in the Solar System. The discovery of planets with highly eccentric orbits (Fig. 10) was also strange. Finally, the detection of gas giants near their parent stars was absolutely incredible. The discovery of these “hot Jupiters” required a significant addition to the theory of the formation of planetary systems, in particular, the development of views on the mechanisms of migration of young planets in protoplanetary disks.

The term “hot Jupiter” originated at the very end of the XX century due to the fact that among

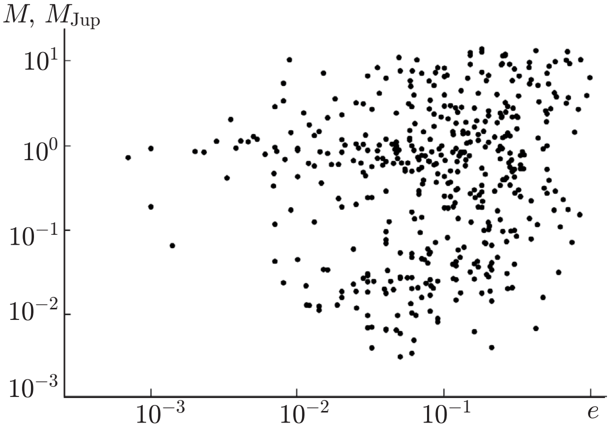

Fig. 10. Distribution of objects of the network "Encyclopedia of Exoplanets" [5] as of May 5, 2020 (M is the mass of the planet and e is the eccentricity of the orbit). Planets with masses less than $14M_{\rm Jup}$ are shown.

the exoplanets discovered first after 1995, most turned out to be giants of the Jupiter type, but, in contrast, revolving in short-period orbits so close to the parent star that their upper cloud layer of the atmosphere is heated by the star radiation to more than 1000 K, and sometimes up to several thousand kelvin.

The fact that such exoplanets were exactly the first to be discovered is not surprising: the Doppler method used to search for them, which records periodic variations in the star radial velocity, primarily reacts to the close neighborhood of a star with a massive planet. However, the attempts to explain the origin of hot Jupiters face problems. Within the framework of modern cosmogony, a giant planet, mainly consisting of light elements (hydrogen and helium), can only appear far from the star, where volatile substances (water, methane, carbon dioxide and monoxide, and ammonia) can remain in a solid state. This requires a temperature of 145–170 K. The distance from the Sun at which this happens is called the ice line, or the frost line, or the snow line. In the era of planet formation, when there was a lot of dust and gas in the protoplanetary disk, and the Sun radiance was lower, the ice line passed at a distance of 2.7 to 3.2 a. u. from the Sun. At present, it has moved to a distance of 5 a. u., to the region between the orbits of Mars and Jupiter. Therefore, it seemed quite natural that the ice line should divide the planetary system into an inner region devoid of volatiles and containing solid bodies and an outer region rich in volatiles and containing icy bodies.

Most experts still agree that giant planets appear far from the star, but later some of them, interacting with a massive protoplanetary gas-dust disk, migrate closer to the star and become hot.

The term "hot Jupiter" has become so familiar that it was no surprise to discover the WASP-18 b planet in 2009, which has a mass of $10.4M_{\rm Jup}$ and revolves in an almost circular orbit at a distance of 0.02 a. u. from its star. The orbital period of this planet is only 22.6 h. In view that the WASP-18 star (HD 10069) is of F9 spectral class and has a higher luminosity than the Sun, the surface temperature of the planet should reach 2100 K. Due to its proximity to the star and its large mass, the planet causes strong tidal disturbances on the star surface, which, in turn, slow down the planet and will lead to its falling on the star in the future.

In 2019, the WASP-18 star was found to have a second planet in a circular orbit with a period of 2.16 days. Its mass is $0.17M_{\rm Jup}$, i. e., much less than that of the inner, neighbor planet. It is not clear how the massive WASP-18 b planet could migrate from far away to the star and pass by the less massive WASP-18 c planet without hitting it or even disturbing its motion. One possible answer to this question is that it may have previously been a binary planet that broke up during the migration process.

The discovery of hot Jupiters and the vast variety of planetary systems in general has caused unprecedented activity in the field of planetary cosmogony. The creation of a unified theory of the formation of planets is still far away. But it is already clear that the theory will be much more complicated than the theory of star formation, since it contains many more free parameters. For example, many planets have been found near binary, triple, and even quadruple stars [15, 16]. It will not be easy to build a dynamic model of the formation of such planets.

For a quarter of a century, the study of exoplanets has yielded one indisputable result: planetary systems are not an exceptional, but quite an ordinary product of protostellar evolution. The fact that we are surrounded by a variety of planetary systems is now stimulating astronomy, astrobiology, and even cosmonautics. At the same time, special interest is drawn to the Earth-type exoplanets with conditions on the surface close to those on the Earth. After all, the possibility of extraterrestrial life is being discussed.

If to the Earth-type planets we conventionally refer the exoplanets whose masses were measured and lie in a range of 0.3 to 3.0 Earth masses, then there were about 60 of such planets in May 2020, according to the catalog [18]. If the size of the planet is taken as the similarity criterion, then there are about 300 exoplanets in the range ±20% of the size of the Earth. Unfortunately, only 5 or 6 planets among those and others are located at such distances from their stars, where their surface temperatures ensure the existence of liquid water, i. e., are favorable for the development of Earth-type life. A total of 132 exoplanets have been found in this zone (Fig. 11), but they are mostly giants. Here we come across the concept of "habitable zone," and this term requires a separate discussion.

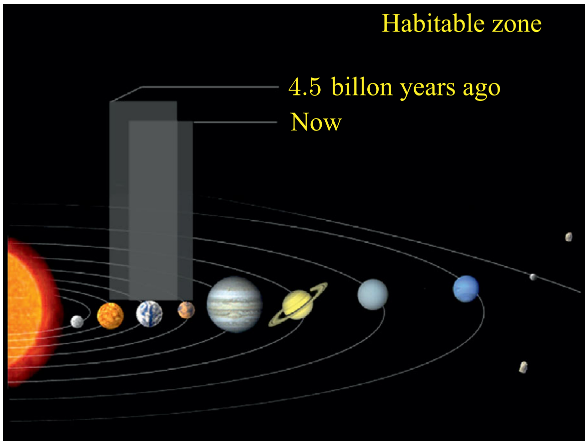

Fig. 11. The zone of possible life on the surfaces of planets with atmospheres in the Solar System and motion of this zone over time due to the Sun luminosity variations.

The introduction of new scientific terms is a responsible task. The translation of English, i. e., international terms into the native language should be given careful consideration. When a new and, especially, inappropriate term comes into use, there is time to discuss the problem and find common ground in a democratic way. Let us discuss the translation of the English term "circumstellar habitable zone," or "habitable zone" for short, which has recently become very popular among researchers of exoplanetary systems. The range of distances from the star, within which the temperature on the surface of the planet lies in a range of 0 to 100 °C, is being discussed. At normal atmospheric pressure, this opens up a possibility for the existence of liquid water, and therefore life in its present meaning (see Fig. 11). Three versions of the translation of the term "habitable zone" are now competing in Russian publications on this topic. In their word-for-word translation from Russian into English they are the life zone, the inhabited zone, and the habitability zone. Let's try to figure it out.

It is obvious that the term "inhabited zone" is completely unsuitable, indicating the presence of living beings in this zone and even hinting at the presence of a human there. Inhabited means populated, and "inhabited zone" means a populated area where someone lives. In reality, we are speaking about a zone in which there can be conditions for the existence of liquid water on the surface of a planet with an atmosphere. At the same time, the possibility of water existence does not mean that water really exists, the presence of water does not provide all the conditions for the development of life, and the existence of conditions for life does not mean the existence of living beings. Obviously, the authors who use this term are the least sensitive to the meanings of their native language.

And what is the zone of habitability? The Russian language has the word corresponding to "habitability." The Ushakov defining dictionary says that habitability is the degree of population of the area. Other dictionaries give a similar interpretation. Therefore, the term "habitable zone" contradicts the traditional meaning of the word "habitability" in Russian.

The direct translation of "habitable" in the dictionary gives the following options: inhabited, comfortable, suitable for habitation, etc. We have done with the habitability, but the suitability for habitation, for life, reflects exactly the meaning of the term "habitable zone." In general, in English, "-able" means opportunity, not availability. Experts in the English language agree with this [14].

Thus, the long expressions "zone of possible life" or "zone suitable for life" would be the most adequate translations. But the simpler and shorter "life zone," according to the author, conveys the meaning of the English expression accurately enough. The convenience of pronouncing plays not the least role. Compare: life zone or zone of habitability. Obviously, the life zone is better.

Let us turn to the meaning of this concept. It is clear that the boundaries of the habitable zone strongly depend on the assumptions made about the albedo of the planet and the composition of its atmosphere (in fact, on the degree of the greenhouse effect). This is despite the fact that the conditions for life only on the surface of the planet are being discussed. And if we take into account that in the presence of internal heat sources and mineral raw materials, life may thrive well under the ground and under the ice, then the cold, distant boundary of the habitable zone is generally pushed away to the interstellar distance.

The position of the boundaries of the habitable zone or the surface of the planet also needs to be discussed in detail, but this is beyond the scope of this brief review. We only mention some facts related to the mass of the parent star.

The luminosity of solar-type main-sequence stars depends on their mass as $L \propto M^4$. The temperature T on the surface of the planet depends on the luminosity of the star and the orbit radius R with fixed atmospheric properties: $T \propto (L/R^2)^{1/4}$. The boundaries of the habitable zone require a fixed temperature, i. e., $R \propto L^{1/2} \propto M^2$ for them. On the other hand, the tidal effect of the star, which slows down the diurnal rotation of the planet, is proportional to M/R^3. This means that the maximum tidal trapping distance of the planet is $R \propto M^{1/3}$. Consequently, as the star's mass decreases, the habitable zone approaches rapidly the tidal trapping region, where the planet's axial rotation is slow and its illumination is asymmetric: one hemisphere is always devoid of light. This changes the dynamics of the atmosphere dramatically, makes the climate more contrasting, and can accelerate the decay of the magnetic field, since the dynamo mechanism requires rapid axial rotation.

The second fact is also related to the mass of the star. The main population of the Galaxy is low-mass red dwarfs of spectral classes M and K, which exhibit high flare activity. The contribution of hard radiation to the star luminosity during a flare increases significantly, and the flare power at these stars relative to their luminosity is much higher than that of the Sun. Therefore, the approach of the habitable zone to low-mass stars increases the radiation flux at the surface of these planets significantly, making it more likely that life will develop under the surface.

Nevertheless, the concept of the zone of possible life on the surface of the planet is useful in the sense that remote observations with a telescope or a flyby probe (meaning the Breakthrough Starshot project [20]) permit one to explore only the atmosphere and surface of the exoplanet, but not its interior. Proposals for spectral biomarkers [21, 22] indicating the presence of Earth-type life have already been prepared for these studies, but new methods of observation will be required to obtain the spectra of Earth-like exoplanets in the habitable zone.

The HabEx (Habitable Exoplanet Imaging Mission, NASA) project, proposed for launch in 2035, is considered one of the most ambitious. It is suggested that a telescope of the ultraviolet, infrared, and visible wavelength ranges (from 91 to 1000 nm) with a lens of 4 m in diameter and an internal stellar coronograph, as well as a screen with a diameter of 56 m, separated from the telescope by 72 thousand kilometers, is brought to the point L2 of the Sun–Earth system (Fig. 12). This will make it possible to examine the atmospheres of Earth-like exoplanets in the habitable zone.

The goals for the study will be chosen in accordance with the Earth Similarity Index (ESI) based on the similarity of the exoplanet with the Earth in several physical factors (size, mass, surface temperature, etc.) that affect the "habitability." The ESI value lies in the range from 0 to 1 (the Earth has 1). Teegarden b (ESI = 0.95), TRAPPIST-1e (0.95), and yet unconfirmed planet KOI-4878.01 (0.98) were considered the most "Earth-like" in May, 2020. The top ten also includes the exoplanet Proxima Centauri b (0.87), which is the closest to us. Interestingly, Mars and Mercury have the same and rather low ESI = 0.73. Teegarden b is now considered the most habitable exoplanet according to the totality of a larger number of features [24].

8. CONCLUSIONS

The search for and study of exoplanets is the most actively developing area of modern astronomy. Not all tasks in this field require large telescopes with diameters of more than 8 m, which do not exist in

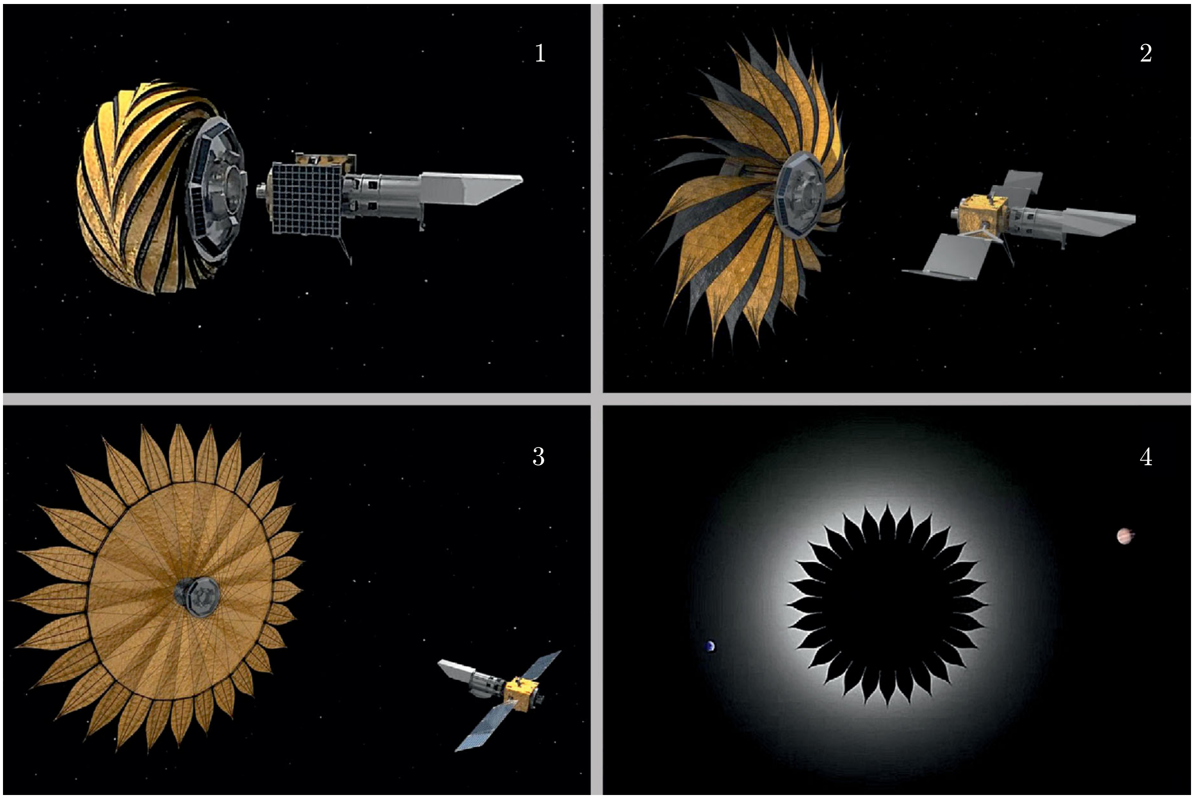

Fig. 12. Deployment stages of the advanced HabEx space stellar coronagraph [23].

Russia. Many problems of transit photometry and gravitational microlensing can be solved with telescopes 1–2 m in diameter, which are present in Russia in considerable quantity.

The Russian school of astrometry has deep roots and a high international status. The publication of high-accuracy astrometric catalogs based on the results of the Gaia Space Observatory has already been started and will continue in the near future, which will provide excellent material for the discovery of new and examination of known exoplanets by astrometry methods. This should be taken into account in the work plans of astronomical organizations.

The existence of several interactive catalogues of exoplanets [5, 10] provides opportunities for scientific statistical research, as well as for organizing the educational process, in particular for coursework and theses.

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