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Exoplanets: nature and models

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Contents

Abstract. **Exoplanets represent a broad new class of astronomical objects, which became accessible for observations and studies only just before the end of the last century. Owing to continually improving techniques of ground-based observations, and especially observations from space, for a little bit more than two decades thousands of planetary systems of other stars have been discovered, and this process is escalating. Exoplanets are of paramount interest for astrophysical, astrochemical, and dynamical studies. Exoplanetary studies have opened up new horizons to gain insights into fundamental problems of stellar-planetary cosmogony and, in particular, into the question of the origin and evolution of the Solar System. Discoveries of Earth-like planets, especially those orbiting in stellar habitable zones favorable to giving rise to and sustaining life, open new prospects for progress in astrobiology.**

Keywords: exoplanets, cosmogony, planetary systems, Solar System

1. Introduction

Exoplanets (planets that do not belong to the Solar System and orbit other stars) represent a very broad new class of objects for astronomical, physical, and dynamic research, primarily for exploring stellar–planetary cosmogony and cosmochemistry. The formation of planets is a widespread, but at the same time rather complex, process, which consists of several stages, including various physicochemical mechanisms and interactions. Using statistical data based on the number of planets discovered in the nearest regions of our Galaxy and the basic concepts of the formation and evolution of stars, it can be estimated that at least about a third of the stars in the Galaxy have planets, which implies that their total number is comparable to or even larger than that of stars. Should this estimate be extended to other galaxies, the total number of planets in the observed Universe may be comparable to or exceed the number of stars ($\sim 10^{22}$). However, it has not been possible until recently to detect exoplanets due to the insufficient capabilities of astronomical methods and instruments.

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The hypothesis that planetary systems are widespread in the Universe, and in particular in our Galaxy, was put forward long before the discovery of the first extrasolar planet. This idea was supported by the observed shape of the distribution of fixed-mass protostars by their angular momenta. Indeed, binary and multiple stars are born from protostellar gas-and-dust clouds if their angular momentum exceeds a certain threshold value, while restrictions imposed on the angular momentum of main sequence stars to ensure the stability of their own rotation are orders of magnitudes weaker. Stars with planetary systems are born in the intermediate range; in other words, they transfer an excess of their angular momentum to the planets. Similarly to the Solar System, the total mass of the entire system is concentrated in this case in the star, while the bulk of the total angular momentum belongs to the formed planetary system. However, the exact mechanism of the transfer of angular momentum from the protostar to the planetary system is still not entirely clear.

Unlike the stars available for statistical analysis and classification, for example, in the Hertzsprung–Russell diagram, which allows tracing their evolution, until recently we only had one example of a planetary system — our Solar System. Its mechanical, physical, and cosmochemical properties are used as limitations in developing scenarios regarding the origin and evolution of other planetary systems. The regularities that exist in the systems of planets and satellites of the Solar System definitely indicate a single process of their formation, while data on the properties and composition of surface substance and atmosphere in case of planets and small bodies, when compared with samples of the material of their embryos, provide a basis for solving fundamental cosmochemical problems.

The data obtained from observations of exoplanets led to the conclusion that planets may comprise various types, ranging from 'hot Jupiters' — planets that are more massive than Jupiter and located in orbits very close to the parent stars — to low-mass planets in a wide range of orbit sizes. It may be assumed based on the available statistics that about 20% of the total number of exoplanets can be comparable in size to Earth and the terrestrial planets in the Solar System. The architectures of the discovered planetary systems turned out to be completely different from those of the Solar System, and their natural structures feature high diversity. It is important, though, to keep in mind that some known exoplanets are located in zones with favorable climatic conditions (so-called 'habitable zones'), suitable for the existence of various forms of life. The above estimate of the total number of planets shows that billions of planets may be located in habitable zones, which increases the chances of finding life outside Earth.

The growth in the number of discovered exoplanets with various natural properties has made it possible to proceed to a new stage of research based on geophysical methods of analysis. Given the size and mass of a planet, it is possible to determine its average density, which is the main indicator of the planet type: gas, rocky, or ice. Data on the structure and chemical composition of atmospheres significantly advanced the analysis of the properties of their gas envelopes and, combined with estimates of temperature and pressure, improved our understanding of the natural conditions expected on the surface. The observational results obtained made it possible to impose stringent restrictions on mathematical models of the physical and cosmochemical features of planets, the dynamics of planetary systems, and evolution scenarios. And, of course, the discovery of exoplanets and protoplanetary disks heralded a real breakthrough in stellar-planetary cosmogony, which has become one of the key areas of modern astrophysics.

2. First discoveries

The first exoplanets were discovered in the early 1990s by Aleksander Wolszschan and Dale Frail [1] in studies of the PSR B1257-12 pulsar, a neutron star whose mass is 1.4 times that of the Sun. Additional modulations were revealed in its radio pulses with a period of 6 ms that correspond to the natural rotation period of the pulsar. They were explained by the presence of two planets orbiting the neutron star with orbital periods of 66.54 and 98.21 days and masses of $3.4M_{\mathrm{E}}$ and $2.8M_{\mathrm{E}}$ (where M_{E} is the mass of Earth), respectively. More accurately, the mass estimate means a product $M_{\mathrm{p}} \sin i$, where M_{p} is the mass of the planet and i is the inclination of the planetary orbit plane with respect to the plane of the sky. Later, planets have been found around other pulsars; it should be noted, however, that discoveries of planets around pulsars are generally very rare due to the supposedly small number of planets around 'residual' stars that have experienced the supernova stage.

An exoplanet around a main-sequence star was first found in 1995 by Michel Mayor and Didier Queloz [2]: a hot Jupiter orbiting 51 Pegasi was discovered.[1] Since then, owing to the improvement in astronomical methods and observation instruments, but mainly due to research performed using space telescopes, progress has been impressive: in less than a quarter century, more than four thousand exoplanets have been discovered, the vast majority of which belong to more than three thousand planetary systems. The pace of discoveries, which is continuously accelerating, is directly related to the timeframes of operation of specialized space missions such as the Kepler space telescope. About a third of the discovered exoplanets belong to multiplanetary systems, i.e., systems that consist of two or more planets [3]. The predominance of single-planetary systems is explained, however, by the effect of observational selection, since relatively low-mass planets are much more difficult to detect than giant planets, which, moreover, can be located in orbits close to the parent stars; the most massive planets are discovered first. This reason is also behind the observed 'shortage' of multiplanetary systems, since the detection of planets of relatively small (terrestrial) sizes requires the employment of more sophisticated methods and instruments of observation.

The history of the main astronomical methods used in the exploration of exoplanets dates back to the late 20th century. They include the measurement of radial velocity variations (1989, first success in 1995), pulsar timing (1992), the transit method (1999), the microlensing method (2004), and direct imaging (2004). We briefly describe these methods below.

3. Detection methods

We discuss, primarily, the most effective of the currently known methods employed to detect exoplanets, but also briefly touch on some promising areas. Unfortunately, most

[1] Michel Mayor and Didier Queloz were awarded the 2019 Nobel Prize in Physics "for the discovery of an exoplanet orbiting a solar-type star."

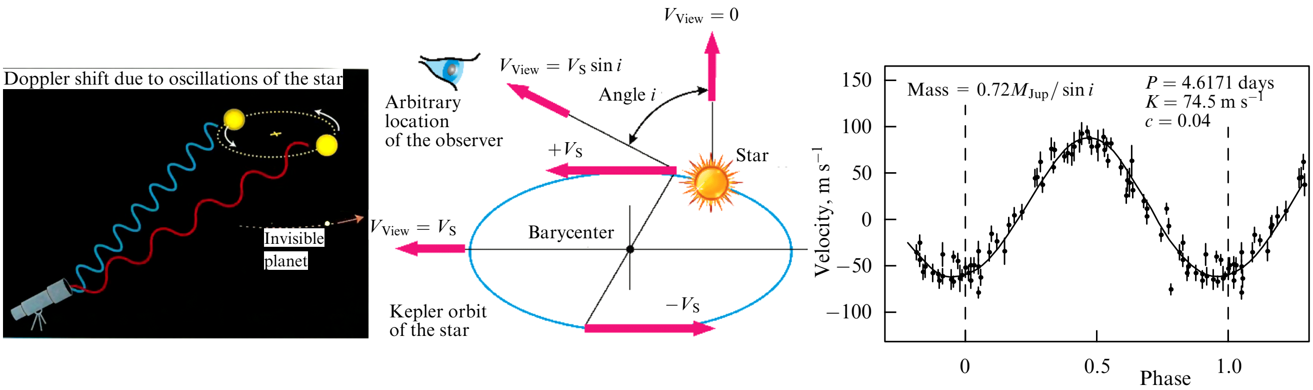

Figure 1. Schematic representation of the radial velocity method and the measurement curve in the presence of a planet; K is the half-amplitude of the radial velocity variations, c is the phase shift of the curve. (According to [2].)

of the methods applied are plagued by the effects of observational selection, because of which, as already mentioned, massive planets in the orbits close to the parent stars are discovered first.

The methods for detecting exoplanets are subdivided into *indirect* and *direct*.

The indirect methods include *astrometry*, the measurement of small oscillations of a star in the plane of the sky due to the presence of a planet(s); the *RV* (radial velocity) *method*, the measurement of periodic variations in the radial velocity of a star from shifts of its spectral lines; *pulsar timing*, the measurement of variations in radio signals from pulsars over time; and *microlensing*, the measurement of features on images of stars in observing gravitational lensing events.

The direct methods include techniques based on direct observations of the intrinsic or reflected radiation of planets. Direct observation methods are extremely difficult to apply due to the immense difference between the light fluxes from the parent star and the planet; for example, the contrast of fluxes in the optical range from the Sun and from Earth for a distant observer is no less than $\sim 10^{10}$. The contrast is slightly less in the infrared region. It was through direct observations that planets around *brown dwarfs* [2] were discovered; the first planet discovered by this method is the giant planet 2M1207-39b [4, 5], but the use of direct methods to detect planets close to stars is problematic.

Considered as a technique intermediate between direct and indirect methods should be the now widely used technique of observing *transits*, i.e., the passage of a planet across the disk of a star, which causes a short-term weak decrease in the brightness of the star. Transits can definitely be observed only provided the inclination of the planet's orbit relative to the line of sight is sufficiently small. Close to this technique is the *transit timing variations* (TTV) method, which consists of the analysis of deviations of transit times from strict periodicity. [3]

[2] The mass of planets (~ 0.001 solar masses $M_{\rm S}$ or less) is insignificant compared to that of stars ($M > 0.08 M_{\rm S}$) and intermediate objects — brown dwarfs (substars) $\sim (0.02-0.08) M_{\rm S}$. Heat is released in the interiors of brown dwarfs primarily due to reactions that involve nuclei of light elements (deuterium, lithium, beryllium, boron), in contrast to the classical proton–proton reaction of thermonuclear fusion in stars. After reserves of light elements are fairly rapidly depleted, brown dwarfs become massive planet-like objects whose chemical composition is homogeneous in depth, which is due to fully convective heat and mass transport at the active stage of evolution.

[3] An analysis of phase deviations is also used in framework of the RV method.

We now discuss the methods listed above in more detail.

The RV method. Also referred to as *Doppler spectroscopy*, this method consists of measuring periodic variations in the radial velocity of a star due to the presence of planets (Fig. 1). If the planet's orbit is circular and the parent star's mass is approximately that of the Sun, the basic formula of the RV method is very simple:

$$m_{\rm p} \sin i = 0.035 P^{1/3} \Delta V ,$$

where $m_{\rm p}$ is the planet's mass (in Jupiter mass units), P and ΔV are the observed period (in years) and the half-amplitude of the variation of the radial velocity of the star (in m s^{-1} units), and i is the angle between the orbital plane and the plane of the sky (see, e.g., [6, Eqn (2.29)]). The effect is apparently not observable if $i = 0$.

The observed RV curves that represent the star's radial velocity as a function of time provide primary data for modeling planetary orbits. As follows directly from the above formula, Earth makes the Sun perform radial (as perceived by a distant external observer) periodic oscillations with a maximum speed of 10 cm s^{-1}, a value which is far beyond the capabilities of modern instruments: the best resolution is currently about 50 cm s^{-1}. Thus, a terrestrial-type planet located in the zone of potential existence of life around a solar-type star cannot currently be detected by the RV method.

As was already noted, the first exoplanet 51 Peg b [2] around a main-sequence star was discovered by the RV method. Its parent star is almost a twin of the Sun (spectral type G5V, mass $1.06 M_{\rm S}$; here and below, $M_{\rm S}$ is the Sun's mass). Planet 51 Peg b is the first member of a new class of exoplanets known as *hot Jupiters*.

Transit method. The phenomenon of transits has been well known to astronomers for a long time: it was applied in observing the passage of Venus and Mercury across the disk of the Sun. The transit of Venus causes a 0.01% decrease in the total light flux from the Sun. A 'transit signal' of the same order should be expected from terrestrial-type exoplanets orbiting solar-type stars. It is of interest that the method of transits was first proposed for the search for exoplanets (in observations of periodic darkening of a star due to the passage of a planet across its disk) in 1952 by Otto Struve, a member of the famous Struve astronomical dynasty.

Charbonneau et al. [7] were the first to discover, in 2000, a planet by the transit method in analyzing the light curve of the star HD 209458, around which this planet was discovered

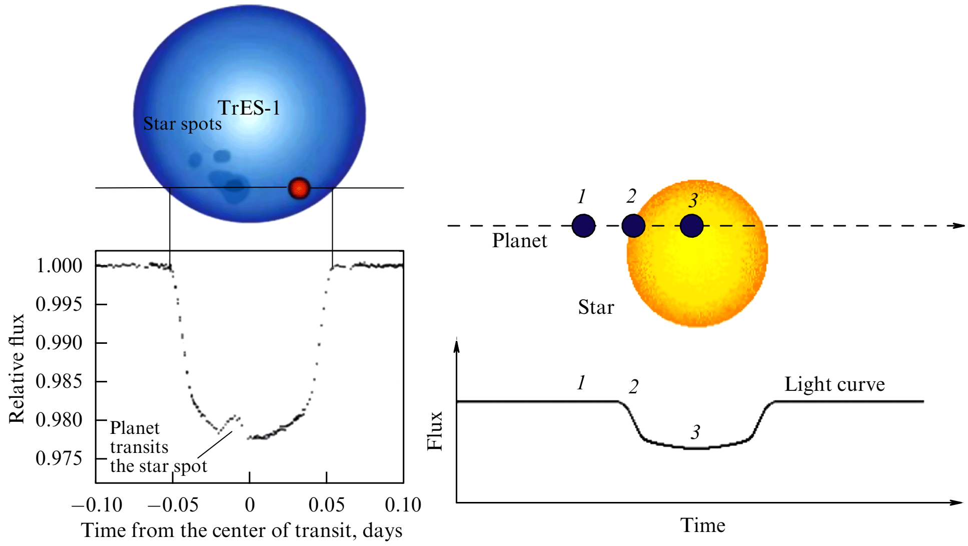

Figure 2. Light curve of the TrES-1 star [8]. The small peak during transit is caused by the planet covering a star spot, an analogue of sunspots. (Source: G Laughlin, http://oklo.org.)

earlier using the RV method. Figure 2 shows the light curve of the TrES-1 star plotted by Charbonneau et al. [8] based on the observations made by the Hubble Space Telescope (HST). A curious detail of the curve is a small secondary peak near the minimum brightness: it is caused by the planet eclipsing the star spot on the parent star.

It should be noted that the effect of observational selection takes place in the case of hot stars: it is difficult to observe transits for such stars, and the RV method is of little help for suchlike systems. Perhaps for this reason, planetary systems are primarily observed around stars that are late spectral types. On the other hand, it is the stars of the later spectral types (G, K) that are the best candidates for possessing 'habitable' planets. However, the insufficient mass may lead to another scenario of evolution, in which objects such as brown dwarfs are formed.

TTV method. If a system contains more than one planet or the parent star is multiple, the transit planet passes between the observer and the star at irregular time intervals: due to perturbations of orbital elements, the transit time fluctuates relative to a strictly periodic signal. The TTV method is based on an analysis of variability of transit times. Theoretical studies [9, 10] have shown that TTV-simulation enables the obtainment of virtually complete information about the masses and orbital elements of transit planets. The first simulation results were obtained for systems with several transit planets [11]. Nesvorný et al. [12] were the first to discover a 'nontransit' planet by this method, by analyzing the TTV signal of a transit planet. Thus, according to the figurative statement by A Morbidelli, a famous planetary scientist [13], "TTV analysis revives the glorious era of celestial mechanics, when Le Verrier predicted the existence and position of Neptune from the analysis of anomalies in the motion of Uranus. Now the 'miracle' of Le Verrier emerges routinely."

Pulsar timing method. This method consists of observing and analyzing variations of radio bursts from pulsars in time (in the absence of planets, the bursts are strictly periodic). As was noted above, the very first known exoplanets were discovered by this method in 1992 [1, 14]. However, the configuration of their orbits probably formed at the stage when the pulsar was created after a supernova explosion, which should have 'scattered' the old system, if such existed.

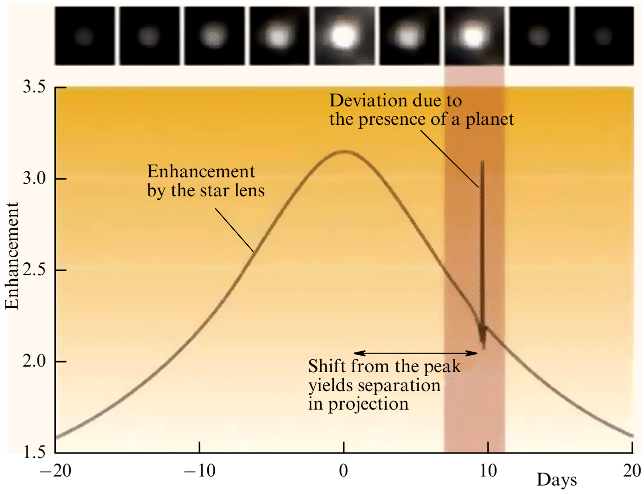

Figure 3. Simulation of an increase in the observed brightness of a distant star due to the gravitational lensing of its light by a star–planet system that crosses the line of sight 'observer–star'. The secondary narrow peak is the 'planetary signal'. (Source: PLANET Microlensing Collaboration.)

Microlensing method. This is perhaps the most exotic of the currently used techniques, but it gives real results, and with its help exoplanets are discovered. The method is based on photometric observations of an increase in the brightness of a distant star due to the gravitational lensing of its light by the star–planet system, which crosses the line of sight 'observer–distant star'. If the lensing star has a planet, a narrow secondary peak caused by the planet is observed during the passage (Fig. 3). To detect planets using this method, thousands of stars are currently being monitored in the direction of the Magellanic Clouds and the center (bulge) of the Galaxy as part of the OGLE (Optical Gravitational Lensing Experiment) and MOA (Microlensing Observations in Astrophysics) projects. A complete observation of a microlensing event can last for several days or even about a month. A remarkable advantage of this method is that it is only slightly affected by selection effects: with its help, even planets of Earth's mass are being discovered. At present, only this method and the pulsar timing method enable the discovery of planets of such small masses. Therefore, it can provide in the future valuable material about the *mass function* of planets, i.e., the distribution of planets by mass.

Astrometry. Historically, the very first among the indirect methods through which attempts have been made to discover exoplanets. The technique is based on observations of periodic oscillations of a star in projection onto the plane of the sky: if a star has a planet(s), it moves in projection around the barycenter of the star–planet system. However, the size of this projection is very small. Van de Kamp announced in the 1960s that he had discovered periodic modulation caused by a planetary-mass satellite in the apparent motion of Barnard's star, one of the closest stars to the Sun. Observations made later by the Hubble Space Telescope did not confirm this discovery. It should be noted that, although this method has a very long history of declared planetary discoveries, so far none of them has been independently confirmed. Nevertheless, quite recently, in 2018, it enabled, on the basis of data from the Gaia spacecraft, refinement of the mass of the planet β Pic b discovered earlier through direct observations [15].

The method requires extremely high astrometric accuracy. Indeed, variations in the position of the Sun relative to the barycenter due to the presence of Jupiter, if the Sun is observed from a distance of 10 pc, will be less than one millisecond of an arc (0.001 arc second); the accuracy of HST astrometry is ~ 0.1 arc seconds. However, this method is a promising one, since the value of the planet's mass determined using this technique is not affected by the uncertainty in the inclination of the planetary orbit relative to the line of sight. It is expected that from 10,000 to 50,000 giant planets will be discovered by the Gaia spacecraft using the astrometric method.

Differential spectrophotometry method. This method provides information on the composition of planetary atmospheres. Spectral data obtained during transits are compared with the data before and immediately after the transit (i.e., immediately before and after the secondary eclipse). However, it can only be employed using very large telescopes. This method was applied using HST observations to discover for the first time the presence of sodium (by absorption lines) in the atmosphere of HD 209458b [16], and, using the Spitzer spacecraft, the presence of water and methane in the atmosphere of HD 189733b [17, 18]. Much additional interesting data on the chemical composition of exoplanet atmospheres has been obtained.

Finally, other promising *direct methods* for separating a weak planetary signal that exclude in some way the star's light should be mentioned. The list of these techniques includes coronography, 'zeroing' interferometry, and polarimetry. An *externally occulted coronagraph* is a lens or camera obscura located on the line of sight behind an eclipsing disk that occludes light from a central (bright) object. Such devices are especially promising for deployment aboard a spacecraft. *Zeroing interferometry* is based on combining light fluxes. While the maxima of the electromagnetic wave in a conventional interferometer are combined and amplified, in a zeroing interferometer, on the contrary, the maxima and minima are superimposed, so the signal from the main (bright) object is zeroed, while the signal from the planet remains unaltered since it is shifted relative to the main one. This method, similar to coronography, is the most promising one for observations by space telescopes. *Polarimetry* may be used to exclude unpolarized light from a star to effectively separate a polarized planetary signal. The expected fraction of the polarized signal is no more than 10^{-5}. Berdyugina et al. [19] were the first, in 2008, to observe a polarized signal from a previously discovered hot Jupiter HD 189733b.

4. Closest and most distant exoplanets discovered

4.1 Planets in the Alpha Centauri and Proxima Centauri systems

The binary star Alpha Centauri is located at a distance of 1.34 pc from the Sun. Its components are the solar-type stars closest to us. Even closer to us (by 0.02 pc) is the star Proxima, a red dwarf whose luminosity is 6×10^{-5} of the Sun's luminosity. Calculations by Anosova et al. [20] show that Proxima is not gravitationally related to the binary Alpha Centauri, i.e., they do not form a triple system. Alpha Centauri A and B are the fifth and eleventh most visible stars in the sky; their observed magnitudes are 0.06 and 0.59, respectively. They have historical names of their own: Toliman and Hadar.

Dumusque et al. [21] announced on October 17, 2012 the discovery of a planet of the Alpha Centauri B star. Dumusque et al. used precision Doppler spectrometry to detect variations in the radial velocity of the star with a half-amplitude of 51 cm s^{-1} and a period of 3.2 days. The semi-major axis of the planetary orbit was determined to be 0.04 au, and the planet's mass is $> 1.1\ M_E$.

Similar to Alpha Centauri A, the characteristics of component B are very close to those of the Sun (see the Hertzsprung–Russell (HR) diagram in Fig. 4). Alpha Centauri B is colder than the Sun (temperature $T_{eff} = 5214$ K, while for the Sun $T_{eff} = 5772$ K), is spectral type K1, and has a mass of $0.934\ M_S$. The star exhibits low stellar activity,

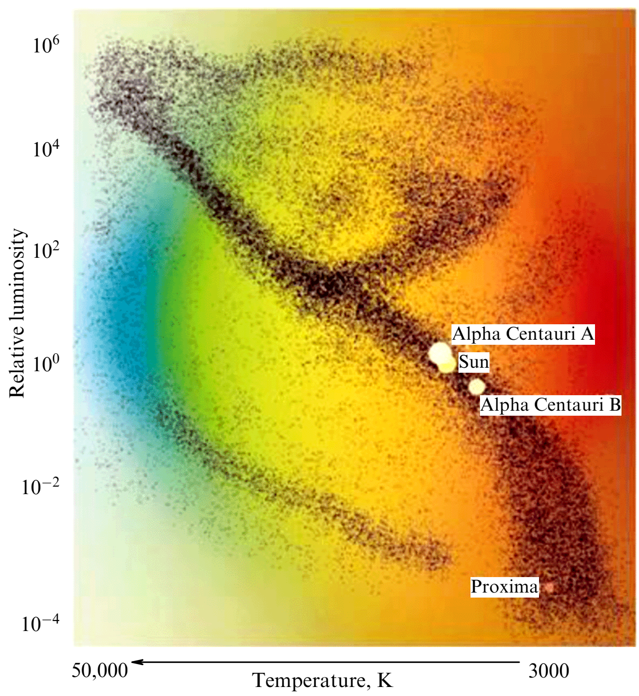

Figure 4. (Color online.) Stars Alpha Centauri (A, B), Proxima Centauri, and the Sun in the HR diagram. (Source: ESO images.)

which favors RV observations. These observations spanned the period from February 2008 to July 2011. A HARPS (High Accuracy Radial Velocity Planet Searcher) spectrograph was used at the 3.6-meter telescope of the La Silla Observatory (Chile, ESO). It is currently the best instrument for detecting planets using the RV method; its accuracy is $\sim 80\ \mathrm{cm\ s^{-1}}$. The number of observations of the star spectra is 459; the error probability (false alarm probability) is $\sim 0.3\%$.

Since the discovery was made at the limit of the instrument's capability, there is a possibility of a false discovery; however, according to Dumusque et al. [21], it is only 0.3%. Therefore, observations of the planet's transit are of great importance. They would make it possible to qualitatively improve the data on the discovered planet and its orbit. However, the probability of transit is small; it is estimated to be 10%, with a transit depth of 10^{-4}. Anyway, reaction from specialists on the possible discovery of a planet around Alpha Centauri B is controversial. Indeed, the probable 'planetary signal' is literally lost in noise. There are various 'non-planetary' astrophysical (for example, associated with the parent star activity) or methodological effects that can potentially induce a weak periodic signal or a phenomenon resembling it. Rajpaul et al. [22] showed that the detected 3.24-day period is possibly set by the time sampling scale adopted by Dumusque et al. in the statistical processing of observational data.

A planet has been discovered recently with a much lower declared error probability orbiting around a star that is even closer to us than Alpha Centauri. The European Southern Observatory (ESO) announced on August 25, 2016 the discovery by a team of observers [23] of the exoplanet Proxima Centauri b, a planet orbiting the red dwarf (spectral class M) Proxima Centauri. As was already mentioned, Proxima is the star closest to us; the distance to it is only 1.32 pc (4.3 light years). The planet Proxima Centauri b was also discovered by the RV method. The measurements were carried out using two spectrographs: HARPS with the 3.6-meter telescope based at the La Silla Observatory and UVES with the 8-meter VLT (Very Large Telescope).

The star Proxima Centauri, which is not visible to the naked eye from Earth, has an apparent magnitude of 11.1, a value well beyond the visibility limit, which is approximately 6 stellar magnitudes. In solar units, the star has a mass of 0.12, a radius of 0.14, and a luminosity of 0.0015. The effective surface temperature is ~ 3000 K, which is half the Sun's temperature. The age of Proxima is ~ 4.9 billion years; thus, it is about 300 million years older than the Sun.

According to measurements [23], the planet Proxima Centauri b has a mass of $1.27 \sin i$ (in Earth's mass units). If it is a rocky (terrestrial) type planet, its radius is 1.1 Earth radii or more. The radius of the Proxima Centauri b orbit is 0.05 au, which is 8 times less than that of Mercury; the orbital period is 11.2 days. The habitable zone near Proxima Centauri extends from ~ 0.042 to ~ 0.082 au. Anglada-Escudé et al. [23] found that the orbit of Proxima Centauri b is located within the habitable zone of the parent star, i.e., the planet's insolation at a given orbital radius (0.05 au) is such that, theoretically, liquid water can exist on its surface.

It should be noted that, although Proxima Centauri b is located in the habitable zone, it is hardly suitable for life, since it is affected by the stellar wind, whose intensity exceeds that of the solar wind near Earth by more than 2000 times [24]. Moreover, Proxima Centauri is a flare star that undergoes strong sudden changes in luminosity. However, the mere fact that Proxima Centauri b is, most likely, a rocky planet located in the habitable zone makes it an object interesting from the point of view of searching for extraterrestrial life in any form. Most of the light flux from Proxima Centauri is radiated in the infrared range, so life on Proxima Centauri b, if it exists, should be, apparently, very different from that on Earth.

4.2 Most distant exoplanet systems

The planets SWEEPS-04 and SWEEPS-11 were discovered as part of the SWEEPS project (Sagittarius Window Eclipsing Extrasolar Planet Search) based on the observations of planetary transits in a star-rich area in the direction of the Galaxy bulge [4] by the Hubble Space Telescope. Observations were carried out as part of the SWEEPS project for 7 days [25, 26] in the Sagittarius constellation in the direction toward the Galaxy center. The dimensions of the SWEEPS field are 202×202 arc seconds; it includes 180,000 stars, around which the HST can discover Jupiter-type giant planets.

The planets SWEEPS-04 and SWEEPS-11 are the most remote from the Sun among the exoplanets known today. The estimated distance to them is 8.5 kpc, i.e., about 30 thousand light years! The masses of these two planets are approximately 4 and 10 Jupiter masses, and the orbital periods are 4.2 and 1.8 days. These exoplanets are typical hot Jupiters. Their parent stars are solar-type stars. Sahu et al. [26] plotted RV curves for SWEEPS-04 and SWEEPS-11 based on the data from observations made using the 8-m VLT telescope of the European Southern Observatory (Chile). The phases of transits and RV variations for SWEEPS-11 were found to be consistent, which is good confirmation of the discovery of this planet.

5. Types and physical properties of exoplanets

5.1 Main types of exoplanets

A fundamental contribution to the discoveries of exoplanets and their classification was made by observations performed using the Kepler space telescope (NASA) with a mirror 90 cm in diameter. The spacecraft has observed in about three years of operation over 170,000 stars in the constellations Cygnus and Lyra and discovered 3,630 confirmed planets and 4,175 candidates that require confirmation. The apparatus itself and the observation area are shown in Fig. 5, and examples of the main types of exoplanets discovered by Kepler according to the currently accepted classification are displayed in Fig. 6.

5.2 Mass and size statistics

The discovery of thousands of exoplanets made it possible to set characteristics for this class of astrophysical objects and to systematize them in the form of a kind of 'demography' of exoplanets. Initial observations of radial velocity might give the impression that most planets have masses of the order of Jupiter's (this is the contribution of hot Jupiters); however, it turned out that this is clearly an *effect of observational selection*, since the most massive planets are discovered first. The number of discovered planets with masses of the order of the mass of Neptune or smaller is constantly increasing [27]. On the other hand, there is a sharp drop in the number of planets at large masses. The mass distribution of planets is

[4] The bulge is the central spheroidal component of our Galaxy. It primarily consists of old stars: red giants, red dwarfs, and RR Lyrae-type variables; it also contains globular clusters. The bulge radius is about 2 kpc.

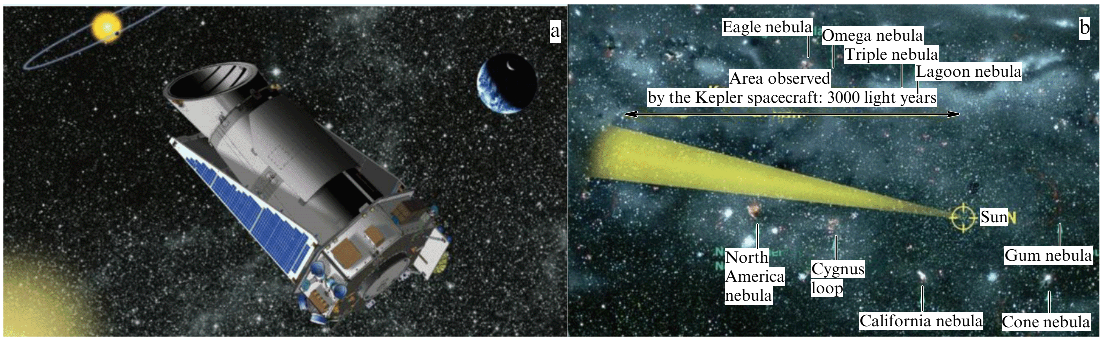

Figure 5. (Color online.) (a) Kepler telescope and (b) its area of observation on the celestial sphere (NASA site).

Planets discovered by the Kepler space telescope (as of February 27, 2012)

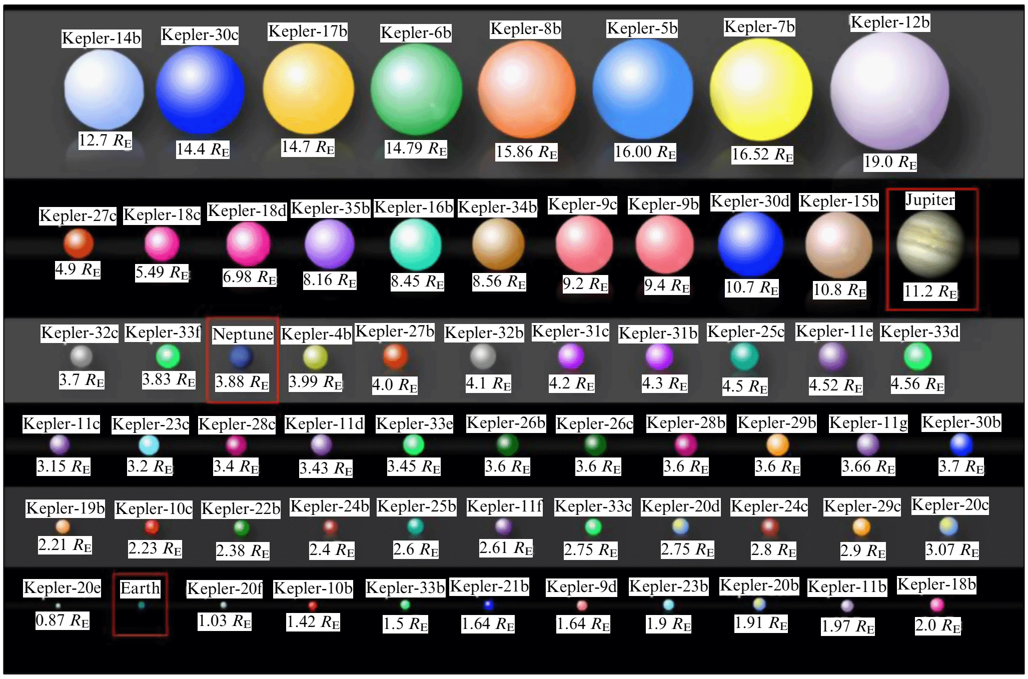

Figure 6. (Color online.) Examples of the main types of exoplanets discovered using the Kepler spacecraft (selective 'demography' of exoplanets). (Source: Ames Res. Center, NASA.)

described by the function $1/M$, i.e., has the form of a hyperbola (Fig. 7). This phenomenon is, most likely, a real one, since the known selection effects do not affect the observation data for planets with masses this large. Figure 8 displays the masses of observable exoplanets as a function of the semi-major axis of the orbit a. The graph shows both the dominance of hot Jupiters and, on the other hand, the deficit of planets of lower masses at relatively large values of a.

The mass–radius plot for 138 planets with known masses and sizes [28] exhibits a clear-cut kink (Fig. 9) that corresponds to the transition from terrestrial planets and ice giants $(M < 150\, M_E)$ to gas giants $(M > 150\, M_E)$. In the former case, the line of equal density of a solid body would have a slope of $1/3$ in logarithmic coordinates, but the observed slope is approximately $1/2$. This indicates an increasing contribution of volatiles with increasing mass. In the second case, the radius remains almost constant or even decreases with increasing mass; this indicates the contribution of the degenerate electron gas. In addition, statistically significant in the second case are the increased sizes of the planets at high levels of insolation (the flux of stellar radiation falling on the planet); this is explained by the 'swelling' of gas giants at high temperatures.

It can be seen that the spectrum of masses and sizes of discovered exoplanets is quite wide: it spans three orders of magnitude in mass and slightly more than one order of magnitude in size (see Fig. 9). The largest among the planets discovered to date is TrES-4 (discovered as part of the Trans-Atlantic Exoplanet Survey project); its radius exceeds that of Earth's by 19.8 times and Jupiter's radius by a factor of 1.8, while its mass is almost the same as Jupiter's. The density of this planet, therefore, is about 0.3 g cm^{-3}, which is a record-setting low among planets with known sizes and masses [29]. The smallest exoplanet discovered is 'sub-Mercury' Kepler-37b, which is only slightly larger than the Moon and has a mass of ~ 0.01 Earth masses. Overall, it should be noted that the range of densities of the discovered planets is very wide, which is possibly related to the effect of the loss of volatiles due to intense erosion by stellar radiation in the close vicinity of the star.

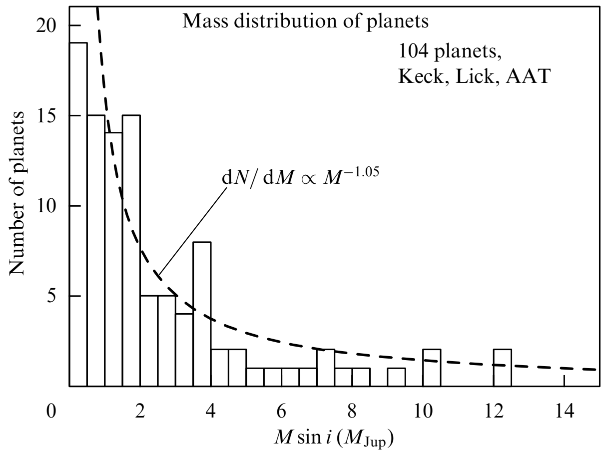

Figure 7. Mass distribution of planets [27].

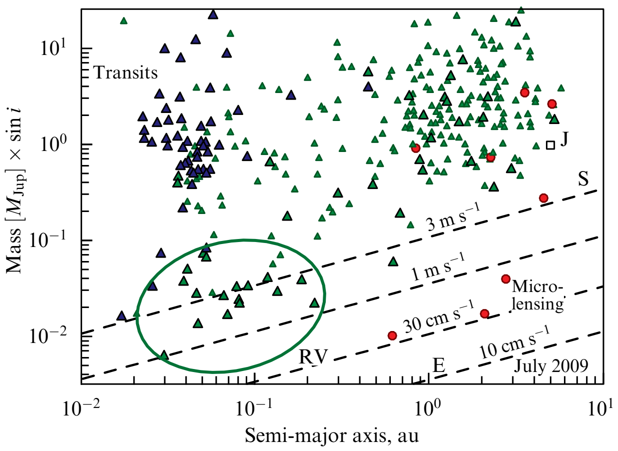

Figure 8. (Color online.) Exoplanet masses as a function of the semi-major axis of the orbit. Green triangles — radial velocity method, blue triangles — transit method, red dots — microlensing method. J, S, E — solar system planets (Jupiter, Saturn, Earth) and the corresponding amplitudes of their radial velocity (for Earth, 9 cm s^{-1}). (According to [28].)

5.3 Connection with the metallicity of stars

Metallicity is an important parameter of stars. This term characterizes the relative abundance in a star of elements heavier than hydrogen and helium. Observational data show a correlation between the metallicity of a star and the presence of planets around it: low-metallicity stars do not have planetary systems, while if metallicity is higher than solar,[5] the probability of the presence of planets around the star sharply increases (Fig. 10). The reason, most likely, is that stars with planets are born in molecular clouds enriched with nucleosynthesis products during the evolution of the previous generations of stars, i.e., with a relatively high content of heavy elements [30]. As metallicity grows, the presence of iron silicate rocks, of which the nuclei of giant planets consist, increases; volatiles accrete on the rocks, gas-ice giant planets are formed, and planets entirely consisting of rock are accumulated.

Some conclusions regarding the internal structure of exoplanets can be made by modeling the observed statistical dependences, such as the mass–radius dependence (see Fig. 9). It may be expected that the internal structure of exoplanets corresponds as a whole to models of the terrestrial planets and giant planets. The differences may depend on the metallicity of the parent star and the composition of the protoplanetary disk. Surface temperature, composition, and properties of the atmosphere are primarily determined by the radial distance from the host star and partly by the internal heat flow. The surface temperature of planets close to stars may be as high as ~ 1500 K!

If potential selection effects are taken into account in analyzing the statistics of discovered exoplanets, a conclusion may be drawn that at least 25% of the solar-type stars in the Galaxy have planetary systems [31]. Thus, as was already noted, the presence of planets around stars, especially of late spectral classes, is by no means a rare event, but a common phenomenon. However, the natural properties of most exoplanets discovered are not at all similar to those of planets of the Solar System. Hot Jupiters are a prime example of this. They are giant exoplanets with Jupiter and super-Jupiter masses orbiting close to the parent star: orbital periods T of the order of several days are observed. Hot ($T < 10$ days) and warm ($10 < T < 200$ days) Jupiters may be distinguished. The other most known (and possibly predominant) types of exoplanets are mini-Neptuns and super-Earths, whose properties are close to those of terrestrial planets in the Solar System. Earths and super-Earths distinguished among exoplanets have masses of $\sim 1-2\,M_E$ and $\sim 2-13\,M_E$, respectively. They are sometimes defined as planets with nondomi-

[5] The Sun consists of hydrogen (74.9%), helium (23.8%), and heavier elements ('metals') as admixtures. The Sun contains 99.85% of the entire matter (mass) of the Solar System.

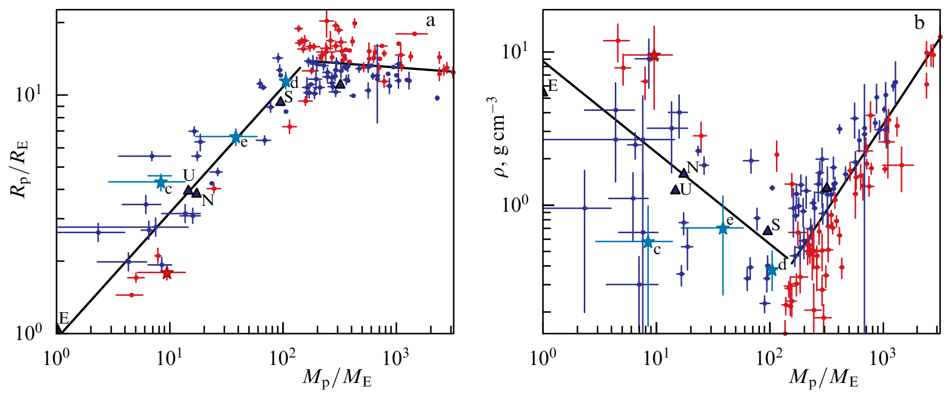

Figure 9. (Color online.) (a) Mass–radius and (b) mass–density relationships for discovered exoplanets according to [28]. Red crosses — high insolation, blue crosses — low insolation.

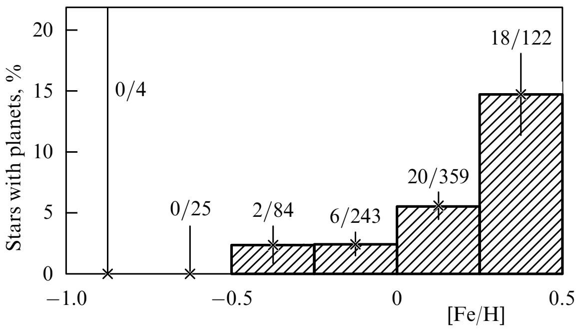

Figure 10. Relation between the metallicity of a star and the presence of planets [30]. Horizontal axis shows metallicity, and vertical axis shows the proportion of stars that have planets.

nant atmospheres, when the extent of the atmosphere, like that of Earth, is much less than the planet radius.

An important parameter is I/R, the ratio of the masses of water (ice) and solid matter (metals and rocks). Depending on the value of this parameter, different types of planets are distinguished [32, 33]: (1) $I/R \sim 10^{-4}$ — a rocky planet whose water content is similar to that of Earth's; (2) $I/R \sim 0.3-0.5$ — a planet with a liquid ocean under an ice shell, similar to Jupiter's moons Europa and Ganymede; (3) $I/R \sim 1$ — a completely oceanic planet. The formation and properties of super-Earths are possibly associated with the gaseous envelopes of giant planets being torn off by ultraviolet radiation from the parent star or massive stars adjacent to the planetary system. In general, the presence of systems with super-Earths can be expected in regions where large-mass stars are formed, and the presence of systems of the same size with giant planets in regions where low-mass stars are created [34].

A new, very unconventional class of exoplanets is formed by free-floating planets, *rogue planets*, orphan planets, i.e., planets that do not belong to planetary systems of stars. Such objects have been discovered in a star cluster in the Orion nebula [35]. They may emerge due to ejection from parent planetary systems into hyperbolic orbits. A relatively large part of the planets formed in binary star systems can be ejected [36]. According to calculations [37], some of the planetesimals could also be thrown into hyperbolic orbits during the formation of planets beyond the orbit of Jupiter. A numerical simulation of the long-term dynamics of the Solar System [38] shows that Mercury can be ejected from the Solar System on timescales of the order of a billion years.

Exoplanets that are not rogue planets belong to systems whose structure and composition are mostly very different from those of the Solar System. The following main types of planetary systems can be distinguished [39]: (1) systems without observable planets (example: Tau Ceti [6]); (2) systems with observable planets and residual disks (debris disks), which usually have a strongly asymmetric shape, consisting of small bodies and dust that are presumably left after the formation of planets (example: Epsilon Eridani); (3) systems with gas giants in orbits greater than 0.1 au ('cold Jupiters'), without noticeable debris disks (example: the Solar System); (4) systems with gas giants in orbits of less than 0.1 au, without debris disks.

[6] However, observations by Feng et al. [40] show that Tau Ceti most likely has a planet.

6. Atmospheres of exoplanets

6.1 General properties

Observations of planets that pass across the disks of parent stars (transits) have offered unique opportunities for studying the properties of their atmospheres. The most general information about the atmosphere is provided by data on the presence of Rayleigh scattering, which is obtained by broadband photometry in the optical wavelength range [41] and enables certain properties of the medium to be determined.

Information about the chemical composition and structure of an exoplanet's atmosphere can be obtained using transmission spectrometry, which determines the character and degree of absorption of the star's light by the planet's atmosphere as a function of the wavelength. The best conditions for such measurements are provided by the extended atmospheres of large planets, primarily hot Jupiters, but also planets with the masses of Saturn and Neptune, in observing high-resolution spectra of which it is easier to separate the spectral properties of a star and a planet, though their brightness values are significantly different. This limitation even more strongly affects the identification of lines/bands in the emission spectra, taking into account the nonequilibrium processes and photochemistry in the chromosphere/corona of the star and the upper atmosphere of the planet. Along with the standard techniques, the transmission spectrometry method also makes it possible to find in the absorption spectra unusual atmospheric components, which are products of degassing and atmospheric chemistry. For example, sulfur lines were found in the high-resolution spectra of exoplanets HD 189733b and WASP-17b, an observation that is of interest to associate with the detection of molecules of sulfur-containing compounds in protostellar disks [42–44]. The transmission spectrometry method is constantly being improved, making it possible to use ground-based telescopes along with spacecraft, especially those that use adaptive optics. New perspectives are opened by the multipurpose CHEWIE (Clouds, Hazes and Elements vieWed on gIant Exoplanets) program — survey observations of the composition of the atmospheric gases, clouds, and atmospheric haze of giant exoplanets.

Such measurements, in turn, make it possible to refine observational techniques and instruments that open up prospects for studying less dense atmospheres of exoplanets with a solid surface (sub-Neptunes, super-Earths, Earths), typical for systems of the most numerous active M-class dwarf stars (such as Proxima Centauri, Trappist-1). It may be expected that additional data on the structure of the atmosphere, combined with data on the size of the transit planet and model estimates of temperature, will come from observations of disk-edge darkening and atmospheric excess. Information on the presence of solid or liquid particles in the atmosphere of a transit exoplanet (for example, water droplets in clouds or atmospheric haze particles) is provided by polarimetry, which makes it possible to distinguish the polarized light reflected by the planet's atmosphere or surface from unpolarized light from a star. The continuously increasing number of observed transits from space and ground-based telescopes (especially the 8-meter class) provides the accumulation of data on the variety of properties of exoplanet atmospheres, including composition, albedo, thermobaric profiles, the greenhouse effect, heat redistribution, and even dynamics. The combination of transit and radial velocity methods enables determination of the density of a planet with an atmosphere, which contributes to understanding its climatic evolution. The chemistry of minor atmospheric constituents opens up prospects for the discovery of life. Closely related to this problem, along with atmospheric chemistry and the gas envelope density, is the issue of whether the planet has its own magnetic field and magnetosphere and the problem of interaction with the stellar wind plasma, including the formation of a detached shock wave and contact discontinuity, at the boundary of which the material of the incoming gas and atmosphere are separated.

6.2 Atmospheric dissipation

The formation of the planet's climate and its evolution are closely related to the formation and retention of its atmosphere. Exoplanets in orbits close to their parent star are exposed to extreme ultraviolet (XUV) and X-ray radiation. This factor strongly affects the current state and properties of the upper atmosphere and, apparently, its effect was even stronger at the initial stage of planetary evolution. A certain analogy can be drawn here with such grandiose events on the Sun as coronal mass ejections (CMEs), which considerably affect the state of Earth's atmosphere and magnetosphere. These effects could be even more pronounced for nearby planets around class G, K, and M stars, leading to atmospheric dissipation and even atmospheric erosion, and thereby preventing the emergence of life.

The problem of dissipation of the atmosphere into space has always received great attention (see, e.g., [45]). Investigating the processes based on the interaction of energetic solar radiation with the highly rarefied gas of the planetary exosphere required the development of original kinetic models using statistical analogs of the Boltzmann equation and numerical Monte Carlo simulation algorithms [46–48]. These models underlie the interpretation of the emission spectra of the upper atmosphere, estimates of the formation of particles with superthermal energies, and escape fluxes in the absence of thermochemical equilibrium in a rarefied gas and in the presence of diffusion processes and nonequilibrium photochemistry. Their correctness as applied to the exploration of Earth and terrestrial planets is confirmed by a comparison with the results of the corresponding spacecraft measurements (for example, in the case of Mars, by the Mars Express and MAVEN spacecraft). The application of this approach to the study of exoplanets enabled development of models of dissipating neutral gas flows in the hydrodynamic regime and the estimation of the rates of atmospheric losses for hot Jupiters and Neptunes [45, 49].

Despite the differences among the details of these models (numerical solution methods, the assumed main atmospheric components, and the chemical complexity of the medium), all these models generally correspond to observations of the hydrogen cloud, and the calculated hydrogen loss rates coincide with each other within several orders of magnitude. Unfortunately, they fail to provide a detailed study of the evolution of exoplanets located in close orbits and at long time intervals. The problem is mainly associated with large uncertainties in the factors employed in the models, such as the stellar energy flux in the extreme ultraviolet radiation range, heating efficiency (conversion of absorbed photon energy into heat), geometric factors, and the contribution of heavy elements. Moreover, the models of the atmospheres of exoplanets at various stages of evolution, which are of interest per se, enable exploration of the history of the escape of atoms from the atmospheres of terrestrial planets in the early solar system.

Dissipation of hydrogen-dominant atmospheres of hot Jupiters is discussed in detail in [45]. The study presents the results of model calculations of the escape of hydrogen from the detected extended hydrogen cloud surrounding hot Jupiters, which occurs in the hydrodynamic regime, since the atmospheres of many of them go beyond the Roche lobe. A one-dimensional self-consistent model of the atmosphere of a hot Jupiter, which includes a Monte Carlo module, a chemical kinetics module, and a gas-dynamic module, was applied to calculate the rates of heating of the atmosphere in photochemistry processes and the profiles of macroscopic parameters of the atmosphere during the transition from the hydrostatic flow regime to the hydrodynamic regime, with which thermal and nonthermal escape processes are associated. The atmosphere of hot Jupiter HD 209458b was simulated taking into account the Roche potential, and the effect of reactions that involve epithermal photoelectrons on the dynamics, changes in the chemical composition, and the rate of outflow of its hydrogen-helium envelope was established. The combination of these processes distorts the gas envelope of the planet, making it substantially asymmetric (Fig. 11). The results proved to be in good agreement with the estimates that follow from observations made by the Hubble Space Telescope and with the results of other gas-dynamic models. The obtained values of atmospheric parameters can be used as boundary conditions for 3D gas-dynamic calculations that simulate the interaction of a planet with the stellar wind. Estimated was the efficiency of converting the stellar radiation energy into heat in the soft X-ray and extreme ultraviolet radiation ranges, which plays a particularly important role in ionization, photochemistry, and thermal dissipation of the upper atmospheres of planets exposed to strong fluxes of hard radiation. It was found that the calculated heating efficiencies obtained for the solar spectrum can also be applied to stars younger than the Sun after scaling the photon flux in the soft X-ray and extreme ultraviolet ranges in accordance with the observational data of the stellar

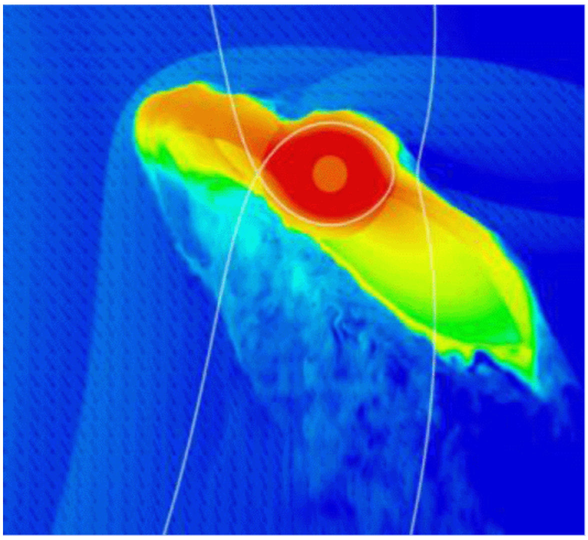

Figure 11. Gas envelope of the planet HD209458b. Simulation results show that it becomes significantly asymmetric due to interaction with the stellar-wind gas [50].

spectra. This approach enabled estimation of the rate of atmospheric outflow for planets around young stars whose spectrum differs from that of the Sun [50].

In contrast to previous aeronomic models, the authors of [45] studied in detail the photoionization of H and dissociation of H_2 (photodissociation, dissociation by electron impact, dissociative ionization, etc.), which are the main sources of thermal and epithermal hydrogen atoms $H_2 \to H \to H^+$ in hydrogen-dominant atmospheres of exoplanets and, primarily, hot Jupiters. It is shown that the efficiency of energy transfer strongly depends on the energy of elastic collisions at small scattering angles and that the features of elastic scattering of epithermal hydrogen atoms by thermal components of H_2, He, and H largely determine the parameters of the fraction of epithermal hydrogen in the upper atmosphere of an exoplanet. The distribution of hydrogen atoms in the transition $H_2 \to H$ region of the upper atmosphere of an exoplanet was found in the developed stochastic model from the solution of the Boltzmann kinetic equation. This equation includes a photochemical source of epithermal hydrogen atoms with an excess of kinetic energy formed in the processes of H_2 dissociation, and the source functions of such atoms are determined from the rates of photolysis of the atmospheric gas by the UV radiation from the star and the accompanying flux of photoelectrons. The numerical model takes into account that the absorption of extreme UV radiation from a star is accompanied by excitation, dissociation, and ionization of atmospheric components and the formation of a flux of photoelectrons with energies sufficient for the subsequent excitation and ionization of atomic and molecular hydrogen. To calculate the rates of photoprocesses, transport, and collisional kinetics of photoelectrons, the Monte Carlo model adapted to hydrogen atmospheres was used. The developed model made it possible for the first time to estimate the production rate and the energy spectrum of hydrogen atoms formed with an excess of kinetic energy during the dissociation of H_2 in the upper atmosphere of exoplanet HD209458b and to show that the source of epithermal hydrogen atoms due to the dissociation of H_2 should be included in modern aeronomic models of physical and chemical processes in the upper atmospheres of exoplanets.

Unfortunately, as was already noted above, due to the uncertainty in the energy and geometric factors, such calculations fail to clarify the extremely important issue of the evolution of the atmospheres of exoplanets that are located near the parent star and exposed to intense plasma and electromagnetic radiation fluxes. Nevertheless, the proposed models make it possible to set important restrictions on the variety of photochemistry processes in planetary atmospheres and, at the same time, create the necessary prerequisites for dedicated programs for observing exoplanets using ground-based and space telescopes. It can be expected that expansion of the field of research far beyond the Solar System and further improvement in the developed mathematical models based on exoplanetary aeronomy will contribute to a better understanding of evolutionary processes and key problems of planetary cosmogony.

7. Architecture and dynamics of exoplanetary systems

The Solar System is very different from most known exoplanetary systems: exoplanets often have large orbital eccentricities, while in the Solar System the eccentricities of all eight planets are close to zero; giant planets are located in many discovered exosystems in orbits close to the parent star (hot Jupiters, mini-Neptuns); moreover, there are no super-Earths in the Solar System. It should be emphasized that the Solar System is compared here with known exoplanetary systems; when taking into account the effect of observational selection, the differences are somewhat smoothed out. In particular, hot super-Jupiters, which are absent in the Solar System, are a phenomenon which is rather rare in exoplanetary systems, but show themselves much more easily during observations. Among the plethora of discovered planetary systems, there are some whose physical properties are quite close to those of the Solar System, for example, Gliese 581, 47 UMa, μ Arae. For instance, three planets were initially discovered around red dwarf Gliese 581 (a star of spectral type M3V): hot Neptune b and two super-Earths c and d [51], and later the presence of three more planets, e, f, g, was reported, which proved to be located, according to calculations, in the habitable zone. Later, the existence of hot Neptune b and two terrestrial planets was confirmed, while the existence of planets f and g was not. The reason for the false identification of the last two was the presence of an artifact in the observational data (noise in the RV signal), as was revealed by R V Baluev [52].

7.1 Dynamic classification

The dynamics of forming protoplanetary bodies are closely related to those of residual disks. Images of the residual disks of the closest stars exhibit a wide variety of structures that can be interpreted based on their dynamics. The observed distributions of dust provide information on the distribution of larger objects — planetesimals and the planets themselves.

The most important phenomena that determine the dynamic structure of exoplanetary systems are *resonances* and *migration*. Resonances play an essential role in the dynamics of planetary systems at various stages of evolution, largely determining their architecture. There are *mean-motion resonances* and *secular resonances*. The former represent the commensurability between the average frequencies of the orbital revolution of the planets (or planets and stars in multiple star systems), the latter, the commensurability between the orbital precession rates. According to modern cosmogonic concepts, the captures of a planetary system into orbital resonances are natural evolutionary stages due to the migration of planets in a gas-and-dust disk, which proceeds for different planets at different rates [53, 54].

Modern dynamic classifications of planetary systems distinguish as the first (primary) class precisely those systems with mean-motion resonances. Examples of systems with planets in a 2:1 resonance are Gliese [7] 876 and HD [8] 82943, and in a 3:1 resonance, the 55 Cancri system. The presence of mean-motion resonances and their interaction in planetary systems determine the chances of *chaotic behavior* [9] in the orbital dynamics of planets, for example, in the case of the Kepler-36 planetary system [55].

[7] The 'Gliese' prefix indicates that the star is included in the catalog of the stars closest to the Sun, which was published by V Glise (1969). The Glise catalog contains the stars located no more than 25 pc from the Sun.

[8] The 'HD' prefix indicates that the star is included in the Henry Draper catalog (1918–1924).

[9] For more details regarding the phenomenon of dynamic chaos induced by 'overlapping' of resonances, see the review by B V Chirikov [73].

7.2 Stability criteria

Observational errors in determining the orbital parameters of exoplanets are often larger than the ranges of their values in which the long-term stability of the system is sustained. Therefore, an analysis of stability makes it possible to impose more stringent constraints on the orbital parameters. To date, both analytical and numerical-experimental *criteria for the stability* of planetary systems have been developed. The analytical criteria are based on the adaptation of the *Hill criterion* [56–59] and the *Chirikov resonance overlap criterion* [60, 61]; and numerical-experimental criteria are based on calculations of *FLI* [62], *MEGNO* [63-65], *Lyapunov exponents* [66, 67], fundamental frequencies of motion (*frequency analysis* [68, 69]), and numerical analysis of escape/collision conditions [70–72]. The Lyapunov time, the inverse of the maximum Lyapunov exponent for a dynamical system, sets the characteristic time of its predictable motion for given initial conditions. If a resonance is described in the perturbed pendulum model [73], the Lyapunov time can be estimated in many cases not only in numerical-experiment terms, but also analytically, using the theory of standard and separatrix mappings [74, 75].

We now characterize the analytical criteria in somewhat more detail.

Hill criterion. The Hill criterion sets the boundary of the region of stable orbits around a low-mass body ('second body' — a 'satellite', 'planet', binary star component) orbiting a body with a larger mass ('first body' — a planet, a star, the main component of a binary, respectively). According to this criterion, the radius of the stability zone is directly proportional to the radius of the Hill sphere calculated at the pericenter of the second body's orbit:

$$r_{\mathrm{H}} \approx \left(\frac{\mu}{3}\right)^{1/3} a(1-e)\,,$$

where $\mu = M_{\mathrm{sec}}/M_{\mathrm{prim}}$ is the ratio of the masses of the second and first body. This formula defines the so-called 'scaling of the Hill sphere radius to the pericenter' [76]. The conventional radius of the Hill sphere is determined by the formula $r_{\mathrm{H}} = (\mu/3)^{1/3} a$.

Wisdom criterion. The Wisdom criterion is an adaptation of the Chirikov resonance overlap criterion [73, 77] regarding a specific celestial-mechanical problem. It gives the dimensions of the area 'cleared' by the planet in the radial vicinity of its orbit due to the overlap of $(p+1):p$ resonances at large p. These are first-order resonances; they overlap in the vicinity of the planet's orbit. The motion of particles captured in the overlap area becomes chaotic, and the area is cleared up.

According to this criterion, the radial half-width of the vicinity of the disturbing body, where the orbits are unstable, is given in the planar circular restricted three-body problem by the formula

$$\Delta a_{\mathrm{cr}} \approx 1.3\,\mu^{2/7} a'\,,$$

where $\mu = m_2/(m_1+m_2)$ is the mass parameter ($m_2 \ll m_1$), a' is the semi-major axis of the disturbing body's orbit; particle eccentricity $e < 0.15$. Particles with semi-major axes of orbits in the range $a' \pm \Delta a_{\mathrm{cr}}$ move chaotically. The value of p critical for the overlap of resonances $(p+1):p$ is in this case [60, 78]

$$p_{\mathrm{cr}} \approx 0.51\,\mu^{-2/7}\,.$$

Holman–Wiegert criterion. This is a purely numerical-experimental criterion that sets the limits of stability for the orbits of planets in binary stellar systems. For example, in the case of a circumbinary [10] system in the planar problem, the radius a_{cr} of the inner zone of instability of the particle motion on an initially circular prograde outer orbit is given by the following polynomial (in the mass parameter and eccentricity) approximation:

$$\frac{a_{\mathrm{cr}}}{a_{\mathrm{b}}} = 1.60 + 5.10 e_{\mathrm{b}} - 2.22 e_{\mathrm{b}}^2 + 4.12\mu - 4.27 e_{\mathrm{b}}\,\mu - 5.09\mu^2 + 4.61 e_{\mathrm{b}}^2 \mu^2\,,$$

where $\mu = m_2/(m_1+m_2)$ is the mass parameter of the binary, and a_{b} and e_{b} are the semi-major axis and eccentricity of the binary [70].

Moriwaki–Nakagawa criterion. This criterion sets the conditions for the possibility of planetesimal accretion in the circumbinary disk. Thus, this criterion is not a purely celestial-mechanical one, since it also uses physical assumptions. If the velocities of the planetesimals relative to each other during their collisions exceed the velocity of particle escape from the surface of the body, planetesimals cannot accumulate and form planetary embryos. Therefore, the eccentricities of planetesimals should be sufficiently small.

According to this criterion, the radius of the inner boundary of the planetesimal accretion zone for planetesimals with mass m and intrinsic density ρ is given by the formula

$$a_{\mathrm{acc}} \approx \left[\frac{5}{2}(1-2\mu) a_{\mathrm{b}} e_{\mathrm{b}}\right]^{2/3} \left(\frac{3M^3}{32\pi m^2 \rho}\right)^{1/9},$$

where μ is, as above, the mass parameter of the binary, $M = m_1 + m_2$ is the total mass of the binary, and a_{b} and e_{b} are the semi-major axis and eccentricity of the binary system [79].

Study [80] reports a comparative analysis of modern numerical methods employed for studying global dynamics: the calculation of Lyapunov characteristic exponents (LCEs), the MEGNO method, and the method of maximum eccentricities (MEs). The stability diagrams for the planetary systems γ Cep, HD 196885, and HD 41004 were determined, which made it possible to find the most probable values of the orbital parameters of the planets. By comparing the stability diagrams constructed using various methods, a comparative analysis of the effectiveness of the LCE, MEGNO, and ME methods as applied to planetary problems was carried out. Figure 12 shows as an example the stability diagrams of the γ Cep planetary system [80].

7.3 Migration and tidal effects

As emphasized in [81], modern, successful models of the formation of both the solar and exoplanetary systems are based on two key concepts: orbital migration and dynamic instability. Tidal effects also play a crucial role. There are different types of migration, and the divisions among them are mainly based on whether the migration occurs in the original gaseous environment of the disk or after the planet has formed a ring-shaped gap. Along with migration, tidal interactions provide an approach to solving the problem of

[10] The term circumbinary is used for the orbits of bodies that orbit both companions of a binary.

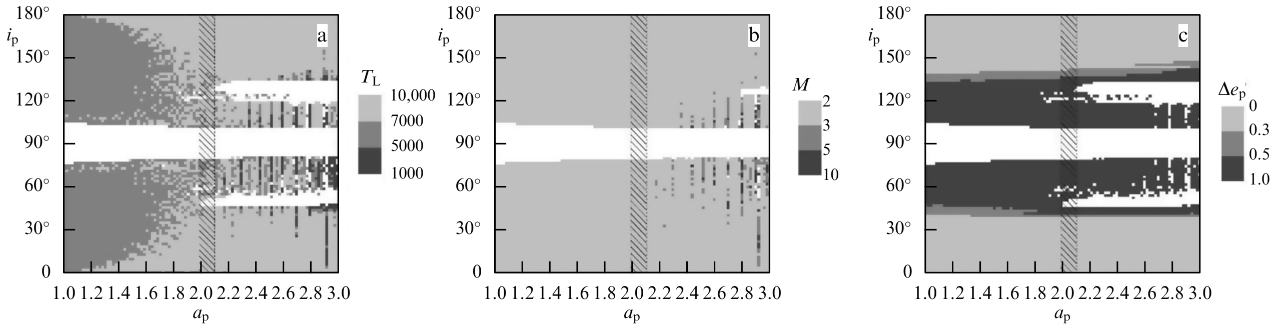

Figure 12. Properties of the long-term dynamics of the γ Cep b planetary system on varying the initial conditions for the semi-major axis and orbital inclination. Stability parameters are presented as grades of black and white. (a) Lyapunov times (in years), (b) MEGNO parameter, (c) maximum change in the eccentricity of the planet (within 10^5 years). The white field corresponds to the instability zone. The shaded bar indicates the interval of the most probable (according to observations) values of the semi-major axis of the γ Cep b orbit. (According to [80].)

hot Jupiters, which are likely to form at a distance from the host star and drift to their current position near the star due to the migration mechanism. The tidal effects from the star may be the mechanism that stops the drift towards the star and ensures the survival of these massive planets [82–84]. The character of migration is also due to the possible occurrence of resonances. The migration rate could be relatively high in the case of intense gas accretion onto the planet at the early stages of evolution, but at the same time, the gas heating that accompanies the accretion could result in an increase in the eccentricity of the protoplanet's orbit and capture into a resonance [85, 86].

The configurations of planetary systems in the early era were probably very different from those observed today. As was already noted, the dynamics of primary bodies are closely related to those of residual disks. This is confirmed by the images of remnant disks of the closest stars, on which a wide variety of structures have been found. They can be interpreted based on an analysis of the dynamics of small bodies in early planetary systems, and the observed distributions of dust provide information on the distribution of large objects such as planets and their embryos.

Of particular interest are the configurations of planetary systems with supermassive planets located in the immediate vicinity of the star — super-Jupiters. Probably, planets of this type, which are born in the low-temperature zone and migrate to the high-temperature zone, are sooner or later absorbed by the parent stars. Thus, this mechanism can limit the lifetime of the planet. The displacement and circularization of orbits in planetary systems is a natural consequence of the interaction between planets and the residual gas in the disk. The migration and dynamics of massive planets can also be associated with the formation of planets such as Earths and super-Earths.

An alternative model is based on a concept that an important role in the evolution of the system is played by massive planetesimals remaining near the formed planet. They could exert a strong gravitational effect on the evolution of the planet's original orbit and cause it to drift along with a swarm of planetesimals located near and far from the star to satisfy the condition of conservation of orbital energy and angular momentum in the protoplanetary disk. Their gravitational effect on the evolution of the orbit of the formed planet could be significant and could largely determine the migration rate. Together with dynamic instability processes, the migration of planets leads to a transformation of their orbits and determines the architecture of the emerging planetary system. Mutual planetary perturbations are also added in a multiplanetary system to the planet-disk interaction, and convergent migration leads to the emergence of orbital resonances between planets, primarily first-order ones (2:1, 3:2).

It should be noted that the migration processes probably affected the evolution of planetary orbits in the outer regions of the early Solar System. According to modern concepts, Saturn migrated inwards in the system and was temporarily trapped in a 3:2 resonance with Jupiter. The emergence of this resonance could, in turn, delay or even completely halt the migration of Jupiter to the Sun [87, 88]. This process inevitably affected the planetary embryos in the inner region of the Solar System, including the formation of the terrestrial planets and their orbits and the position and accumulation of the remaining primary bodies in the main asteroid belt. In addition, migration processes at the stage of early evolution are associated with the motion of Uranus and Neptune from the region of their initial formation near the Jupiter–Saturn zone in a direction farther from the Sun, as well as the formation of the Kuiper belt.

This scenario is supported by estimates of the time that would be required for the accumulation of Uranus and Neptune in their present orbits. Simulation results show that this would take time that exceeds the age of the Solar System. The model, which is sometimes called the model of reconfiguration of the orbits of giant planets, or the *Nice model* [89], assumes the existence of an initial disk with a mass of several dozen Earth masses that consists of comet-like objects and is located beyond the orbits in which the giant planets were subsequently formed. It is assumed that this disk was scattered within the Solar System due to gravitational interactions between the giant planets and also caused the migration of these planets. It should be noted that the Nice model is roughly consistent in timing with the *late heavy bombardment* (LHB) of the Moon and terrestrial planets and the chronology of lunar craters. It is also supported by a number of cosmochemical considerations.

The migration of giant planets and their interactions should have a strong effect on the arrangement of the orbits of the planets in the emerging exoplanetary system, creating, for example, configurations with large eccentricities. The eccentricity of the orbits can lead to close encounters of planets and the ejection of some of them from the system into hyperbolic orbits. Such a planet becomes the above-mentioned 'rogue' or 'homeless' planet (orphan planet). About 20 such rogue planets have already been observed, but their actual number can be immense and comparable to the number of stars in the Galaxy. Moreover, it is also assumed that a category of intergalactic orphan planets may exist in galaxy clusters, but such planets are barely observable.

It may be thought that the migration and transport of matter that occurred in the early Solar System significantly affected the geological history of Earth and the terrestrial planets and the formation of their natural complexes. First and foremost, this relates to the transport of water and volatile substances into the Solar System from regions beyond the snow line (from the feeding zones of Jupiter–Saturn and the beyond-Neptune region) by planetesimals, ice comet nuclei, carbonaceous chondrites, and dust. They are considered important exogenous sources for filling Earth's oceans [37, 90, 91]. Similar processes probably occurred in other planetary systems, changing the bulk composition of the planets and affecting their thermal regime and natural conditions.

8. Formation of planetary systems around single stars

The question of how planets are formed and how, in particular, the Solar System was formed, is the core of stellar-planetary cosmogony and one of the key issues in astrophysics. Scenarios concerning the formation of planetary systems around single and binary stars have quite definite similarities and differences at the stages of formation and evolution. The problems of genesis and stellar-planetary evolutionary dynamics in systems of multiple stars are very important. We consider first the modern concepts of the formation of planetary systems around single stars (see [92, 93]).

8.1 Gas-and-dust disks

Stars are born in gradually condensing clusters of interstellar clouds. High-precision observations using the ALMA and SPHERE radio telescopes revealed inside the clouds various fine structures, such as rings, intermittencies, vortices, and spiral arms [94], which may indicate the initial stage of planetary birth. Observations of stellar cluster areas indicate a complex relationship of filaments and magnetic fields with the formation of stars and the formation of *protoplanetary gas-and-dust accretion disks*. Many young stars are surrounded by such circumstellar disks — the remnants of the *protoplanetary nebula* after the formation of the protostar and the precursors of the formation of planetary systems. The nebula itself is a fragment of a giant interstellar molecular cloud tens of parsecs in length that consists primarily of hydrogen and helium, but is also enriched with heavier elements formed as a result of nucleosynthesis in stars of previous generations and supernova explosions. Molecular clouds also contain numerous organic molecules involving nitrogen, oxygen, and biologically important carbon forming complex compounds based on these elements. The estimated size of a molecular cloud fragment is 0.1–1 pc, and the gas outflow velocity is as high as $\sim 10-100$ km s^{-1}. The early protostellar object, which includes a protostar with an embryonic disk and an accretion envelope, is classified by the distribution of spectral energy in the protostar and its surrounding disk as belonging to class 0 (it should not be confused with the spectral type of hot stars O). Classes I and II are also distinguished depending on the distribution of spectral energy due to changes in the distribution of masses, velocities, and temperatures.

Planetary systems similar to the Solar System are formed in the process of physicochemical and dynamic evolution from the substance of gas-and-dust disks. Modern observations of star-formation regions with high spatial resolution have revealed the structural features of such disks — flat dust structures $\sim 50-100$ au in diameter around protostars and young main-sequence stars. The dust they contain is replenished by the accreting nebula material, and, in the case of residual *debris disks*, shock processes in a population of bodies similar to trans-Neptunian objects are likely to be a renewable source of dust. Observations of the spectra of T Tauri stars made it possible to estimate the accretion rate (total mass flux) from the disk to the central star: it is for most stars in the range of $\sim 10^{-9}-10^{-7}$ solar masses per year with an average of 10^{-8} solar masses per year. The tendency for the flux to decrease to the lower limit of 10^{-9} solar masses is observed for stars in the age range of $\sim 10^5$ years [95]. Molecular lines of sulfur-containing compounds observed, as already mentioned, in the clouds of Taurus using the ALMA radio telescope [42, 43] are used as tracers of the matter falling onto the disk at the T Tauri stage.

According to existing concepts, the sequence of the processes in which planetary systems are formed includes the fragmentation of the gradually densifying interstellar molecular cloud, the formation of a protoplanetary accretion gas-and-dust disk around the parent star, and its decay into primary clusters, from which solid bodies (planetesimals), planetary embryos, and, finally, the planets themselves are formed. A key role in this sequence is played by various types of instabilities in the disk, which are the basis for its fragmentation, the formation of solids, and their subsequent growth. The main role is played by hydrodynamic (flow) and gravitational instabilities, together with the various dynamic processes discussed above — resonances, tidal interactions, and migration (see, e.g., [96–99]).

Historically, protoplanetary disks have been found around stars more massive than the Sun, such as Vega (α Lyrae). The first indirect evidence of the existence of disks had been observations of infrared excesses in T Tauri stars — young variable stars with ages of 10^5 to 10^7 years [100], long before their direct images in the infrared and submillimeter spectral regions were obtained. Young protostellar and stellar objects are currently observed in the entire observable wavelength range. An analysis of infrared, submillimeter, and millimeter spectra revealed the Keplerian rotation of gas-and-dust disks around hundreds of T Tauri stars. Gas-and-dust disks were found around most stars whose age is $\leqslant 10^6$ years and around $\sim 20-30\%$ of stars whose age is $\leqslant 10^7$ years, with an average age of 3–6 million years. The masses of the disks turned out to be $\sim 0.01-0.2$ solar masses, and their size, up to $\sim 10-100$ au, a value comparable to the size of Neptune's orbit in the Solar System. A gas-and-dust disk was discovered around the star TW Hydrae with a young planet inside it. Observations made using the Spitzer space telescope made it possible to concurrently detect several young stars surrounded by disks, in a limited area. The disks were observed in the case of UX Ori stars [101, 102] from the edge, and β Pic was the first example of observing a disk with a planet in an inclined orbit [103, 104]. The most significant contribution to the study of disk chemistry was made by measurements of gas and dust emission in the infrared and submillimeter wavelength ranges with high angular resolution. This encompasses 2% of admixtures to the initial content of 98% hydrogen and helium by volume (the hydrogen/helium ratio per se is 70.5/27.5% by mass or $\sim 10/1$ by the number of particles). The admixtures are in this case in a gaseous or solid (ice) state, depending on the temperature. The estimated content of hydrogen-containing compounds among them ranges from 0.5 to 1.5%.

The tremendous progress in studying circumstellar disks and the formation of planetary systems was driven by observations of their structure, composition, and dynamics carried out in millimeter wavelengths by the network of ground-based radio telescopes ALMA (Atacama Large Millimeter Array), in particular, in research within the programs Resolving Star Formation with ALMA and the Protostellar Interferometric Line Survey (PILS) (see [105–108]). They displayed, together with the data of infrared observations obtained by the Hubble, Spitzer, and Herschel space telescopes, a breathtaking picture of how all the components of the protostellar nebula are combined to create planetary systems from this 'cosmic stew'. The discovery of extrasolar planets confirmed as a whole the main scenario for the formation of planetary systems. As was mentioned in Sections 2 and 5, observations using the Kepler space telescope constituted the main contribution to the discoveries of thousands of exoplanets, although only a small part of the galactic star field (in the constellations Lyra and Cygnus) has been investigated. A variety of configurations have been found among planetary systems, including hot super-Jupiters in orbits near the parent star, and later less massive planets, including those like Earth. A significant contribution to the reconstruction of these processes was made by mathematical modeling of the physical and chemical mechanisms responsible for the formation and evolution of protoplanetary gas-and-dust disks, including the diverse processes of thermal and dynamic evolution of the disk environment and the formation and growth of primary solid bodies in it. A number of in-depth numerical-experimental studies are devoted to the formation of planets, including terrestrial planets, in planetary systems of single stars (see, e.g., [109–117]). Nevertheless, many problems remain unsolved, and yet there are no answers to many questions about the key mechanisms that drive the formation of planetary systems in various classes of stars and their stability and evolutionary paths.

8.2 Evolution of disk matter

The formation of stars, gas-and-dust disks, and planets is a continuous process of the evolution of matter in the Universe. The material of the protoplanetary disk is a complex system of various phase compositions, densities, temperatures, and degree of ionization, which depend on the radial distance from the parent star. This inhomogeneous gaseous medium containing dust particles of various sizes and origins is, as a whole, a magnetized dust plasma in a state of turbulence, the properties of which depend on the radial and azimuthal position in the disk [118, 119]. When the main dynamic forces that drive the state of the rotating disk are in equilibrium, weaker factors such as thermal/viscous processes, turbulence, and electromagnetic phenomena become dominant. They have a significant effect on the condensation of volatiles, the relative content of gas and dust, and the transport of energy and angular momentum in the disk. An important role in the formation of the disk is played by the magnetic field, which, in particular, causes the transfer of the angular momentum of the gas from the star to the disk; this effect is known as 'magnetic braking' (see, e.g., [120–122]).

If plasma effects are ignored, the motion of the gas-and-dust disk medium is most adequately simulated by the mechanics of heterogeneous turbulized media with consideration for the physicochemical properties of phases, heat and mass transport, variations in the opacity of the medium regarding stellar radiation, viscosity, chemical reactions, phase transitions (positions of the evaporation-condensation boundary), coagulation, etc. A rigorous mathematical exploration of this problem is provided in [123–125]. These studies analyzed the nature of the dynamic interaction of turbulent gas and dust, including the effect of the turbulence energy of the carrier phase on the behavior of solid particles and the reverse effect of the dust component on the dynamic and thermal regimes of the gas phase.

The presence of a polydisperse admixture of particles in a turbulent medium significantly complicates the hydrodynamics of the disk, facilitating the emergence of new structures and additional flow regimes. In many disks, substructures in the form of rings and complex spiral formations were indeed observed, with which the growth of dust particles can be associated. Local areas of increased gas pressure can capture solid particles, which acquire a speed close to that of the gaseous medium. In other words, gas affects the dynamics and evolution of solids ('gas drives the solids evolution') [126], although the threshold size for particles to be entrained by the gas is not known. At the same time, turbulent vortices affect the phase transformations associated with the accumulation of solid particles (both initial dust particles and those formed as a result of coagulation), their fragmentation during mutual collisions, and their deposition on the disk midplane, where they form a geometrically thin flattened layer — a high-density dust subdisk. An additional mechanism that sets the properties of a viscous accretion disk at various stages of its evolution is tangent strains in the boundary layers due to the differential rotation of the disk medium [127]. The dynamics and processes of heat and mass transport in differentially rotating disk matter are also affected by the inertial properties of a polydisperse admixture of solid particles and the difference in velocities at the interface between the gas and condensed phases. Such a flow regime corresponds in the continual model of a heterogeneous turbulent disk medium to the parameters at the Ekman layer boundary, including the development of the Kelvin–Helmholtz instability [125, 128]. It is also assumed that the evolution of turbulence in a rotating accretion disk is affected by hydrodynamic helicity, which is responsible for the emergence of negative viscosity in the medium and the cascade process of reverse energy transport from small to large vortices [119].

It is apparent that the dust component plays a decisive role in the evolution of the disk in the process of its vertical and radial compression during the differential rotation of matter. The founder of the Russian cosmogonic school, O Yu Schmidt, noted: "We attach decisive importance to the solid phase, i.e., dust and other solid particles in a cloud of gas and dust." He associated the process of evolution with the irreversible loss of mechanical energy by particles during inelastic collisions, but with the conservation of angular momentum, which leads to "flattening of the system, to the collection of particles into a flat layer of increased density" [129]. The composition and properties of dust and the size of particles actually shape to a significant extent the features of the inhomogeneous structure of the protoplanetary disk and its thermal regime and dynamics, especially those of the inner regions.

In regard to the genesis of disk particles, it can be expected that the dust of a molecular cloud fragment was partially included in their composition, while other particles were formed inside the disk near the protostar and probably underwent evaporation–crystallization processes during the radial motion of particles and gas. In addition, the particles could undergo heating by shock waves in the accretion zone and subsequent rapid cooling. Particles of refractory crystals in comets and carbonaceous chondrites are in line with this concept. Their presence in bodies born outside the snow line at low temperatures is explained by radial transport from regions near the Sun, where they were initially formed in a young disk at temperatures of $\sim 1000\,^{\circ}\mathrm{C}$. In addition, refractory particles could be present in gas flows of a collapsing cloud that surrounded the protosun, to be transported later to the outer regions of the forming planetary system. Signatures of water in the spectra of the gas-and-dust disk that surrounds a young star could also be associated with the fallout on it of ice bodies, such as cometary nuclei, at a later stage of evolution.

Apparently, whatever the nature of the events under consideration, it is clear that complex physicochemical processes that accompany the evolution of a heterogeneous medium, in which collisions of dust particles occur, are responsible for the emergence of the first solid bodies and their subsequent evolution [130, 131]. It should be taken into account that turbulence in the gas of the disk can both hinder the growth of particles and facilitate their combination in vortices, which further complicates the problem [132]. In developing models, it is necessary to take into account the sequence of changes in the state of aggregation of the main components of protoplanetary matter, the location of condensation-evaporation fronts depending on the thermodynamic parameters of the disk (especially in the vicinity of the snow line, which is extremely important for the formation of primary solids and planetesimals; see [133]), the role of the sublimation–coagulation of particles in a two-phase medium, and the redistribution of dust. The mechanisms of development of hydrodynamic and gravitational instabilities are associated with these processes.

8.3 Gravitational and hydrodynamic (flow) instabilities

The surface density of the massive dust layer in the subdisk is quite high, while the internal gas pressure is insufficient to prevent gravitational collapse. Provided that the chaotic turbulent velocities of dust particles do not exceed a certain limit, a gravitational (Jeans) instability develops in the subdisk that corresponds to the classical Goldreich–Ward scenario of planetesimal formation [134]. Gravitational instability is believed to be responsible for the emergence of primary dust clusters in the prevailing ring-shaped subdisk configuration [135–137]. A modification of the Jeans instability criterion for astrophysical disks has been proposed recently, which is based on a generalized Boltzmann–Gibbs statistics, the Tsallis statistics [138]. This criterion, derived from a modified kinetic equation with a special form of the collision integral, better meets the conditions for the development of instability in a homogeneous disk medium of a fractal structure in the phase space [139, 140].

Another mechanism for the emergence and development of instability in a heterogeneous disk medium is a hydrodynamic-type instability [141, 142]. This mechanism is based on an imbalance between surface gas-and-dust density and mass transport. Two main scenarios of such instability have been proposed, and both are associated with the presence of polydisperse dust in the gas. The first is related to the idea that disk/subdisk turbulence can create local areas of high dust/gas ratios that grow, eventually reaching the size of larger bodies. It is assumed that either particles are passively concentrated by turbulence at large scales comparable to the dissipative interval of turbulence, or particles are concentrated inside turbulent vortices, which perform as a kind of trap, which was also pointed out in [125]. Such formations may emerge in zonal flows [143], including those that emerge between vortices of the aerodynamic region [144, 145].

The second scenario assumes the presence of feedback between the gas and condensed (dust) particles in a two-phase flow due to inertia (friction) and gravity, in other words, the reverse reaction of particles to the gas flow. Such a relationship between gas and dust is usually referred to as linear flow instability [137, 141], which is responsible for the generation of the initial nuclei of protoplanetesimals (hence the name 'flow instability'). The dust/gas density and some other parameters necessary for the implementation of this mechanism were estimated in a numerical simulation. Large 'lumps' of dust, especially those containing centimeter-sized grains such as pebbles formed in a preceding collision and coagulation/coalescence processes, can significantly affect the stability of the gas-and-dust medium flow. It has also been shown that the nonlinear evolution of flux instability can be accompanied by gravitational instability at lower dust/gas ratios (see [99, 143, 146–148]).

Anyway, the flow instability of a disk two-phase gas-and-dust medium can be considered a promising mechanism for the formation of planetesimals due to its ability to concentrate solid particles into dense structures that can cause gravitational collapse in the protoplanetary disk [146]. The degree of condensation strongly depends on the height-integrated ratio of the mass of solid particles to that of gas in the protoplanetary disk. The deposition of particles to the central plane of the disk together with the radial drift is in this case the key process for increasing their concentration. The resulting high mass load on the gas is then the main factor necessary to attain a large specific gravity of dust aggregates, while turbulent diffusion of the gas phase facilitates the sweeping of a certain fraction of such condensations from the dust subdisk [143]. When the ratio of the density of the dusty component of the disk to that of the gas approaches unity, the effect of dust on the motion of the carrier phase becomes strong enough to accelerate this flow and move along with it in a circular orbit at a velocity close to Kepler's. As a result of the radial drift of dust particles, an instability of the gas-and-dust flow not associated with the force of gravity arises, as a result of which local fluctuations of the particle density emerge and fractal dust agglomerates (clusters) are formed in the central plane of the disk.

The clusters formed during the initial fragmentation of the disk due to gravitational instability initially contain submicron-sized particles, including nebular dust and disk medium condensates; the latter are formed at various temperatures that depend on the radial distance: from refractory compounds in the immediate vicinity of the protostar to ice behind the snow line. Coagulation/coalescence plays an important role in the growth of particles, and further enlargement of particles occurs with the participation of flux

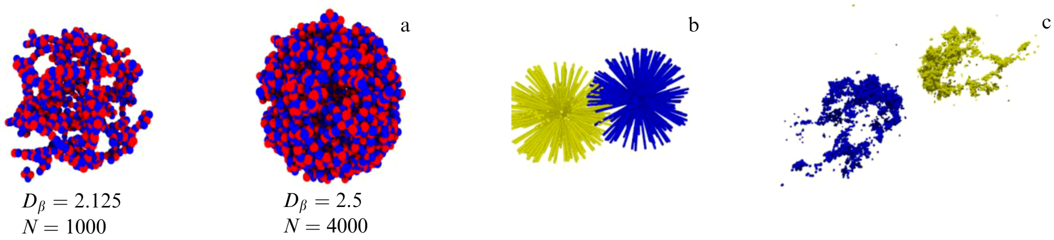

Figure 13. (Color online.) (a) Structure of dust clusters with a characteristic size of ~ 20 nm. (b) Collision of two fluffed dust clusters with a characteristic size of 50 nm, a fractal dimension of 2.55, and 8192 particles in each cluster. (c) Collision of two dust agglomerates with a characteristic size of 75 nm, a fractal dimension of 2.15, and 3072 particles in each cluster [149].

instability. Unfortunately, since a large number of discovered exoplanets are located in the immediate vicinity of the parent star, the zone of their formation narrows to poorly resolvable regions of the inner disk within fractions of an astronomical unit, where matter actively accretes onto the young star. This leads to a change in the optical opacity and thermal regime of the medium, the kinetics of photochemical processes, and the concurrent evaporation-condensation processes, which significantly complicate the analysis of matter transport and obtainment of estimates of the dust/gas ratio. In addition, the possibility of observing the formation of primary solid particles and their growth in a disk environment is significantly complicated.

8.4 Fractal dust clusters

Estimates and results of laboratory experiments show that the direct combining of even fine dust particles is ineffective. Particularly problematic from the point of view of unification are those bodies whose size ranges from centimeters to meters. However, the growth of dust particles for which van der Waals and electrostatic forces should be probably responsible as the main tool of interaction, is problematic even in the range of nano and micrometer sizes (the typical size of dust in interstellar clouds). Some exceptions may be particles of amorphous water ice concentrated behind the snow line. However, there is evidence that rather large bodies, such as pebbles–cobblestones, are formed that are further unified in the form of 'pebble piles' held together by gravitational forces.

The unification occurs much more easily in mutual collisions of bunches of particles, dust clusters. According to the approach in [123, 149], low-density (fluffed) dust clusters of a fractal nature and their interaction during collisions at moderate velocities are a key mechanism for the agglomeration of dust particles and the growth of primary solids as the basis for the subsequent formation of planetesimals and planetary embryos. Physically, this process seems to be quite reasonable. The actual structure of dust clusters is characterized by an extremely complex and irregular geometry, and although the employed mass fractal dimension does not fully reflect the geometric properties of a fractal, it nevertheless enables taking into account the main properties of loose fractal structures in modeling cluster–cluster association (see [150, 151]) and its space–time evolution. Moreover, not all particles of the gas-and-dust disk necessarily belong to clusters; some of them can form dust clouds that fill the Hill's sphere and are then deposited on planetesimals and planetary embryos.

The interaction between dust clusters during collisions leads to the formation of denser structures, and the clusters can contain both dense and loose (porous) particles [140, 149]. The clusters themselves presumably feature a porous, or fluffy, structure, and, like snow particles, they are capable of forming very loose formations of a fractal nature (Fig. 13). This approach greatly facilitates mathematical modeling of the growth of bodies in the disk due to the collision of clusters and particles inside them. When a large number of small dust clusters are combined, homogeneous fleecy aggregates with self-similar properties at short distances are formed, in which the sizes of voids in the occupied volume gradually increase with a simultaneous increase in the average density of the combined bodies.

Indeed, such fluffy aggregates, due to their extremely high porosity, are resistant to destructive collisions at high collision velocities, and their radial drift in the disk is very slow. For typical fluffy aggregates, which have relatively large geometric cross sections compared to compact dust particles, the entire regime of motion in the gas carrier flow changes and, in particular, the conditions for the occurrence of flow instability in the disk alter due to a significant modification of the aerodynamic frictional force of dust and gas. In addition, the efficiency of bouncing in the collision of porous structures can be significantly modified [93, 149].

As can be seen, we consider the set of loose dust clusters of the protoplanetary subdisk as a special type of continuous medium, a fractal that contains locations and regions not filled with its components, which greatly facilitates the process of combining/growing particles and the formation of primary solid bodies. It should be noted that spectral observations of disks in young T Tauri stars indicate the existence in them of fine dust ($\lesssim 1$ μ) for 1–10 million years. However, given the model estimates, much larger clusters of equivalent mass could have grown in the inner part of the disk (at distances of < 10 au from the star) during this time.

8.5 Primary solids, planetesimals, and planetary embryos

The subsequent process in the considered scenario includes further continuous growth (enlargement) of forming bodies, the largest of which absorb smaller bodies and dust as a result of collisions and begin to play a noticeable role in gravitational attraction, while gas is gradually swept out of the inner regions of the disk. Modeling the protoplanetary accretion disk shows that it is completely dispersed in the first 4–5 million years after its formation. Concurrently, primary solids inherited from the initial phase of evolution were accumulated. The irreversible process of *oligarchic growth* leads to the formation of numerous denser bodies — planetesimals that range in size from tens to hundreds of kilometers across, and further, when they are combined, planetary embryos, from which planets are ultimately formed. The bodies grow both through collisions of planetesimals and due to the accretion of dust and larger particles inside the disk. Some ice planetesimals apparently disappear due to evaporation upon collision. The entire process takes $\sim 10^8$ years (see, e.g., [96, 152]). A certain role in it could be played in the presence of self-gravity and viscosity effects by resonant excitation of density waves, which strongly affect the morphology and dynamics of nonlinear chaotic systems. The configuration of the Solar System prototype, which consisted of some primary system of large bodies, was probably very different from the existing one. Its modern architecture, which includes the terrestrial planets and giant planets, was shaped in the process of migration and mutual gravitational interactions, as discussed in Section 7.

According to modern theoretical concepts, scenarios on the formation of terrestrial planets and giant planets in the Solar System had quite certain differences [93, 153]. In the first case, the scenario included three stages.

• Formation and oligarchic growth of planetesimals that occurs at the expense of smaller bodies, up to the exhaustion of their resource (the duration of this stage is about one hundred thousand to a million years).

• Runaway accretionary growth of large bodies in the disk: large bodies grow faster than smaller ones due to their large masses and lower eccentricities of their orbits; the duration of this stage is of the order of a million years.

• The emergence of planetary embryos with masses from lunar to Martian against the background of the initial instability of the embryo system. Impact collisions due to orbital intersections at times of the order of 100 million years. Unification of embryos in collisions into bodies with the size of terrestrial planets in the inner region of the planetary system.

However, according to standard concepts, the giant planets were formed by the accretion of a significant part of the disk gas onto the core, although models of the formation of gas giants without solid cores are also discussed [154, 155]. They were gradually growing by accumulating on their rock cores, whose size ranges from one to tens of Earth radii, gases beyond the snow line border, where water ice and other volatile substances become thermodynamically stable. This explains the composition of gaseous (Jupiter, Saturn) and icy (Uranus, Neptune) planets, their icy satellites, and trans-Neptune bodies.

It is natural to hypothesize that the fundamental physical concepts of the formation of planets in the Solar System as a whole are characteristic of planets in other stellar systems. The specific features of their formation that depend primarily on the class of the star, the ratio of gas and solid components in the disk, temperature at various radial distances from the star, the relative position of protoplanets of various masses, and other factors could, however, greatly affect the configuration of the planetary system being formed. It is likely that such restrictions are imposed on the formation of planetary systems in both single and binary stars with nonstandard system dynamics [156].

9. Planetary systems of binary and multiple stars

9.1 Genesis and stability

The physical mechanism of the formation of a planet itself in systems of binary and multiple stars most likely differs little from that considered for single stars. However, it is of utmost importance to study in such systems the possibility and conditions for the formation and existence of the planet. Therefore, the behavior and stability of dynamical systems come to the fore, and these issues are the focus of this section.

Prior to or in the process of a sufficiently fast ($\sim 10^4$ years) collapse, a rotating fragment of a molecular cloud can either preserve its central densest part (core) that forms a single star or break into separate fragments, which give rise to a binary or multiple star during subsequent evolution. An important factor that provides stability and resilience to additional fragmentation of such protostellar objects is presumably the magnetic field. A gas-and-dust disk(s) is formed around rapidly collapsing protostars that attain a state of hydrostatic equilibrium, onto which the remaining matter of a molecular cloud fragment is accreted, gradually decreasing its mass.

More than half of all observed main-sequence stars are known to belong to multiple (including binary) star systems [157, 158]. Circumstellar gas-and-dust disks around single stars have much in common with circumstellar disks in binary stars.

Studies of the long-term stability of hypothetical planetary systems in multiple star systems were pioneered as early as the 1980s by French scientist D Benest. Planets are currently known to exist in more than a hundred multiple star systems. Most of the planets found in binary stars are in *S-type* orbits (around one component of the binary; these orbits are also referred to as inner), while the rest are in *P-type* orbits (around both components; such orbits are referred to as outer or circumbinary). Planetary formation scenarios and observed planetary dynamics (often 'at the limit of stability') in binary stellar systems are theoretically challenging, especially in relation to circumbinary planets [159, 160].

Astronomical observations led to the conclusion that both S- and P-type planets exist in binary star systems. The Lidov–Kozai effect can play a decisive role in the long-term dynamic evolution of S-type planets in binary star systems. Its essence consists of periodic high-amplitude coupled oscillations of the eccentricity and inclination of the planet's orbit due to perturbations from the side of the star in the outer orbit that has a large inclination relative to the orbital plane of the planet [161]. Study [162] explored the orbital dynamics of S-type planets of binary stars 16 Cyg and HD 196885. The dynamics of the planet in the wide visually binary star system 16 Cyg turned out to be virtually regular with a Lyapunov time of more than 30 thousand years (while the planet's orbital period is 2.2 years). The planetary system HD 196885 is close to the Lidov–Kozai resonance (see [163]). The Lyapunov times have been calculated for the most probable values of the orbital parameters of HD 196885b. It turns out that the dynamics of HD 196885b are virtually regular, with a Lyapunov time of more than 50 thousand years if the motion occurs far from the separatrix of the Lidov-Kozai resonance (with the planet's orbital period equal to 3.7 years). Figure 14 shows stability diagrams for the 16 Cyg planetary system.

The study carried out in [66] enabled the determination of the areas of stable motion of hypothetical planets in the Alpha Centauri binary system in the space of the planet's orbital parameters (Fig. 15) even before the announced discovery of the planet in this system. The discovered planet is in the stability region — deep within the white 'triangle of stability' displayed in Fig. 15. The outer boundary of the *chaos region*

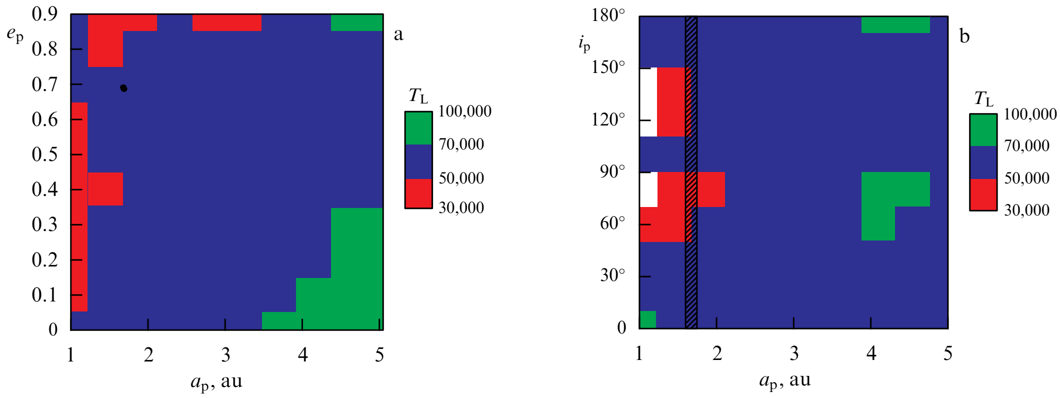

Figure 14. (Color online.) Lyapunov times of the planetary system 16 Cyg presented as color gradation, in years. a_p (in au), e_p, and i_p are the initial values of the semi-major axis, eccentricity, and orbital inclination of 16 Cyg Bb, respectively. The position of the planet is indicated by (a) a dot and (b) a hatched stripe. (According to [162].)

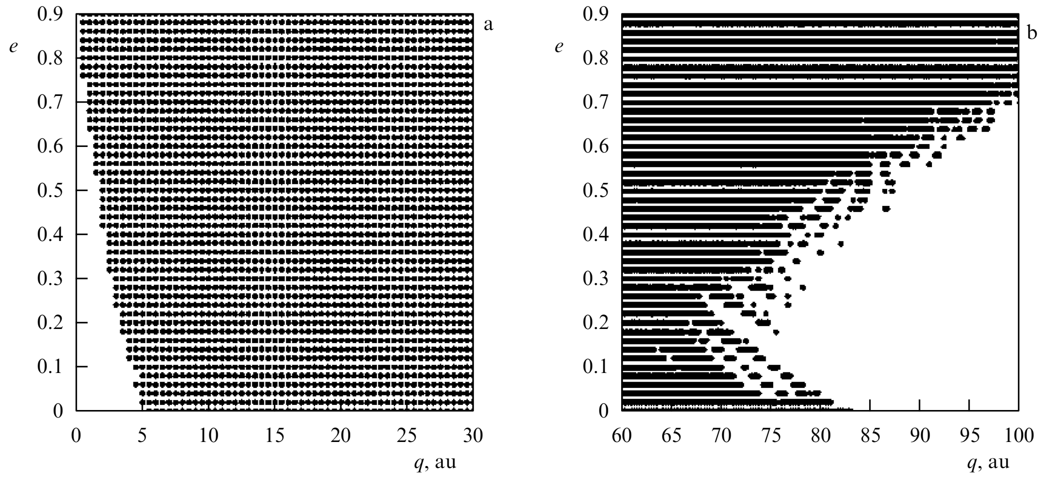

Figure 15. Diagrams of stability in the 'pericentric distance q – eccentricity e' plane of the planet plotted for the Alpha Centauri system. The areas of stability are shown in white, and instabilities are shown in black. Diagram for (a) inner orbits and (b) outer orbits [66].

on the stability diagrams corresponds in the case of circumbinary motion to the semi-major axis of the planet's orbit over 80 au. The calculations show that the most probable values of the Lyapunov time (characteristic time of predictable motion) in the instability zones are ~ 500 years for outer orbits and ~ 60 years for inner orbits [66].

Prior to observations made by the Kepler spacecraft, ~ 50 planets in binary star systems were known, most of them being inner planets, i.e., orbiting one of the stars. Several circumbinary systems (HW Vir, NN Ser, UZ For, DP Leo, FS Aur, SZ Her) were also known belonging to close binaries with components that are not main-sequence stars. Several circumbinary planetary systems were discovered by the Kepler telescope using the method of transits for main-sequence stars: they are Kepler-16, 34, 35, 38, and 47 systems [164–167], among them Kepler-47 is a *multiplanetary* system which contains two planets.

The orbital configuration of the Kepler-16 circumbinary planetary system is shown in Fig. 16. The size of the binary (0.22 au) is about 100 times smaller than that of Alpha Centauri (23.4 au). The stability diagram in the 'pericentric distance–eccentricity' plane of initial conditions shows that the planet Kepler-16b is dangerously close to the chaos region (Fig. 17): it is located between the 'teeth' of instability in the space of orbital parameters. However, the planet Kepler-16b 'survives' (neither escapes from the system nor falls on the parent stars), because its orbit is close to half-integer orbital resonance 11/2 with the central binary. This phenomenon in the Solar System is similar to the survival of Pluto and Plutino objects in the Kuiper belt, which are in half-integer orbital 3/2 resonance with Neptune. The chaos–order boundaries in the stability diagrams demonstrate a fractal structure due to the presence of orbital resonances.

Of great interest is the issue of how circumbinary planets are formed. According to modern calculations based on the *planetesimal accretion* model, the preferred scenario is the one in which the planetary core is formed in the outer regions of the protoplanetary disk (where conditions for accretion are favorable) and then migrates inward until migration stops at the boundary of the inner disk cavity generated by the central binary [159, 160, 168]. The cavity roughly corresponds in size to the region of chaos for orbits around the binary. Although the formation of circumbinary planets *in situ* is in principle possible, this is less likely due to the unfavorable conditions for planetesimal accretion — high collision velocities of planetesimals and their relatively low concentration.

In what way can the chaos–order boundary be theoretically described in diagrams similar to that shown in Fig. 17?

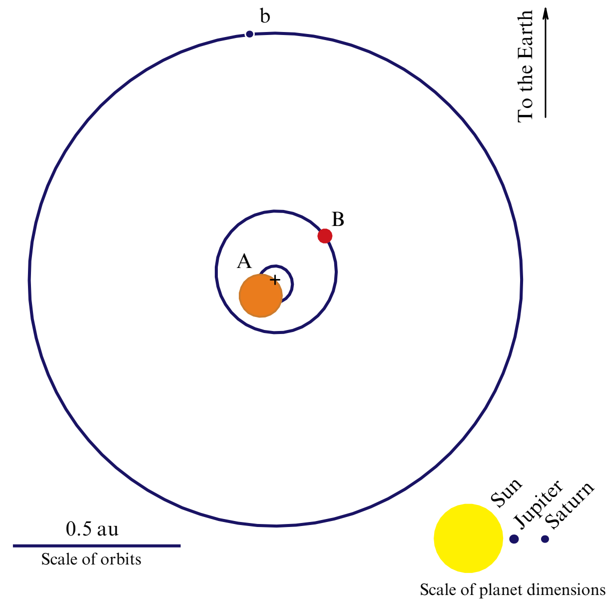

Figure 16. Kerler-16 system [164].

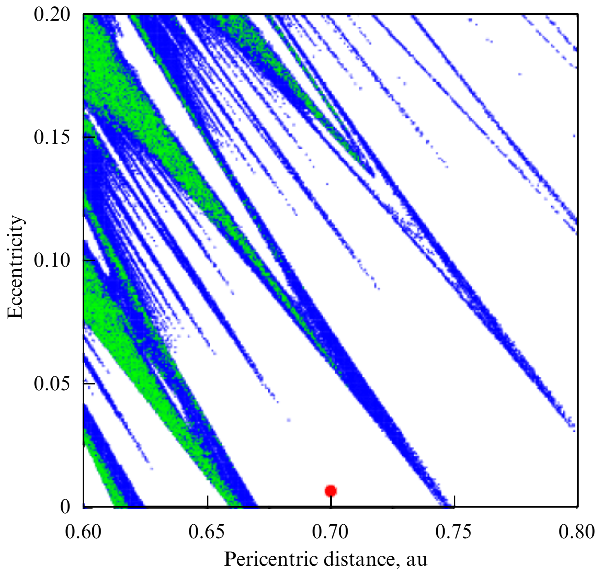

Figure 17. (Color online.) Stability diagram for the Kepler-16 system. Orbits that are unstable according to the collision–escape criterion are shown in green, and according to the Lyapunov exponent criterion, in blue [67].

The radial extent of the zone of chaotic orbits of a low-mass particle around a system of two gravitationally bound bodies (a binary star, a binary black hole, a binary asteroid) was analytically estimated in [169] as a function of the eccentricity of the particle's orbit. The separatrix mapping theory was used to show that the central continuous chaos zone manifests itself above a certain threshold in the mass parameter value of the central binary due to the overlap of orbital resonances that correspond to integer $p:1$ ratios between the orbital periods of the particle and the central binary. Unlimited chaotic orbital diffusion of a particle, up to the ejection of that particle from the system, occurs in this zone. The value of the mass parameter ($\mu = m_2/(m_1+m_2)$, where m_1 and m_2 are the masses of the components of the central binary, $m_1 \geqslant m_2$)

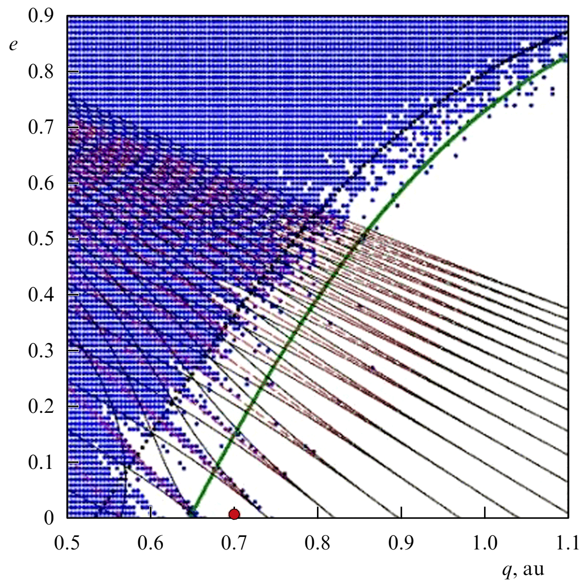

Figure 18. (Color online.) Stability diagram for the Kepler-16 system in the pericentric distance–eccentricity coordinates. The chaos zone is displayed as the blue-shaded background. The large red dot represents the planet. The solid and dashed curves indicate the boundaries of the region of chaos and the separatrices of integer resonances of the mean motions with the central binary, according to modern theoretical models. (According to [170].)

above which such a chaotic zone is universally present at all initial particle eccentricities was estimated.

Massive numerical experiments were carried out to reveal regions of chaotic motion in the plane of initial conditions 'pericentric distance–eccentricity' for planetary orbits [170]. Using the analytical criterion [169] of chaoticity of planetary orbits in binary star systems, an analytical description of stability diagrams has been given: theoretical curves have been constructed that describe the global boundary of the dynamic chaos region around the central binary for each of the systems. Based on theory [171], which describes individual resonant 'teeth' (corresponding to the integer resonances between the orbital periods of the planet and the binary), the local boundaries of chaos have been determined. Theoretical models (Fig. 18) successfully describe both global and local chaos–order boundaries in numerically constructed stability diagrams, which indicates the applicability of these theories and their efficiency when analytical criteria for the chaos of planetary orbits are utilized.

Study [169] has shown that the observed variety of orbital configurations of bi-planetary systems [11] and circumbinary planetary systems is consistent with the existence of a threshold value of μ. The analysis was carried out by plotting the empirical dependence of the ratio of the orbital periods $T_{\text{out}}/T_{\text{in}}$ of the particle and the central binary on the mass parameter of the central binary μ. For the employed theoretical criterion to be applicable, it is necessary that the planet in the most distant orbit have the smallest mass in the system, and only such systems were included in the sample.

The obtained plot is displayed in Fig. 19; the position of exosystems is indicated by dots. All biplanetary systems prove to be located to the left of the vertical dashed line that indicates the theoretical threshold $\mu \approx 0.05$ for the emer-

[11] Here, the bi-planetary system is defined as a single star with two planets.

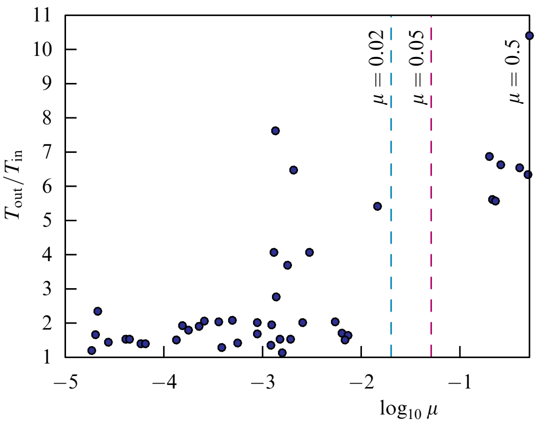

Figure 19. Ratio of orbital periods as a function of the mass parameter for biplanetary and circumbinary exosystems (shown by dots). The vertical dashed lines correspond to the theoretical thresholds in μ at which the central chaotic zone emerges. Data (as of June 30, 2014) for exosystems are taken from *The Extrasolar Planets Encyclopedia* (exoplanet.eu). (According to [169].)

gence of the central chaotic zone, while circumbinary systems are located to the right of it. What is obvious is the complete absence of exosystems with $T_{\mathrm{out}}/T_{\mathrm{in}} < 5$ at $\mu > 0.05$, which agrees with the theory: the central chaotic zone is formed at $\mu > 0.05$, where the orbits of a particle with any initial eccentricity are subject to unlimited chaotic diffusion, up to particle ejection from the system. It should be noted also that, according to Fig. 19, if $\mu < 0.01$, many exosystems cluster near the $2/1$ resonance, whereas if $\mu > 0.01$, exosystems cluster at half-integer rather than any integer resonances. This observation agrees with the conclusions of Ref. [67]: although the observed circumbinary planets are located near the chaos boundary in the space of orbital elements, they 'survive' because they are 'safe' in regular regions inside resonance cells formed by unstable high-order integer resonances.

Of considerable interest is the long-term orbital evolution of circumbinary systems. How 'durable' are they? It was shown in [172] that circumbinary planetary systems are subject to universal tidal decay that occurs due to their inherent forced orbital eccentricity of orbits. Circumbinary planets are released from parent systems when they enter the circumbinary chaotic zone due to the slow 'contraction' of their orbits. This effect can explain (at least in part) on relatively small time scales (much smaller than the age of the Universe) the observed absence of circumbinary planets in sufficiently close binary stars (with periods of less than 5 days). On longer time scales (of the order of the present age of the Universe, ~ 14 billion years), which are nevertheless much shorter than the lifetime of parent stars (in the case of red dwarfs, the lifetime can be trillions of years), this process can provide a massive release of evolved circumbinary planets. Observational manifestations of the effect may include: (1) the predominance of large rocky planets (super-Earths) in the total population of free-floating planets (provided this mechanism is the only source of such planets); (2) a deficit of circumbinary planets in systems of low-mass stars, which depends on the mass of the parent stars, and the smaller the mass of the parent stars, the greater the deficit.

Indeed, let us consider a planar system of three gravitating bodies: a central massive binary star and a much less massive object (particle) orbiting the binary. The initial orbit of a particle is assumed to be circular, but the eccentricity of the orbit is periodically disturbed on secular and local time scales [79, 173]. Therefore, the initial orbit cannot remain circular all the time. This effect provides a natural universal mechanism of intrinsic tidal friction and heating of circumbinary planets [174]. The particle in a slowly contracting circular orbit eventually enters the chaotic zone around the central binary and, therefore, leaves the system [169]. As was originally suggested in Ref. [174], the planet's escape may eventually take place due to the orbital evolution of the binary host (due to the loss of star mass and mutual tides), rather than that of the planet itself. In particular, the orbit of the binary can expand at an early stage of the evolution of a close binary due to the tidal transfer of angular momentum from rotating stars, until the state of tidal synchronization (spin-orbital resonance 1:1) [12] is attained. According to [175], the size of the circumbinary chaotic zone is at this moment maximal.

It should be noted that the absence of close binary stars with circumbinary planets can also be explained by the destabilization of the planetary orbits due to their entering the circumbinary chaotic zone [175]. However, the escape mechanism considered in [175] differs from that explored in [172]. In scenario [172], the planetary orbit is slowly contracting, while the size of the chaotic zone remains constant. In the tidal scenario [175], on the contrary, the chaotic zone expands (as the binary's orbit expands due to the tidal transfer of angular momentum from the rotating star), while the semi-major axis of the planetary orbit remains constant. It should be noted that tidal scenario [175] refers to the early stage in the evolution of the parent star (before reaching the main sequence), while scenario [172] operates on much longer time scales and, thus, it is able to ensure the escape of already highly evolved planets.

9.2 Multiplanetary systems

About a third of the exoplanets discovered to date belong to multiplanetary systems, i.e., the systems with two or more planets [3]. Orbital resonances in multiplanetary systems are a widespread phenomenon; this is confirmed by calculations of the time behavior of resonance arguments. The well-known systems with a $2/1$ mean motion resonance are Gliese 876 and HD 82943; an example of a system with resonance $3/1$ is 55 Cancri. The Gliese 876 system is an example of a system with the orbital period ratios of 4:2:1 [176], the same as that of the inner Galilean moons of Jupiter — the Laplace resonance. Moreover, 'densely packed' resonant multiplanetary system Kepler-223 has been discovered recently and demonstrates the mean-motion resonance 8:6:4:3 [11]. A list of other very interesting examples of multiplanetary systems includes 55 Cancri, Upsilon Andromedae, Kepler-11, and Kepler-223.

The multiplanetary system of the binary star 55 Cancri has been studied in great detail. At least 5 planets with masses from 0.034 to 3.84 M_{J} orbit the main component — a yellow dwarf (star of spectral type G8); their orbital periods range from 2.8 to 5200 days. Planets b and c are in $3/1$ resonance. The system as a whole is stable; it may contain other planets, as it is far from the 'dense packing' state [177].

Upsilon Andromedae is a binary star consisting of yellow (spectral class F8) and red dwarfs; the size of the binary is 750 au. Three giant planets with masses from 0.69 to 3.93 M_{J}

[12] A spin-orbital resonance 3:2 of a similar nature is present in the motion of Mercury in the Solar System.

[178] and orbital periods from 4.6 to 1290 days orbit the yellow dwarf. The system as a whole is stable [179]. Planets c and d are close to 11/2 resonance. Note the similarity of the resonant configuration with the resonance discussed above in the Kepler-16 circumbinary planetary system.

Kepler-11 is a single yellow dwarf, in the system of which 6 transit planets with masses from 4.3 to 300 M_E and orbital periods from 10.3 to 118 days have been discovered. The five inner planets move in very close orbits: the distances between them are small both in relative units (in units of the radius of the inner planet's orbit) and in absolute ones: the orbit of the fifth (outermost) planet is only slightly larger than that of Mercury. The system as a whole is nonresonant and stable; however, its configuration is completely atypical [180]. The two planets closest to the parent star are close to 5/4 resonance. It is possible that the system contains other, external (nontransit), planets.

Kepler-223 is a yellow dwarf (star of spectral type G5V), around which 4 transiting planets have been discovered. Observations of the transit yielded their radii: 1.8, 2.1, 2.8, and 2.4 R_E, i.e., these planets are super-Earths. Orbital periods are 7.4, 9.8, 14.8, and 19.7 days; thus, the planets are close to 8:6:4:3 resonance. This planetary system is the most prominent example of a densely packed resonance system now known [11].

If the disturbing body is located in an inclined orbit, the above-mentioned Lidov–Kozai effect, which also has a resonant nature, can play a decisive role in the formation of the dynamic architecture both in multiplanetary and in multiple-star systems [161]. Such objects include Kepler-56 and about a hundred other similar objects, in each of which a compact multiplanetary system of super-Earths and mini-Neptunes with periods of < 200 days (systems of tightly packed inner planets, STIPs) has been discovered. This compact configuration is likely due to the presence of a second stellar companion.

9.3 Statistics of resonances

How common are orbital resonances in exoplanet dynamics? Data from the *Exoplanet Encyclopedia* were used in [181] to study the statistics of manifestation of resonances in multiplanetary systems (containing two or more planets belonging to a single star) and in systems with one or more planets around binary stars. The total number of planetary systems in the sample was 143. In the case of binary stars, either the most massive component or the component which is orbited by the planet was considered to be the 'main' star. The ratios of the orbital periods were calculated for all pairs of objects in each system. As a result, differential distributions of the period ratios were constructed for two alternative cases: (a) a more massive ('disturbing') body is in an orbit located closer to the main star than a less massive one; (b) on the contrary, a less massive ('disturbed') body is in an orbit closer to the main star than a more massive one, and, therefore, the orbital period of the less massive planet is smaller than that of the more massive one. The inner body is referred to in each case as the second body (orbital period T_2), and the outer body as the first body (orbital period T_1).

Figure 20 shows a histogram of the T_1/T_2 ratios plotted for case (a): an inner disturbing body. The plot shows that the peaks near the first-order resonances 3/2 and 2/1 are especially prominent; there are also peaks near resonances 5/2, 3/1, and 4/1. Figure 21 displays a histogram for case (b): corresponding to an outer disturbing body; here, the maxima

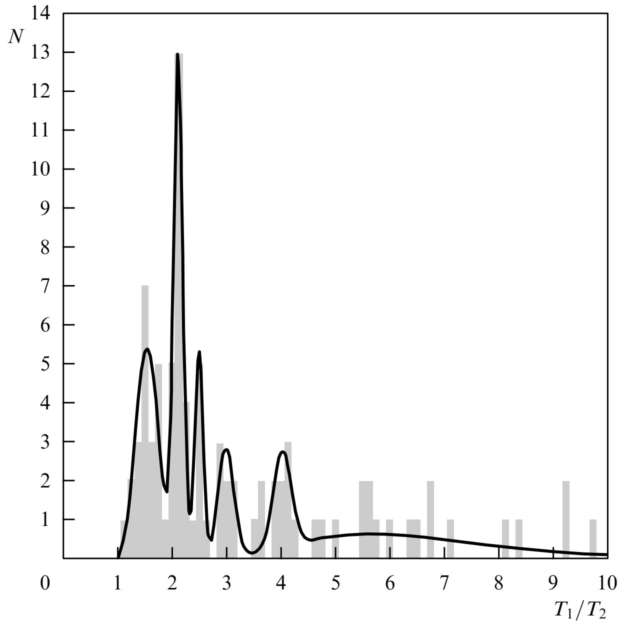

Figure 20. Histogram of orbital period ratios for the case of an internal disturbing body. The solid curve shows the model approximation. (According to [181].)

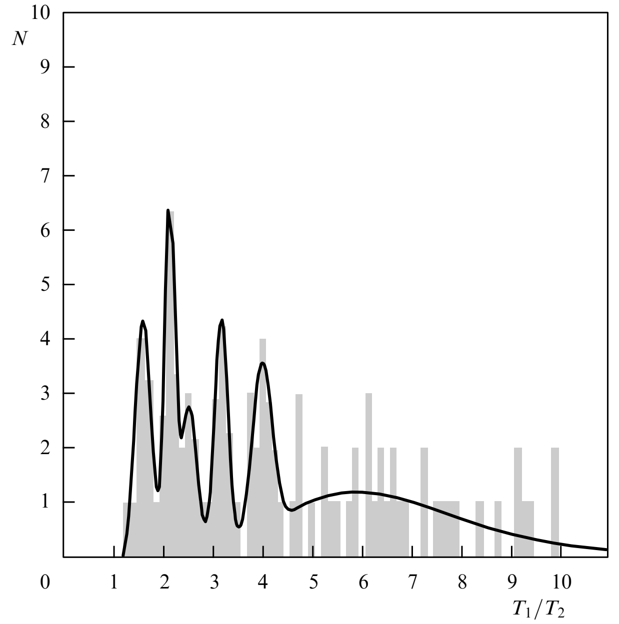

Figure 21. Histogram of orbital period ratios for the case of an external disturbing body. The solid curve shows the model approximation. (According to [181].)

are present in the regions of the same T_1/T_2 values, with the exception of 5/2 resonance. Both histograms are approximated by an analytical expression in the form of a sum of normal distributions of the period ratios in the vicinity of resonances and a function that describes a monotonic decrease in the distribution tail. The obtained approximations are shown by solid curves. The dominant peaks 3/2 and 2/1 are slightly shifted in both histograms to the right relative to their nominal resonance positions. An analytical fit provides accurate values of the shift. The existence of such shifts is a well-known and widely discussed phenomenon

[182–184]. Two main hypotheses regarding the reasons for the statistical deviations of T_1/T_2 relative to the nominal values have been suggested: (1) the shift occurs at the initial stages of the dynamic evolution of the system if the planets increase their mass with time [184]; (2) the shift occurs in the course of long-term tidal evolution [182, 183].

9.4 Structures of planetesimal circumbinary disks

Dynamic perturbations play an essential role in the cosmogony of the circumbinary protoplanetary disk (a disk surrounding a binary star), especially in the epoch when the disk is losing the gas component. A theory for the secular dynamics of planetesimals in a circumbinary gasless disk was proposed in [173], which shows how a circumbinary spiral structure is formed. The evolution of the structure during the propagation of the density wave across the disk on the secular time scale has been studied numerically and analytically; analytical formulas have been derived that describe the emerging structural features; they exactly reproduce the numerical-experimental picture. The effect of the residual gas on wave propagation is estimated. An example of a circumbinary spiral structure is shown in Fig. 22.

The planet in the planetesimal disk forms in it a characteristic multiband structure. Theoretical techniques and numerical simulations were used to investigate how such a structure is formed, which consists of several rings around a central single or binary star; the rings represent either matter swarms of matter-free gaps [185]. This effect is most pronounced in the case of circumbinary disks. The many-ring system is reduced at a certain limiting mass of the planet to a three-band system: a ring filled with matter co-orbital with the planet and two ring-shaped cavities, the position of which corresponds to 2:1 and 1:2 orbital resonances with the planet. Figure 23 shows a numerically simulated example of a ring structure in a circumbinary disk with a planet.

The regularities of the formation of multiband ring-shaped structures due to the presence of planets in planetesimal disks of single and binary stars were considered in [185],

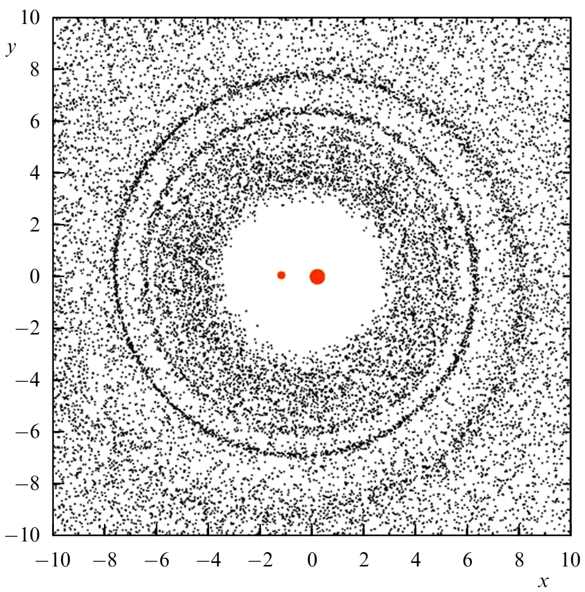

Figure 22. Example of a spiral structure in a planetesimal circumbinary disk [173].

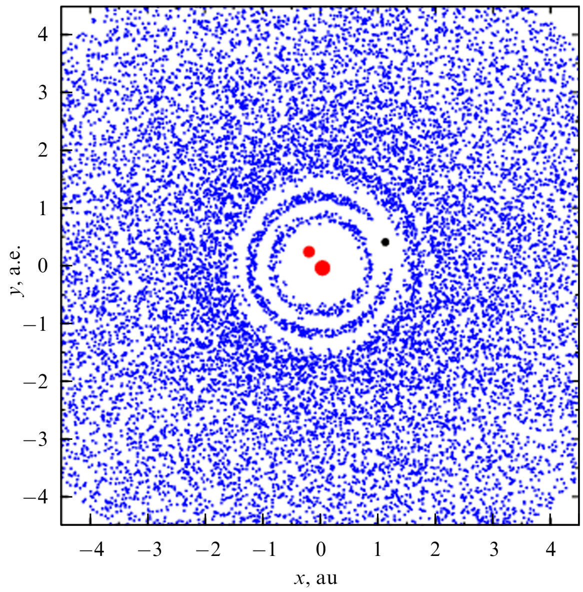

Figure 23. Example of a ring structure in a circumbinary disk with a planet, obtained in numerical simulation [185].

and an explanation of the nature of the three-band structure in the protoplanetary disk HL Tau was proposed based on analytical criteria of stability. The multiband ring structure in the disk, as observed by the ALMA telescope [186], is shown in Fig. 24.

The formation of resonant multiband structures in circumbinary residual young stellar disks with planets can be effectively investigated using numerical simulation [187]. Numerical experiments made it possible, in particular, to detect the formation of horseshoe-shaped structures co-orbiting with planets. These long-lived resonant structures controlled by the planets are generally multi-band and consist of several concentric rings. There are clear statistical relationships between the parameters of the rings and those of the orbits of planets [185]. An example of such a ring structure in the model with the HL Tau parameters is displayed in Fig. 25.

Massive numerical calculations of the evolution of planetesimal disks in systems with the parameters of Kepler-16, Kepler-34, and Kepler-35 have shown [188] that co-orbital structures are usually formed in systems with moderate orbital eccentricities of planetary orbits and parent binary stars (as in the case of Kepler-16 and Kepler-35). Thus, any observational identification of characteristic resonant ring-shaped structures in the disks may indicate the presence of planets that control these structures. The spiral structure revealed in [173] is destroyed near the orbits of the planets; however, it persists at the periphery of the disk. While a stable co-orbital ring is formed in the Kepler-16 and Kepler-35 systems, it is hardly noticeable in the case of Kepler-34. Indeed, the significant eccentricity of the Kepler-34 binary (~ 0.5) combined with the noticeably noncircular orbit of its circumbinary planet (eccentricity ~ 0.2) prevent the formation of a long-lived structure.

9.5 Scenarios of planet formation in binary star systems

About half of the stars in the Galaxy are known to belong to binaries and stellar systems of higher multiplicity. Certain differences in the mechanism of planet formation in systems

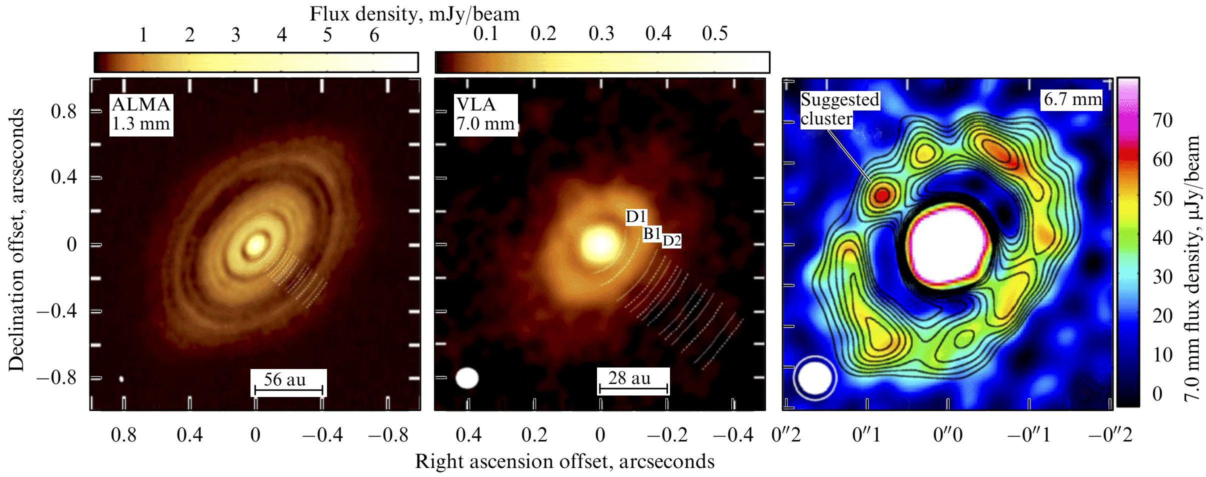

Figure 24. (Color online.) Observed multiband ring structure in the protoplanetary disk HL Tau [186].

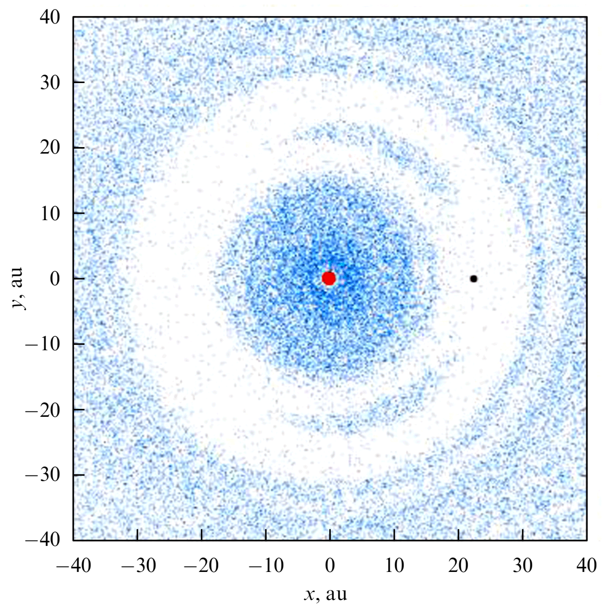

Figure 25. Example of a ring structure in a model with parameters of HL Tau [187].

of binary and multiple stars compared to those of single ones are due to the more complex nature of gravitational fields that affect the structure and evolution of circumstellar disks and the formation of planetary bodies in them.

Unfortunately, it is still difficult to reconstruct scenarios of the formation of planets around binary and multiple systems during the accretion of the initial gas-and-dust cloud and the exchange of matter between the components of the system. The picture of the processes is greatly complicated, first of all, due to dynamic interactions. Nevertheless, the available data make it possible to understand the general nature of the early evolution of such star-planetary systems and to impose a number of additional restrictions on the developed models of planet formation. The study of multiple planetary systems contributes to the development of ideas regarding the dynamics and cosmogony of exoplanets, although answers to key questions of their origin can most likely be obtained only by studying the composition of the substance itself that forms these bodies. Here, astronomy and spectroscopic methods are most closely related to cosmochemistry.

Interestingly, the problem of angular momentum transfer is easier to solve in the model of a disk that is formed and evolves around a close binary or multiple star system than around a single star. Disks are thought to be formed within these systems, and the primary matter contained in the planets has indeed been observed indirectly around one or both components of some young binary stars. Similar to the formation of the Solar System within a gas-and-dust disk, the accretion could be a process common to a system of binary stars as well, although the surrounding primary 'circum-component' disk is distorted by a close companion. Indeed, some of the systems in the space surrounding the binary have stellar companions in fairly close orbits, suggesting a dynamically complex disk evolution for such systems, which differs from that of planetary systems around single stars. An alternative scenario could be a dispersal into the disk of one of the binary system components near a more massive companion. Other possibilities are not ruled out, each of which is of great interest, primarily from the point of view of general problems of the evolution of planetary systems.

The specific angular momentum of the primary gas-and-dust cloud is the main factor that determines the difference between the early evolutionary stages of binary and single stars and controls the stability of the planetary system. Close binary stars may be used as a kind of 'testing ground' for models of the formation of a planetary system, revealing some critical parameters and limiting states. For example, one of the planets in the binary system HD196885 has an orbit with a semi-major axis of 2.6 au in a strongly perturbed region — almost at the limit of orbital stability. Its formation was perhaps most sensitive to perturbations of the primary planetesimals from both companions of the binary system. This scenario is associated with the problems of both the final accumulation of the planet and its further orbital stability.

The formation of planets in S-type systems of binary stars is in many ways similar to the process in single star systems, since the effect of the second star is reduced to secular perturbations of the protoplanetary disk, and the effect becomes smaller as the stellar pair becomes wider. However, the process can be qualitatively different in P-type systems (circumbinary systems), since there is always a circumbinary zone of dynamic chaos around the binary [169], where the formation and existence of planets is not possible.

The masses of the observable circumbinary planets discovered by the Kepler spacecraft are in the range from 0.1 to 0.5 Jupiter masses [164–167], i.e., they are similar to Neptune or Jupiter. Circumbinary planets like Earth or belonging to the super-Earth class have not been found. It is clear, however, that the predominance of large masses does not exclude the possibility of the existence in the same systems of smaller planets due to the effect of observational selection, since the transit signal from a terrestrial planet or super-Earth is about 100–1000 times smaller than that from a Jupiter-like planet.

In contrast to the formation of terrestrial planets in systems of single stars, the formation of such planets in circumbinary systems is a completely new topic, and circumbinary planets themselves belonging to main-sequence binary stars have been discovered relatively recently. There is no physical reason to believe that the previously discussed physicochemical processes of the initial and subsequent stages of formation and growth of primary solids from dust clusters in gas-and-dust protoplanetary disks of single stars differ significantly from those in circumbinary disks. However, it may be assumed that, during the formation of circumbinary planets, of more complexity are the processes that occur at the stage of accretion of kilometer-sized planetesimals under conditions when gravity prevails over the aerodynamic drag forces in the gas-and-dust disk. For example, it has been analytically shown in [79] that the radius of the circumbinary region, which is unfavorable for pair accretion of planetesimals, is substantially larger than the central chaotic zone (cavity). The barycentric radius of this unfavorable zone is usually an order of magnitude larger than the radius of the central cavity. Accretion is hindered by the fact that the central binary induces eccentricity and differential (i.e., depending on the distance from the barycenter) precession of planetesimal orbits, which causes destructive collisions of planetesimals. The relative velocities in collisions become rather small and allow accretion to occur only far enough from the barycenter. Planetesimals, whose orbital eccentricities are due to the binarity of the star, can be apsidally aligned at smaller radial distances only due to deceleration in the residual gas of the disk. However, the drag depends on the size of the bodies, which induces a differential orbital phase shift, enhancing the process of collisional destruction of planetesimals [189].

Regarding the stage of the formation of planetary embryos that is close to the final one, more diverse multiplanetary orbital configurations can apparently be created in circumbinary disks [190, 191]. Preferable in the accretion model is the following scenario of formation of circumbinary planets [159, 160, 168]: the planetary core is formed in the outer zone of the protoplanetary disk, which is favorable for accretion; it then migrates inward and stops at the border of the central cavity. Based on models of the evolution of planets in circumbinary disks, including the formation of kilometer-sized planetesimals, it was concluded that the Kepler-16b, 34b, and 35b planets were unlikely to have been formed in situ [160]. However, as noted in [192], planets are formed in the outer regions of the circumbinary disks in almost the same way as their counterparts in single-star systems. Interestingly, a circumbinary environment may be even preferable for planetary formation. However, migration in the disk appears to be a factor needed for the formation of the final orbital architecture. The arrangement of the orbits of the observed giant planets in the systems discovered by the Kepler spacecraft is reproduced at certain parameters of viscous resistance and disk profile models [193–195].

The migration of circumbinary planets in disks was first investigated by hydrodynamic modeling [196], which showed that a giant planet like Jupiter could be trapped in a 4/1 resonance with a central binary. However, circumbinary planets with a lower mass (from 5 to 20 Earth masses) can stop at the boundary of the central cavity, and this circumstance made it possible to predict the possibility of detecting Neptune-like circumbinary planets here [168], which was confirmed by the discovery of such planets by the Kepler spacecraft. The important role of orbital resonances was also revealed [197, 198]. Resonances with the central binary such as 4/1 and 5/1 can form 'traps' for migrating planets that affect the formation and orbital evolution of giant planets with masses of the order of the mass of Saturn 'embedded' in the disk. These conclusions are confirmed by the results of a more detailed simulation that takes into account the balance of viscous heating and radiative cooling of the disk [194] and the analysis of the growth of planetesimals with consideration for the perturbations due to eccentric disk precession [199].

Of special mention should be the study of the migration of type I planets of small (terrestrial) masses in gaseous circumbinary disks, which showed that migration can be halted at the edge of the central cavity [168]. The halt is explained in the case of a gaseous disk by the balancing of the negative Lindblad torque by the positive co-rotational torque, and such a 'planetary trap' is operative when there is a sharp positive gradient of the disk surface density [200]. Hydrodynamic modeling of multiplanetary systems embedded in circumbinary disks has shown [197] that, in a two-planetary system, where the largest of the two planets stops at the boundary of the cavity, and the smaller one continues to migrate inward, the result is usually an equilibrium configuration with planets locked in orbital resonances. If, however, a smaller planet stops first at the boundary of the cavity, planets of the system are usually scattered. In modeling a system with five planets, a stable final result is the formation of a fully resonant three-planet system. This observation does not contradict the possibility that planets of smaller mass exist in orbits external relative to the observed 'leading' giant planets.

The presented results of hydrodynamic modeling are consistent with the analytical predictions of the above-mentioned concept of a 'planetary trap' in the migration model. The problem is that the migration may be too fast compared to the planet formation rate, so the planet may not have time to form at all. If there is a sharp positive gradient of the surface density of the disk at a certain radial distance from the center, then, as already mentioned, the negative Lindblad torque can be balanced by the positive co-rotational torque, and planetary matter of large mass can accumulate in this zone [200]. Possible locations of the traps have been identified: apart from the edge of the central cavity, the outer boundaries of resonant ring-shaped zones cleaned of gas by giant protoplanets may also be traps, and, as it turns out, the circumbinary version is similar to that with one star. Smaller planets external to the observed 'leading' giant planet can be stopped at these local boundaries.

Based on the concept of the planetary trap, it has been suggested that large planetesimals are formed at the edge of the cavity, where the gas pressure is maximal and the surface density of the contained solid particles is relatively high. Should this be the case, circumbinary planets can be formed in situ, and this process may develop in systems of close binary stars even more easily than for single stars [201, 202]. Indeed, it is generally assumed that the circumbinary disk is completely turbulized and ionized, although it is more likely that it is stratified relative to the midplane and consists of a radially expanded nonturbulent inner layer and two highly turbulent surface layers. It may be hypothesized that the inner zone, where solid particles can deposit on the midplane, is favorable for the formation of planets and that circumbinary planets are formed more easily than in single-star disks [202]; in contrast to single stars, for which the radial positions of planetary traps in the disks are not clearly defined [203], the circumbinary protoplanetary disk has a physically distinguished scale, which is determined by the size of the binary star, and therefore the radial position of the sharp positive gradient of the surface density is clearly defined. In other words, unlike single-star disk models, circumbinary disk models do not need 'fine tuning of parameters' to provide suitable radial positions for planetary orbits.

A wide variety of final orbital architectures of systems of terrestrial planets is theoretically possible for single stars, since the accretion process for such planets strongly depends on the initial orbital configuration and evolution of giant planets that are formed earlier [204]. Generally speaking, even greater diversity may be expected in S-type (circumstellar) planetary systems for wide binaries, but not for P-type (circumbinary) systems. In comparing the architecture of circumbinary planetary systems with that of the Solar System, it can be easily seen that the circumbinary systems can be considered a 'truncated version' of the Solar System, the inner part of which, where the terrestrial planets should be present, is simply absent, since it is formally located in the circumbinary chaotic zone. A giant planet, an analogue of Neptune or Jupiter, orbits in most of the known circumbinary planetary systems close to the border of this zone. If the truncated-system model is correct, the orbital architecture external with respect to the leading giant can be quite simple, similar in structure to the Kuiper belt. Ice/rock bodies in this case tend to be in orbital resonances with the giant that 'shepherds' them; the role of the latter in the Solar System is played by Neptune. This architecture assumes the existence of terrestrial-type circumbinary planets external with respect to the leading giant planet.

Exoplanets such as Kepler-47c, Kepler-1647b, and OGLE-2007-BLG-349L (AB)c [166, 205–208] are observational evidence of the existence of planets that are external relative to the giants captured at the edge of the central cavity. The discovery of these planets shows that not all planets stop migrating only at the edge of the cavity: some planets halt at much greater distances from the central binary. In the case of the Kepler-47 two-planetary system, there is a lot of free orbital space between Kepler-47b and 47c for the possible stable presence of low-mass planets [206], i.e., the observed two-planetary system is by no means 'densely packed'. Systems Kepler-1647 and OGLE-2007-BLG-349L (AB) can also contain low-mass planets in orbits located inside the orbits of the observed giant planets, since the sizes of the orbits of the latter are considerably larger than the central chaotic zone.

10. Possible habitability of exoplanets

10.1 Basic prerequisites

Unfortunately, the detection of signs of life in the planetary 'habitable zones' in space is still beyond the capabilities of modern astronomical methods and instruments. There is no noticeable progress in solving theoretical problems related to the origin of life. V I Vernadskii considered this problem as one of du Bois-Reymond's seven world riddles [13] and believed that the very formulation of the question depends on whether life is recognized as a universal (cosmic) or an earthly phenomenon. He believed that "in geological time, the emergence of a living organism from a dead environment could not occur," substantiating this assertion with geochemical arguments. This point of view promoted the concept that the origin of life on Earth is connected with the outer space environment. The discovery of exoplanets greatly invigorated interest in this problem and led to the conclusion that planets with natural conditions more or less suitable for life actually exist, although no evidence of their biogenicity has been found. And yet there are now more reasons to believe that life is a cosmic rather than a particular Earth-related phenomenon. We now briefly consider some of the available indirect evidence and restrictions.

The metallicity of stars on the outskirts of the Galaxy is low, and this circumstance hinders the formation of rocky terrestrial planets. On the other hand, metallicity is high closer to the center of the Galaxy, where the process of star formation is intense, but the frequency of supernova explosions is also high, and therefore the sustainable development of complex life forms on planets is not possible. The importance of these limitations was pointed out by Lineweaver et al [209]. Using model calculations of the Galactic evolution, they found that the *Galactic habitable zone* — a zone where Earth-type life is possible — is limited by a ring of radial size from 7 to 9 kpc from the center of the Galaxy; it contains stars that formed 8–4 billion years ago (Fig. 26). It turns out that this ring-shaped region is home to most of the stars (75%) that can have planets with complex life forms; these stars are on average 1 billion years older than the Sun. Thus, it is possible that the peak of the emergence of complex life forms in the Milky Way has long been passed [209, 210].

A wide variety of organic compounds has been discovered in the interstellar medium, especially in the regions of giant interstellar molecular clouds; these compounds contain nitrogen, oxygen, and biologically important carbon. The last is especially abundant (up to 10%) in polycyclic aromatic hydrocarbons (PAHs) concentrated primarily in molecular clouds, where they form complex carbon chains and lattices such as fullerenes, and at low temperatures (~ 10 K) are captured by the ice envelopes of dust particles of the cloud. Ice mantles consist of H_2O with an admixture of methanol (CH_3OH), CO_2, CO, and NH_3 [14], and, through photolysis processes, they are functionally linked to the formation of ketones, methyl, alcohol, carboxyl groups,

[13] Du Bois-Reymond was a German physiologist and philosopher, a representative of mechanistic materialism, the founder of electrophysiology (studies of electrical phenomena in muscles and nerves) and the theory of biopotentials. He is the author of the utterance 'ignoramus et ignorabimus' (we do not know and will never know).

[14] CO is considered to be the best indicator of mass transport in the protoplanetary disk. This component is used as such, in particular, in ALMA observations and to estimate the dust/gas mass content.

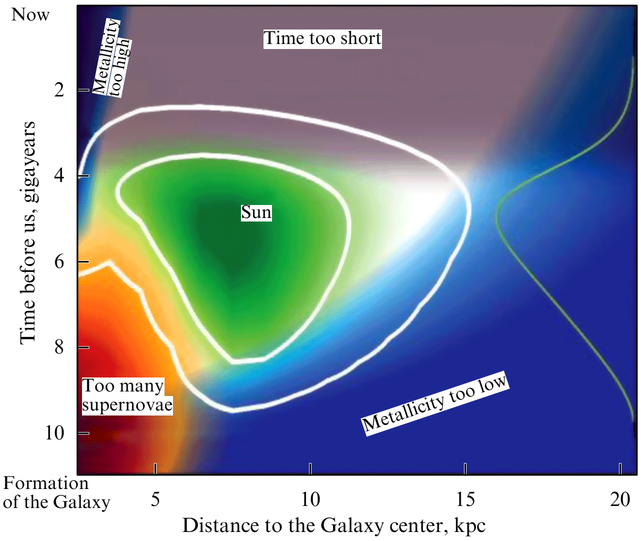

Figure 26. (Color online.) Galactic habitable zone, according to Lineweaver et al. [209]. Horizontal axis: the distance from the center of the Galaxy; vertical axis: the age of the stars. The area where time is not sufficient for the formation of complex life forms is highlighted in gray; red area shows the zone where the development of life is impeded by supernova explosions; blue shows where the metallicity of the parent stars is too low (right) or, conversely, too high (left) for the formation and survival of terrestrial planets. The green curve on the right, plotted vertically, shows the distribution (over time) of the expected number of habitable planets (with complex life forms) calculated by Lineweaver et al. (According to [209].)

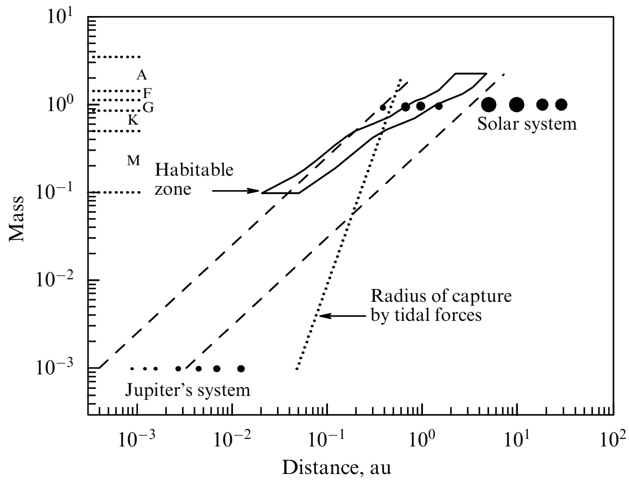

Figure 27. Radius of habitable zone for stars of various spectral classes. The vertical axis shows the spectral class and mass of the star in solar units, and the horizontal axis, the orbital radius in astronomical units. The dashed lines show the boundaries of the region of existence of the terrestrial planets, depending on the class of the star and the radius of the planetary orbit; the dotted line shows the tidal lock radius. Three planets of the Solar System — Earth, Venus, and Mars — are in a favorable zone, within the boundaries of the possible habitability zone (Goldilocks Zone), bounded by a solid line. (According to [216].)

and other complex organic compounds [211]. Measurements with high spectral and spatial resolution performed using the ALMA network of high-sensitivity ground-based radio telescopes have revealed the presence of many complex molecules that are important from the point of view of prebiogenic chemistry. They are molecules of formaldehyde (H_2CO), ethanol (C_2H_5OH), glycolaldehyde (CH_2OHCHO), ethylene glycol (CH_2OH), methyl formate (methyl formic acid ester CH_3OCHO), dimethylether (CH_3OCH_3), and many other compounds, including those enriched in deuterium. Of particular interest are molecules that contain peptide bonds and simple sugars [212], as well as methylamine (CH_3NH_2), a precursor of the simplest amino acid glycine (NH_2CH_2COOH). All these observations point to the extremely rich prebiogenic chemistry of the interstellar medium, especially molecular clouds and vicinities of young stars, which expands the prospects for detecting signs of life in their planetary systems. Nevertheless, this probability itself remains rather low.

10.2 Habitable zones in planetary systems

It is known that life can only exist in a very limited range of natural conditions. This implies the existence from the very beginning of rather strong restrictions on the mechanical, thermodynamic, and cosmochemical properties of a celestial body on which life could arise. A planet suitable for habitation must meet several clear-cut criteria. The first criterion is its size and mass, as a large planet accumulates material until it becomes a gas giant, while a small planet easily loses its atmosphere. The second criterion is a radial distance from the parent star that provides favorable climatic conditions, including surface temperature and pressure, which enable the presence of liquid water. The third criterion is the existence of an atmosphere with a suitable chemical composition, which excludes an aggressive effect on metabolic processes. Finally, there are the orbital sizes that are optimal with respect to tidal effects, since a planet located too close to the star is trapped due to tidal interaction in a synchronous spin-orbit resonance, which is unfavorable for the development of life (Fig. 27). Moreover, it is clear that, for life to arise, be sustained, and evolve, climatic conditions must be stable for a long time [213–215].

The habitable zone within the Solar System that meets the above criteria is shown in Fig. 28. It has the shape of a Sun-centered ring limited by the inner and outer radii: on the inner border, it is too hot, while on the outer border, it is too cold. It can be seen that the most favorable position is occupied by Earth, while Venus is located outside the habitable zone, and Mars is at the edge of the outer border. It should be noted that the boundaries and width of the habitable zone in exoplanet systems can change over time. Therefore, the concept of a *dynamic habitability zone* is introduced — a region around a star where terrestrial planets can exist on long time scales without experiencing significant orbital disturbances from other planets (or companion stars in binary systems).

Of primary interest for the search for signs of life are, of course, terrestrial exoplanets, including super-Earths, located in habitable zones. As was already mentioned, a critical factor is the possibility of liquid water existing on the surface. The presence of carbon and other volatiles is also needed, the supply of which to an Earth-like planet could be provided by the migration of planetesimals and small bodies (comets and asteroids of the carbonaceous chondrite class) from the periphery to the inner zones of the Solar System at an early stage of evolution due to the mechanism of heterogeneous accretion [90, 217]. However, primitive life could arise outside the habitable zone if favorable conditions are created under the surface of a planet or satellite. Such conditions may be expected, for example, on exoplanet satellites, similar to the supposed warm water oceans on Jupiter's Galilean moons

Figure 28. (Color online.) Habitable zone in the solar system.

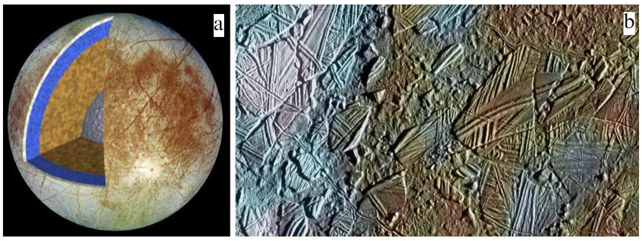

Figure 29. (Color online.) Model of the internal structure of Jupiter's Galilean satellite Europa with a hypothesized warm salty ocean ~ 100 km deep (a) below a ~ 10-km-thick ice surface (b). (Source: NASA.)

Europa and Ganymede (Fig. 29), whose energy source is the release of tidal energy. A similar mechanism is clearly responsible for the geological activity of a satellite of Saturn, Enceladus (Fig. 30), on which water geysers — a manifestation of cryovolcanism — were discovered. A deep-laid biosphere exists on Earth, in its hard shell (in the upper crustal layer ~ 2–3 km thick), which is based on chemosynthesis energy and production processes different from photosynthesis. It cannot be ruled out that a biosphere of this kind exists on Mars.

The deep biosphere of Earth is an underground high-temperature ecosystem that is powered by active microbiological processes. The multicellular eukaryotes inhabiting it have adapted to extreme conditions at a depth of several kilometers: an anaerobic environment and high temperatures (~ 100 °C) and pressures (hundreds of atmospheres). Bacterial life surprisingly turned out to be very rich and varied under these conditions: it consists of heterotrophic and autotrophic bacteria, mainly methanogens, archaea, and eubacteria. Unlike the fundamental process that controls life on the surface, photosynthesis, these bacteria — chemolithoautotrophs — obtain energy through the oxidation of inorganic substances (chemosynthesis). The total biomass of deep bacteria is comparable to that of Earth's surface biomass. These microbial communities were probably formed from surface microorganisms as a result of slow evolution, and their genome may be comparable to the genome of hydrothermal microbes (see, e.g., [218]).

It can be seen that only a small fraction of discovered exoplanets — Earths, sub-Earths, and super-Earths, located in a favorable climatic zone — is of the greatest interest for astrobiology. The equilibrium temperature in this zone ranges from about 185 to 300 K, which allows water to be in a liquid state (taking into account the possible greenhouse effect and sources of internal heat). Most of the discovered planets have a radius 3–4 times larger than Earth's, which probably reflects the character of the distribution of planets in size that actually exists in the Galaxy. Some known terrestrial planets are located in a 'hot' zone close to the parent star. For example, Kepler-78b is only 80% larger than Earth, but orbits a sun-like star at a distance equal to only twice the planet's radius. It should be noted as well that such a location of a low-mass body provides a unique opportunity to concurrently apply the methods of transit and radial velocities and determine in this way the average density of the planet. It turns out that the density of Kepler-78b is approximately 5.5 g cm^{-3}, a value which is virtually identical to that of Earth. Thus, this planet consists of rocks, but its natural properties are an 'infernal world', arguably similar to the artist's presentation displayed in Fig. 31.

The same can be said about the five planets orbiting the sun-like star Kepler-444, which is located at a distance of

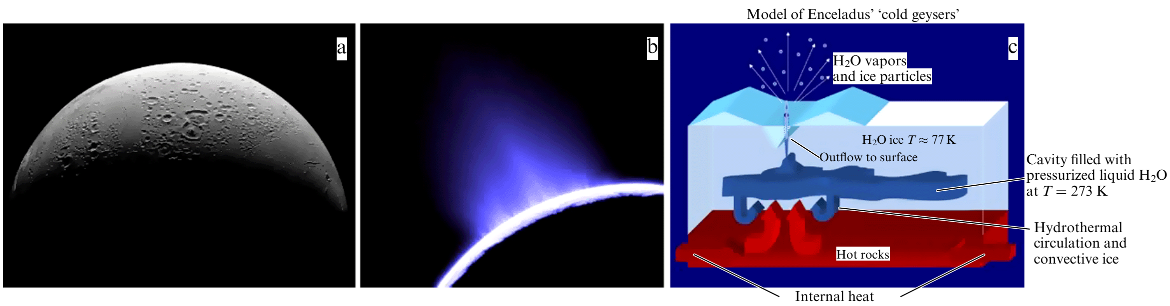

Figure 30. (Color online.) (a) Saturn's satellite Enceladus, (b) water geysers on the limb, (c) a model of the internal structure and nature of cryovolcanism. (Source: ESA.)

Figure 31. Hypothetical view of the surface of a hot planet in the close vicinity of the parent star (artist's image). The point on the stellar disk is the transit of another planet. (According to Astronomy.com.)

117 light years away from us. These rocky hot planets, one of which is similar in size to Mercury, the other to Venus, and the other three to Mars, orbit their star with periods of no more than 10 Earth days. They do, however, draw particular attention; based on the brightness variations of the star, it was possible to determine the speed of acoustic waves in the interior of the star and estimate in this way the ratio of hydrogen to helium, a key parameter used in estimating the duration of stellar evolution. It turns out that the age of Kepler-444 and hence its planetary system is 11.2 billion years, i.e., they formed soon after the birth of the Universe, which is 13.7 billion years old. If we assume that life could arise on other similar planets, but with more favorable climatic conditions, and nothing prevented its evolution, then it is difficult even to imagine how far ahead of earthly life such life could have gone in its development. Of course, the key task is to clearly formulate the restrictions that hinder the emergence and development of life on the immense variety of exoplanets.

Attention among Earth-like planets is also attracted by the exoplanet Kepler-452b that is located at a distance of 1400 light years from Earth and orbits a sun-like star at a distance from it which is only 5% greater than the radius of Earth's orbit. Another example is found at a distance of 42 light years from the Sun: a planet with an orbital period of ~ 200 Earth days around the dwarf star HD 40307, which is less bright than the Sun. Such planets may be shrouded in dense clouds of water droplets and/or crystals, and some may even consist of half of water or have continuous oceans on the surface. A number of planets are located in an intermediate region between hot gas giants (super-Jupiters) close to the star and distant planets with temperatures of $< 100-150$ K, reminiscent of the giant planets of the Solar System and possibly having similar systems of ice satellites. Exoplanets in a temperature range of several hundred degrees may resemble Venus or, for those with a Neptune-like mass, have a completely different natural environment.

Interesting examples of other Earth-like exoplanets are Kepler-186f and Kepler-438b. The former is one of the five planets that orbit a red dwarf with a luminosity 25 times less than the Sun and is located in the constellation Cygnus at a distance of about 500 light years from the Sun. The planet is located in a temperate temperature zone rather close (within 0.4 au) to the parent star, which almost corresponds to the orbit of Mercury in the Solar System, and makes one orbital revolution in 129.9 days. The illumination on its surface is 32% of that of the Sun on Earth's surface, which implies that it is located in a zone suitable for habitation. It should be definitely taken into account that the spectral composition of the radiation, the length of the year and, probably, some other characteristics differ from terrestrial ones. And yet the planet has been called Earth's cousin. The other one of the mentioned planets, Kepler-438b, which also orbits a red dwarf, is almost identical in size and temperature to our planet (only 12% larger than Earth and receiving about 40% more light). It was considered until recently the holder of the currently highest so-called Earth Similarity Index (ESI). However, observations of the red dwarfs themselves revealed their extremely high activity with frequently repeated CME-type flares, which are an order of magnitude more powerful than the solar ones. Such super-emission of plasma should tear off the atmosphere of the planet, even if it has a strong magnetic field, not to mention the catastrophic effects of stellar radiation. It is unlikely that life is possible under such conditions, as on other planets similar to Earth that move in orbits relatively close to their star. Among the latter, the planets Kepler 20e ($R = 0.87\,R_{\rm E}$) and Kepler 20f ($R = 1.03\,R_{\rm E}$), similar in size to Venus and Earth, respectively, but differing in other parameters, are of great interest. The planet Kepler 22b ($R = 2.38 \pm 0.13\,R_{\rm E}$), with an equilibrium temperature of 262 K and an orbital period of 289.86 days, turns out to be the most similar to Earth in climatic conditions, but its size is more than twice that of Earth.

The discovery in 2016 at the Chile-based La Silla observatory of a system of seven planets Trappist-1 near a star — a red dwarf of spectral type M8 V with a surface temperature of ~ 4000 K and a luminosity of almost 2000 times less than that of the Sun (Fig. 32) — was a sensation. All these planets are close in size to Earth ($\sim 0.7\,R_{\rm E}$) and are located in orbits adjacent to each other with orbital periods ranging from several days to ~ 20 days in the close vicinity of the star. Their periods, which are multiples of each other, are in resonance. Three planets are located in the habitable zone with an equilibrium temperature of ~ 300 K. They may have water on the surface and an atmosphere; however, the possibility of retaining them is in question, given the high activity of the parent star. Nevertheless, at least the presence of life cannot be ruled out on any of these planets, and the Trappist-1 system is considered a promising candidate for its detection.

The presence of planets in the habitable zones of low-mass stars seems to be a typical phenomenon. This is confirmed by the recent discovery of two Earth-like planets in the habitable zone of Teegarden's star [219]. However, this star, located only four parsecs away from the Sun, has a mass of about ~ 0.08 solar masses and can in fact be classified as a brown dwarf.

Given the immense number and huge variety of planetary systems, it cannot be ruled out in general that Earth is not a unique place for the emergence and spread of life, although there is no sufficient reason to consider that it belongs to the category of 'typical' inhabited planets. The factors favorable for the emergence of life might be, for example, the large surface area of super-Earths and the 'longevity' of the planet

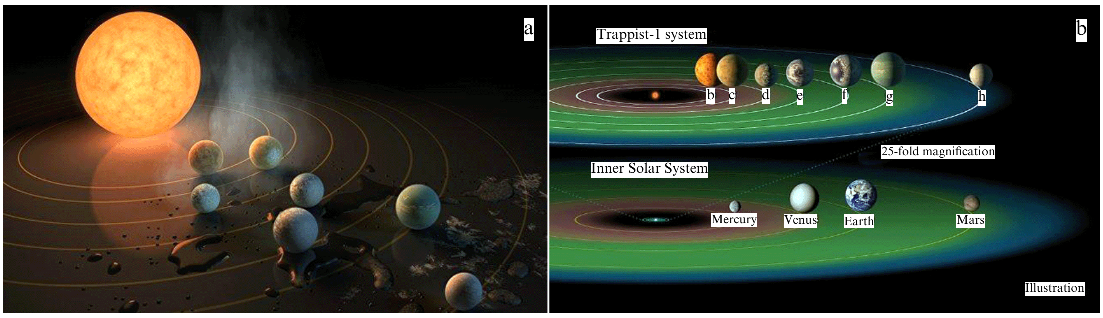

Figure 32. (a) System of seven planets around the red dwarf Trappist-1 and (b) its comparison to the locations and sizes of the terrestrial planets in the Solar System (NASA site, Wikipedia).

around the parent star in red dwarf systems [220]. The multiplicity of the parent star can play an important role. Indeed, as joint analysis of the conditions of stability and habitability of exoplanetary systems of single and multiple stars has shown, a number of habitability conditions can be satisfied on circumbinary planets around main-sequence stars with a greater probability than on Earth, where these conditions may have arisen quite accidentally. Therefore, there is reason to believe that life in any form can exist on circumbinary planets around stars of certain classes, and the issue of their possible habitability deserves further study [174].

Among other options deserving special attention is the potential habitability of large exoplanet satellites. There are reasons to believe that binary planets with components of comparable masses (as in the case of Earth–Moon) are a rather rare phenomenon: the probability of an Earth-like planet acquiring a large lunar satellite is extremely low from a cosmogonic point of view [221]. It is no coincidence that this issue is attracting increased interest. A series of massive numerical experiments that take into account the effects of fragmentation and collisions of bodies without merging yielded statistics of shock interactions at the late stages of the formation of Earth-like planets near solar-type stars and showed that large exo-moons may be formed in protoplanetary systems due to this mechanism [222]. According to [223], they can be very different from the satellites of planets in the Solar System; in particular, they may be much larger. Numerical simulation indicates, for example, that even Earth-sized satellites can form around super-Jupiters. Conditions for the potential habitability of exo-moons depend on orbital stability, insolation, and tidal heating parameters, while magnetic shielding can be provided by the extended magnetosphere of the planet itself [224–227]. The limits for possible habitability are considered to be the residing of the satellite in an orbit either distant from the planet, near the Hill stability boundary, or, conversely, close to the planet, near the tidal synchronization threshold [228].

Regarding binary stars, planets can have satellites within their Hill spheres in both P-type and S-type systems, similar to single-star planets. In particular, since all known circumbinary planets are giants, the size of their exo-moons can be large and, generally speaking, they are potentially suitable for the emergence of life. However, it should be kept in mind that the habitability conditions of exo-moons in binary star systems should be modified, so it is more reasonable to explore hypothetical habitable niches, such as for the hypothetical exo-moon of the giant Saturn-type planet Kepler-16b. Another giant planet Kepler-47c, which is located in the habitable zone, may have a potentially inhabited Earth-type satellite, but its climate is subject to strong fluctuations under the circumbinary-system conditions [223, 229, 230]. This circumstance may be a fundamental limitation on the potential habitability of exo-moons with an atmosphere.

In summarizing the discussion of the possible detection of life on exoplanets (exo-moons) located at distance of thousands of light years from us, a combination of factors should be taken into account. First of all, the planet should be similar to Earth and be located in the habitable zone of the parent star. Apart from the size and surface and atmospheric properties, thermal conditions and dynamics, tidal effects, the presence of a magnetic field (magnetosphere), and an acceptable radiation environment per se, these factors should combine in a unique way to form together a favorable natural environment. For example, strong climatic changes in binary star systems can manifest themselves on various time scales, which are determined by the orbital parameters of an exoplanet (exo-moon), and may prove to be fatal for its biosphere. Variations associated with the orbital motion of the parent star's components further complicate the picture. Strong winds in the atmosphere, similar to those found on the exoplanet HD 189733b using the HARPS spectrograph at the Chile-based La Silla Observatory, can be unfavorable for life. Their speed may be as high as several kilometers per second, which is tens of times higher than that of earthly hurricanes. At the same time, it should be borne in mind that, although life can exist in a very limited range of natural conditions, it features a high degree of adaptation to extremely harsh environmental conditions. It is known that living organisms (extremophiles) are able to survive in a fairly wide range of temperatures and pressures, even in a deep vacuum, in a highly acidic environment (at low pH values), and under high doses of radiation.

And yet, many circumstances, unfortunately, disfavor optimistic expectations of discovering life, similar at least in its basic features to that on Earth. In this regard, the key question is whether there are life forms on exoplanets that have a high degree of adaptability and stability, or even have emerged on a different chemical basis and alternative principles. Although there is no answer to this question yet, it can nevertheless be argued that carbon, which forms the basis of organic compounds and is capable of forming branched polymer chains, and water are the most suitable combination for biosynthesis. Taken together, all this is a basis for biodiversity. It should be added that the creation of very complex organic compounds in space and the matter transport due to migration of celestial bodies are universal processes, and these processes taken as a whole can probably be considered a kind of paradigm.

11. Prospects

Striking advances have been made in just over 20 years in a completely new field of astronomy — the exploration of extrasolar planets. A plethora of celestial bodies of this new class have been discovered, which has immeasurably enriched our insight into the Universe and the variety of natural processes outside the Solar System and advanced to a new basis the star-planetary cosmogony. Observational methods and instruments are being improved, including large ground-based and space telescopes. The nations that are the leaders in world science have developed ambitious plans for the study of exoplanets. This process is constantly evolving, and its prospects are truly immense. We only mention here some of the projects presented in Fig. 33.

Launched into orbit already in 1990, the Hubble Space Telescope is now widely used for spectrophotometric analysis of the composition of exoplanet atmospheres. The Spitzer Space Telescope, which operated in orbit from 2003 to 2020, has been used to study exoplanets in the IR spectral region. CoRoT, the world's first spacecraft equipped with a small specialized telescope for studying exoplanets, was launched into orbit in 2006. It should be noted that, in addition to researching exoplanets, it has made a certain contribution to the development of asteroseismology. The Kepler/K2 spacecraft, launched in 2009, was the first to focus on the detection of exoplanets by the transit method, especially exoplanets in habitable zones. The Gaia mission (launched in 2013), in addition to performing its main task — mapping the Milky Way — was potentially aimed at discovering hundreds and even thousands of planets by the astrometric method; this task, however, has not been fulfilled. The TESS (Transiting Exoplanet Survey Satellite) spacecraft, which has recently begun operation, is designed to continue the discoveries of exoplanets by the transit method so successfully commenced by the Kepler spacecraft. It will carry out observations not in a limited field, but throughout the entire celestial sphere, although inside the relatively close galactic neighborhood of the Sun.

The Cheops spacecraft project, planned jointly by ESA and Switzerland, will enable obtainment of detailed data on the parameters of already discovered exoplanets ranging in size from super-Earths to Neptunes using high-precision photometry and a 30-cm telescope of the Ritchey–Chrétien system. The project will provide a unique opportunity to determine the radii of planets and their satellites in the super-Earth mass range with an accuracy of 10%. The Plato spacecraft (an ESA project) will enable the study of terrestrial planets in habitable zones, which, naturally, is of particular interest. The Ariel spacecraft (also an ESA project) will be used to analyze the composition of the atmospheres of large selections of planets of various types. The spacecraft launch is scheduled for 2028. The mission has been developed by a consortium of more than 60 institutes from 15 ESA member countries. Its goal is to study the atmospheres of planets orbiting distant stars to solve fundamental issues regarding their composition and planetary system formation and evolution. It is planned that for 4 years of operation the spacecraft will observe thousands of exoplanets of super-Earth sizes and larger in the visible and infrared spectral ranges. The studies will be focused on the spectra of warm and hot planets located in orbits near parent stars and planets in habitable zones. The analysis of the spectra will enable the collection of information about atmospheric gases and condensates and the identification of the planets that are most promising for further research.

Planned in the Russian space program are studies of exoplanets as part the Spektr-UF project in the ultraviolet wavelength range. The launch of the spacecraft is scheduled for 2024.

The most extensive exoplanet research program is planned by NASA as part of the Exoplanet Exploration Program (ExEP). As was already mentioned, the Kepler spacecraft, which completed an extremely effective exoplanet research program, was succeeded by the new TESS project, a spacecraft launched in March 2018 (Fig. 34). It is equipped with four 23×23 cm photometric cameras with a total field of view of 2300 degrees, 400 times that of the Kepler telescope. It is assumed that $\sim 200{,}000$ exoplanets around the brightest stars will be investigated in the first two years of operations, including Earth-like planets and planets of binary stars. Images of and photometric data on in total about 30 million stars and galaxies brighter than 16th magnitude will be obtained over 10 years of operations. An expanded survey of regions close to the north and south poles of the ecliptic, which is planned by the TESS program, will make it possible to detect exoplanets that are the most interesting for detailed study by means of large ground-based and space telescopes of the future.

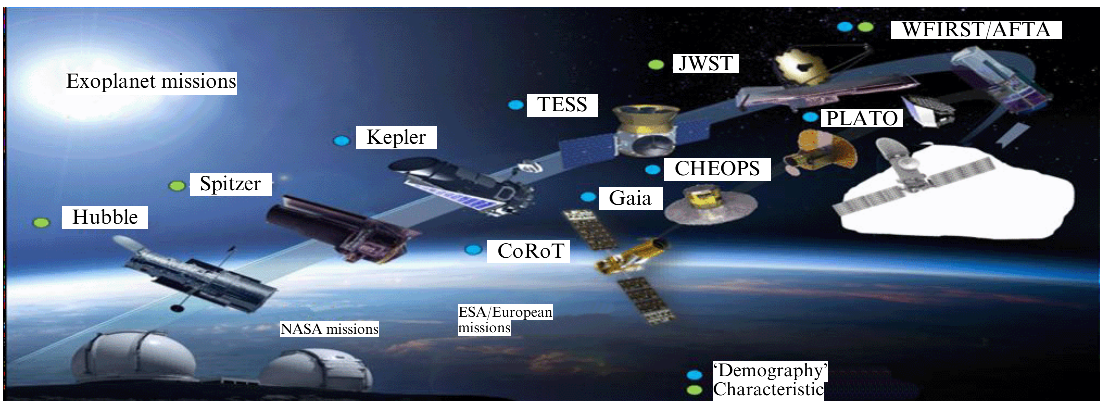

Figure 33. Completed and planned space missions designed for exoplanet research. (Source: NASA.)

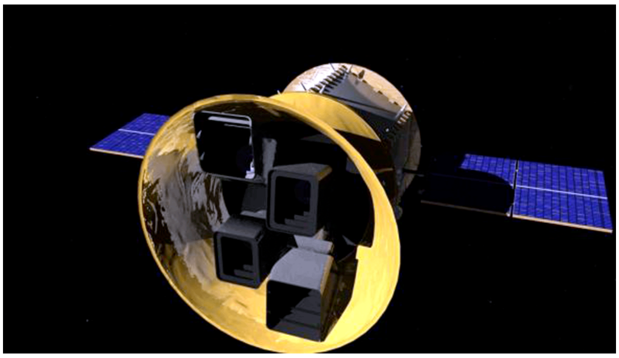

Figure 34. TESS spacecraft. (Source: NASA.)

The first interesting results have already been obtained by the TESS spacecraft. For example, three planets have been discovered around the not very active red dwarf TOI-270 (TESS Object of Interest-270), located only ~ 20 pc from the Sun: one Earth-like (with a radius of 1.25 Earth radii) and two mini-Neptunes (both with radii of ~ 2 Earth radii) [231]. Mini-Neptunes are especially interesting, being a type of object intermediate between Earth-like planets and giant planets. The outer planet is located in the habitable zone.

It is expected that significant time will be allocated for a comprehensive study of exoplanets in the observational program of the most ambitious NASA project: the multi-purpose James Webb Space Telescope (JWST) with an equivalent mirror diameter of 6.5 m. This telescope, whose capabilities significantly exceed those of the Hubble telescope, will make a major contribution to observational astronomy and will open, in particular, a new page in the study of exoplanets. Its launch is scheduled for 2021.

12. Conclusion

Exploration of exoplanets is one of the key branches of modern astronomy, which opens up new avenues for solving the problems of the formation of planetary systems around stars of various spectral classes, including the formation of the Solar System. More than four thousand exoplanets have already been discovered — from the closest one at Proxima Centauri to the most distant planets SWEEPS-04 and SWEEPS-11. Distances to known exoplanets range from 3 to 28,000 light years, i.e., span an interval of about four orders of magnitude.

It is of importance to determine how configurations of planetary systems, including systems with hot Jupiters, are formed and find the conditions for the formation of a class of super-Earths that are absent in the Solar System. Planetary systems of binary stars attract much attention. The scenarios of their formation and evolution are a challenge for theoretical cosmogony and celestial mechanics. Of particular interest are the terrestrial planets located in orbital zones of potential habitability, where conditions favorable for the emergence and existence of life are possible; these studies open a new page in astrobiology.

Exoplanetology has become over the past two decades one of the most important branches of astronomy that enriches stellar-planetary cosmogony, comparative planetology, cosmochemistry, and astrobiology. Research methods and tools are being improved, and the number of publications on various aspects of exoplanet studies in the most authoritative scientific journals is constantly growing. A number of important problems, such as the detection of exoplanets by microlensing [232] and high-precision spectroscopy [233], have been discussed in *Physics Uspekhi*. The contribution to cosmochemistry of astrometric, photometric, and spectroscopic/polarimetric methods in observing planetary transits near parent stars of various spectral classes using ground and orbital equipment developed in Russia should be especially noted [233]. The discovery of Earth-like planets that have a temperate climate and are suitable for the origin of life will represent in the coming decades one of the main stimulating tasks of modern science of the Universe; this also has enormous philosophical significance.

There is no doubt that the implementation of new ground-based and space observational projects to explore exoplanetary systems using improved methods and advanced technologies will immeasurably expand in the coming decades our insight into neighboring worlds in the vast expanses of the Universe. So far, only the first steps have been made on the path of finding these worlds, the features of their nature, the possible potential for the emergence of life, and the diversity of its forms. However, the very fact that exoplanets exist, the actual number of which in our Galaxy alone is comparable to the number of stars it contains, of which at least ~ 10 billion can be similar to Earth, promises many new amazing discoveries.

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