Earth and Planetary Science | Volume 03 | Issue 02 | October 2024

Earth and Planetary Science
https://journals.nasspublishing.com/index.php/eps

RESEARCH ARTICLE

Characteristics of Multiplanetary Systems with One Host Star

Elza Buslaeva[1,2], **Elena Belenkaya**[2*]

1. Physical Department, Federal State Budget Educational Institution of Higher Education M.V. Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow, 119991, Russia

2. Skobeltsyn Institute of Nuclear Physics (SINP MSU), Federal State Budget Educational Institution of Higher Education M.V. Lomonosov Moscow State University, GSP-1, 1(2) Leninskie Gory, Moscow, 119991, Russia

Abstract: The characteristics of 100 multiplanetary systems with single central stars of different spectral classes were examined. The data for these systems were taken from the NASA Exoplanet Archive. Among the systems, those were selected for which the exoplanet mass and radius were simultaneously known. For 293 planets from these systems masses, radii, orbital radii, orbital periods, and types of exoplanets were analyzed. It occurred that the rarest type in such systems were terrestrial planets and after them the gas giants. Most of the exoplanets belonged to the type of super-earths. The distribution of the number of planets in a system showed that systems with many exoplanets are less common than those with a smaller number. The system with the largest number of exoplanets in this sample is TRAPPIST-1 (7 planets systems). The properties of exoplanets in multiplanetary systems with one host star in terms of characteristics, orbital sizes, and number of planets, are investigated and compared with the Solar system. It turned out that the Solar system is rather an exception to the considered extrasolar multiplanetary systems.

Keywords: Exoplanets; Planetary systems; Stars

1. Introduction

According to NASA Exoplanet Archive[1], as of April 2024, there are more than 5600 confirmed exoplanets. While free-floating exoplanets that are untethered to any star exist, most of the discovered planets so far orbit their parent stars. A good number of them are from multiplanetary systems. The Solar system is an example of a multiplanetary system consisting of eight planets. The study of systems with several exoplanets is an actual problem of modern science. It helps us

1 https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=PS

*Corresponding Author:
Elena Belenkaya,
Skobeltsyn Institute of Nuclear Physics (SINP MSU), Federal State Budget Educational Institution of Higher Education M.V. Lomonosov Moscow State University, GSP-1, 1(2) Leninskie Gory, Moscow, 119991, Russia;
Email: elena.belenkaya.msu@gmail.com

Received: 23 January 2024; **Received in revised form:** 11 May 2024; **Accepted:** 23 May 2024; **Published:** 7 June 2024

Citation: Buslaeva, E., Belenkaya, E., 2024. Characteristics of Multiplanetary Systems with One Host Star. *Earth and Planetary Science*. 3(2): 1–13. DOI: https://doi.org/10.36956/eps.v3i2.1025

DOI: https://doi.org/10.36956/eps.v3i2.1025

Copyright © 2024 by the author(s). Published by Nan Yang Academy of Sciences Pte. Ltd. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License (https://creativecommons.org/licenses/by-nc/4.0/).

understand the history of the formation of the Solar system and planetary systems around other stars and expands our knowledge of exoplanets.

By studying exoplanets and their key parameters, scientists try to clarify theories of their formation. In this work we restrict ourselves to multiplanetary systems with one central star. Usually, the key parameters of exoplanets are mass and radius [1]. We also take into account the orbital period and orbital radius, as well as the class of the parent star, as these are listed in almost any exoplanet catalogue and are necessary to gain some insight into the exoplanet.

Previously, for multiplanetary systems around M class stars, it was found that the density of exoplanets in such systems is, on average, significantly greater than in systems with a single planet [2]. The metallicity of M class host stars in multiplanetary systems turned out to be lower than that of stars with a single exoplanet. These data may indicate that there are different physical processes that determine the formation of multiplanet systems compared to single-planet ones [2]. However, it is also possible that in a system with one planet there are other exoplanets that were not discovered at the time of the research.

At present, most confirmed extrasolar planetary systems contain one exoplanet: there are approximately 3500 systems with one confirmed planet[2] and about 860 confirmed multiplanetary systems [3]. This is probably due to the assumption described above that not all exoplanets can now be detected in these systems. According to the reference [3], most stars, like the Sun, have several planets.

The classical theory states that the formation of the Sun and its planetary system occurred simultaneously. Udry and Santos [4], studying the statistical properties of exoplanets, noted that planet formation could occur from a circumstellar disk by solid accretion or by gravitational instability. Various instabilities can exist in this disk [5]. A protoplanetary disk can be dynamically stable with respect to axisymmetric movements only if its inner radius is equal to zero [6]. Belenkaya and Khodachenko [7] showed that accretion and current astrophysical disks in the presence of a magnetic field have inner edges near Alfvenic radii. At Alfvenic radius, the densities of magnetic and kinetic energies are equal. Gravitational instability in the disk is caused by the star's own gravitational field [5]. The higher the rotation speed of the disk, the less gravitational instability there is in it. Williams and Cieza [8] stated that young disks are gravitationally unstable.

When a young star appears, the surrounding material forms an accretion disk. The gas and solids in the protostellar material have too much angular momentum to quickly fall on the star, allowing enough time for planets to form within the disk. Modern science proposes that exoplanets are formed from an accretion disk around a star, which at first is continuous, then, due to instabilities in it, is divided into rings [6], and then from the rings due to constant collisions of matter its parts become larger and begin to attract other parts of matter, gradually forming exoplanets [9]. The evolution of the protoplanetary disk determines the initial conditions for the formation of rocky and giant planets. First, the formation of planetesimals occurs—the objects that are massive enough to attract gravitationally other objects, but do not have a significant effect on the overall dynamics. Having gained enough mass, planetesimals become planets [9]. Early planet formation in protostellar disk is considered in detail in, for example, Cridland et al. [10]. Heller [11] noted that it is likely that giant planets could be formed beyond the ice line at a distance of several AU from solar type stars and after that migrate closer to the star (< 0.1 AU) because of the interaction between stars and disk, becoming hot Jupiters. Dawson and Johnson [12] stated that in spite of numerous works investigating hot Jupiters, there is no clear understanding of their origin. Stars with a higher metallicity possess more giant exoplanets [4,13].

Winn and Fabrycky [13] presented a review of the occurrence and architecture of exoplanetary systems, considering variability in the number of stars in the systems, different mutual inclinations, planet-planet interactions, and the influence of star rotation. Zhu and Dong [14] also review the exoplanet statistics and architecture of planetary systems.

Exoplanets formed from a protoplanetary disk are located approximately in the same plane, so they are greatly influenced by the conditions of their formation in the disk. The formation of systems with a pronounced "non-flat" geometry was probably influenced by external factors. In this work, we study the characteristics of multiplanetary systems with one host star, as this is the first step in our study of the issue. Multiplanetary systems with several stars are much more complex and will be the topic of our future work. Planets may rotate around one or more stars in such systems. There are a lot of options.

A wide range of parameters of exoplanets can be determined by different conditions of their formation. New data on exoplanets are emerging, which will be

2 https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

updated in the future. At this stage, we present a rather complete analysis of the characteristics of multiplanetary systems existing in catalogues. We do not use statistical models to avoid any uncertain assumptions, that are included in them [14].

2. Materials and Methods

The study of multiplanetary systems includes the distribution of exoplanets over orbital distances; the authors of reference [15] stated that for multiplanetary systems it is more uniform than for single-planetary ones. Exoplanets in multiplanetary systems were discovered to be at different distances from the star, while in single-planet systems, planets were closer to the star more often (probably, because it is easier to find them there).

In this work, to find patterns of distribution and properties of exoplanets, 100 multiplanetary systems with one host star were considered, for which most of the characteristics of exoplanets are known. The sample includes multiplanetary systems at any distance from the Sun. The data for these systems were taken from the NASA Exoplanet Archive. Among the systems, those were selected for which the masses and radii of all exoplanets were simultaneously known from the literature. The magnitude of the error for parameters has not been assessed. We were interested in such parameters as the mass of the exoplanet, its radius, distance to the host star, orbital eccentricity, the planet's orbital period, as well as the magnitude of the host star and its spectral class.

Multi-stellar systems were not included in the sample, in which is 100 systems with 293 exoplanets. The chosen systems were sorted into different types of exoplanets and different classes of host stars.

The work used a method of presenting data in the form of histograms. The original data from the NASA catalogue, which includes all currently confirmed exoplanets, were sorted to create a sample of data that differs from the NASA catalogue in that both the mass and radius are known for the exoplanets in the sample. Next, for each of the parameters, a division into intervals was selected and the number of planets for which this parameter falls within the given interval was counted. This data (the number of planets and the value of the interval) is presented in the form of a histogram (the most common way of providing such information). The data do not take into account errors, and the interval step is quite large since this is still an assessment to see if there is any correlation and what it may be associated with.

3. Results

As a result of studying the sample of multiplanetary systems with one host star, several patterns were identified, and graphs were plotted to demonstrate them. In all graphs, either the number of systems or the number of planets is plotted along the vertical axis (depending on whether a specific characteristic of the system as a whole or of an individual planet is analyzed); in each of these options, either all systems, or all planets with known parameters are studied. The horizontal axis shows the range of values corresponding to the characteristic under consideration. The constructed histograms give the distribution of systems or exoplanets according to the selected characteristic.

3.1 The Number of Multiplanetary Systems Depending on the Spectral Class of the Host Star

The number of multiplanetary systems was considered depending on the spectral type of the host star. It turned out that a larger number of such systems were found for stars of types G, K, F and M and fewer around stars of type A (see Figure 1).

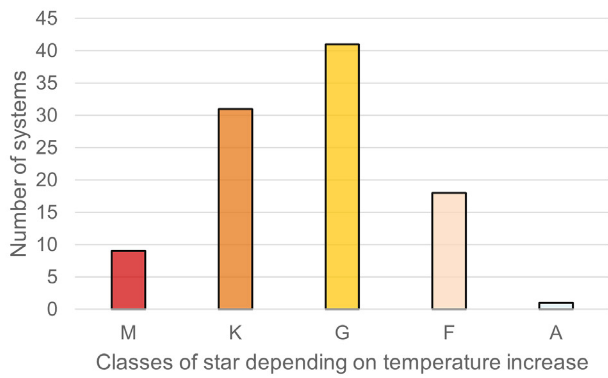

Figure 1. Distribution of the number of multiplanetary systems depending on the class of their host stars. Star classes are arranged in order of increasing temperature (from left to right).

Among the spectral classes of stars with multiplanetary systems, the fewest such systems are found around A-class stars. Although M-class stars are most common in space, there are small number of multiplanetary systems around them. Most systems are found around G-class stars. A little bit less possesses K class stars, they are orange with temperature 3500–5000 K. The largest number of stars visible to the naked eye are K class stars. K and M class stars are cold.

Thus, the number of multiplanetary systems is smallest for the hottest and most massive stars (luminosity increases with increasing effective temperature, size, and mass of the star). According to modern concepts, the accretion disk is formed predominantly near stars of late spectral classes [16], probably for this reason there are more exoplanets near them.

3.2 Analysis of the Type of Exoplanets in Multiplanetary Systems

Exoplanets are classified into different types based on size and mass. Basically, planets are divided into *gas giants*, *neptunes*, *super-earths* and *terrestrial* ones[3]. Each type of planet varies in internal and external appearance depending on its composition. Gas giants are massive planets primarily consisting of helium and hydrogen. These planets are like Jupiter and Saturn in the Solar system, they do not have a solid surface, most of them are composed of gas, and there is a small solid core inside, so the density of such planets is low. Gas giants can be much larger than Jupiter and located much closer to their stars than the planets in the Solar system. In addition, gas giants are divided into "*cold Jupiters*" and "*hot Jupiters*" depending on their distance from the star[4].

Neptunes are similar in size to Neptune or Uranus in the Solar system. Neptunes typically have an atmosphere dominated by hydrogen and helium, and a core made of rocks and heavier metals. Mini-Neptunes are also being discovered, they are planets smaller than Neptune and larger than Earth (there are no such planets in the Solar system). Neptunes often have thick clouds that block any light, thereby hiding the molecules of various substances in the atmosphere[5].

Super-earths are a class of planets unlike any other in the Solar system—they are more massive than Earth but lighter than ice giants such as Neptune and Uranus. They may consist of gas, rocks, or a combination of both. Super-earth is a classification based only on the exoplanet's size larger than Earth and smaller than Neptune but does not imply that they are necessarily like our planet. The true nature of these planets remains uncertain because there is nothing similar in the Solar system, yet they are common among planets found around extrasolar stars[6].

In the Solar system, Earth, Mars, Mercury and Venus are terrestrial planets or rocky planets. Outside the Solar system, exoplanets half the size of Earth and up to twice its radius are considered to be rocky (smaller planets can also be rocky). Exoplanets twice the size of Earth or more can also be rocky, but they are called super-earths. Terrestrial planets are worlds composed of rocks, silicates, iron, water, and carbon. Rocky planets can have a solid or liquid surface, as well as a gaseous atmosphere[7].

The types were considered for exoplanets of each multi-planet system. The type of planets was determined from catalogue[7], where it is indicated. Super-earths and neptunes are more often found in multiplanetary systems, as can be seen from the histogram in Figure 2. The rarest type in such systems were terrestrial planets. This may be explained by the fact that the larger the planet, the easier it is to detect it by transit and radial velocity methods, both noted in Table A1 (Appendix A), and since terrestrial planets have the smallest radius, fewer of them are discovered. In Figure 2 for gas giants there is a decline again, which indicates their smaller number in multiplanetary systems. The type with the largest number of planets is super-earth, totalling 99, accounting for about 44% of all examined exoplanets.

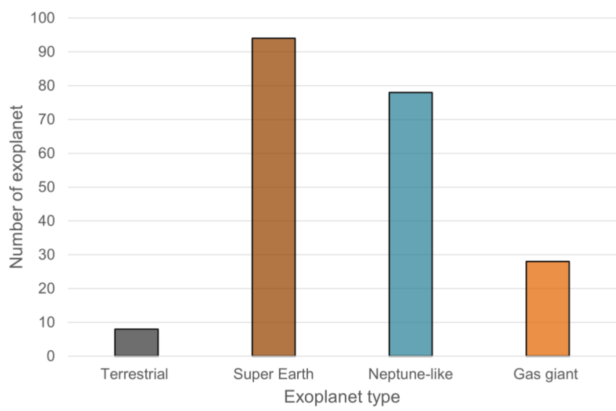

Figure 2. Distribution of exoplanets in multiplanetary systems by type.

Analysis by planet type showed that super-earths and Neptune-like ones are more often located in systems, accounting for 81.9% of all planets considered. The fewest terrestrials are 3.8% of all planets. The most common are super-earths—44.7%, Neptune-like 37.1%, and gas giants 13.3%.

3 http://exoplanets.nasa.gov/what-is-an-exoplanet/planet-types/overview/#:~:text=So%20far%20scientists%20have%20categorized,% 2C%20super%2DEarth%20and%20terrestrial

4 https://exoplanets.nasa.gov/what-is-an-exoplanet/planet-types/gas-giant/

5 https://exoplanets.nasa.gov/what-is-an-exoplanet/planet-types/neptune-like/

6 https://exoplanets.nasa.gov/what-is-an-exoplanet/planet-types/super-earth/

7 https://exoplanets.nasa.gov/what-is-an-exoplanet/planet-types/terrestrial/

3.3 Distribution by the Number of Exoplanets in the System

The distribution by the number of planets in a system shows that systems with many exoplanets are less common than those with a small number. There are 52 systems with two planets, 27 with three, and 15 with four, only 8 systems have a larger number of exoplanets. For comparison, there are 8 planets in the Solar system, which is quite rare for multiplanetary systems, and not a single such system was included in the sample. The system with the largest number of exoplanets in this sample is TRAPPIST-1 (7 planets)—four super-earths and three terrestrial planets around a M-class star.

This distribution may be because systems with fewer planets are easier to detect and confirm. One of the main methods of detecting exoplanets is transit, which is based on the decrease in the brightness of a star as an exoplanet passes between its host star and an observer on Earth or a spacecraft. To confirm the existence of an exoplanet, this drop in brightness must be periodic.

Pichierri et al. [17] showed a similar diagram (Figure 1a) based on the NASA Exoplanet Archive. The tendency is the same: most multiplanetary systems have 2 exoplanets and their number decreases with increasing the number of planets in the system. The maximum number of planets in the system presented in reference [17] is 6, while in Figure 3 it is 7. However, Pichierri et al. [17] did not consider only systems with one central star. The fact that there are more systems with two planets is explained not only by the peculiarities of observations but also by the possible greater stability of systems with fewer planets.

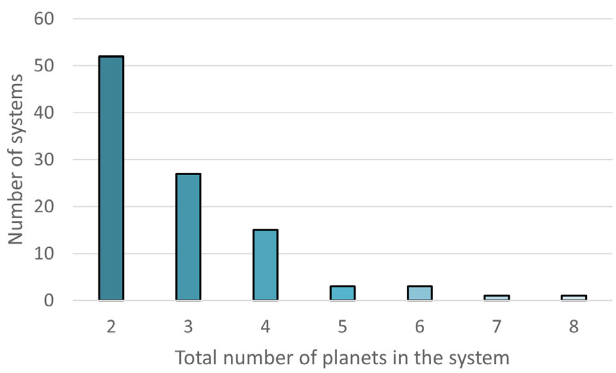

Figure 3. Distribution of multiplanetary systems by the number of planets in the system.

3.4 Distribution of Exoplanets by Mass in Multiplanetary Systems

In multiplanetary systems, the mass distribution of exoplanets was obtained (Figure 4). In general, systems contain both low-mass terrestrial, super-earths and gas giants, including those, whose mass is greater than the mass of Jupiter M_J ($M_J = 2 \times 10^{27}$ kg). In multiplanetary systems, most exoplanets are mass from 1 to 20 M_e (Figure 4), which may be a consequence of the peculiarities of the formation of systems with several exoplanets ($M_e = 6 \times 10^{24}$ kg is the Earth's mass).

From Figure 4a it follows that the masses of most planets are less than approximately 300 Earth mass, which is on the order of the mass of Jupiter (~318 M_e); therefore, most giant planets in multiplanetary systems have masses from ~20–30 to 300 Earth masses, i.e. less than the mass of Jupiter (20–30 M_e is the lower limit of giant planets according to some models [18]. Thus, most gas giants have small masses, which may be associated with a smaller amount of matter that went into their formation in multiplanetary systems. In systems with only one planet, all or a significant portion of the matter may be expended to form a single planet of large mass. If several exoplanets are formed in the system, then the matter is divided between them, and there is less of it left to form one planet, which prevents the formation of massive gas giants in most cases.

Figure 4a shows the distribution by mass for all examined planets. Distribution in Figure 4b corresponds to terrestrial planets, super-earths and Neptunes (up to approximately the size of Neptune). The distribution shows that there are some maximum and minimum in the number of exoplanets of different masses. In addition to two maxima in the distribution for the ranges from 1 to 2.5 M_e and from 3.5 to 6 M_e (these two ranges are mentioned above, but in Figure 4b the distribution is visible in more detail due to the smaller range intervals), the minimum corresponding to the range from 2.5 to 3.5 M_e is visible which corresponds to planets that could be super-earths and mini-neptunes. This is a certain intermediate mass interval in which the minimum may be due to the peculiarities of the formation of such "intermediate" planets in multiplanetary systems. The second minimum in the distribution ranges from 10.5 to 11 M_e and from 11.5 to 12 M_e, followed by a prominent maximum from 11 to 11.5 M_e and from 12.5 to 13 M_e, which is perhaps the characteristic size for Neptunes forming in multiplanetary systems.

3.5 Distribution of Exoplanets by Radius in Multiplanetary Systems

Like the distribution by masses, the distribution by radii of exoplanets was obtained. In Figure 5a, the distribution by radius for all considered exoplanets is shown. It was interesting to see what the "Fulton gap" (Radius Gap, photoevaporation valley, or sub-Neptune Desert) looks like in the number of exoplanets from 1.5 to 2 R_e in multi-planetary systems (R_e is the Earth's radius) [19].

In Figure 5b, the "Fulton Gap" (Radius Gap) range is constructed in detail for exoplanet radii from 1 to 2 R_e, in which a small number of exoplanets are detected compared to planets with radii less than 1.5 and greater than 2 R_e [19]. From Figure 5b it can be seen that there are planets in the range from 1.6 to 1.8 and from 1.9 to 2 R_e, but there are fewer of them than exoplanets in neighboring radius ranges. The Fulton dip range is from 1.5 to 2 R_e. It is also clear that the interval from 2.2 to 2.4 R_e contains more than two times fewer exoplanets than the neighboring intervals, thus, a second "failure" in multiplanetary systems is observed. From Figure 5c it can be seen that, mainly, planets of small radii from 1.1 to 2.9 R_e are observed in multi-planet systems.

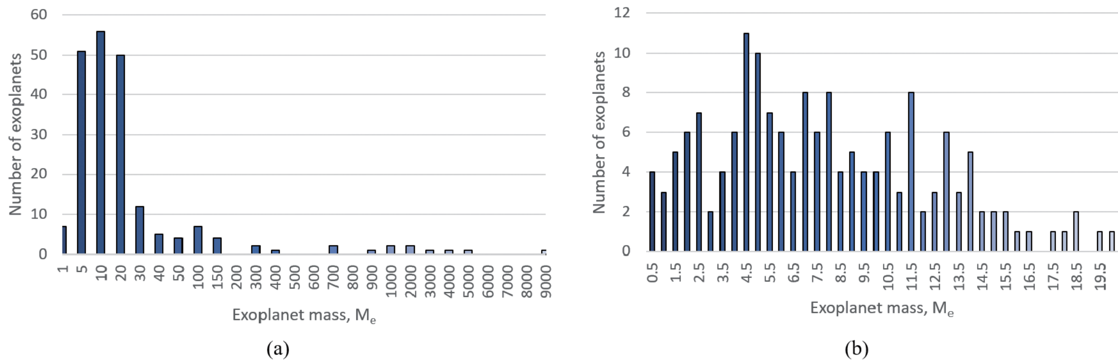

Figure 4. Distribution of planets by mass: (**a**) for all considered exoplanets; (**b**) for planets with a mass less than 20 M_e.

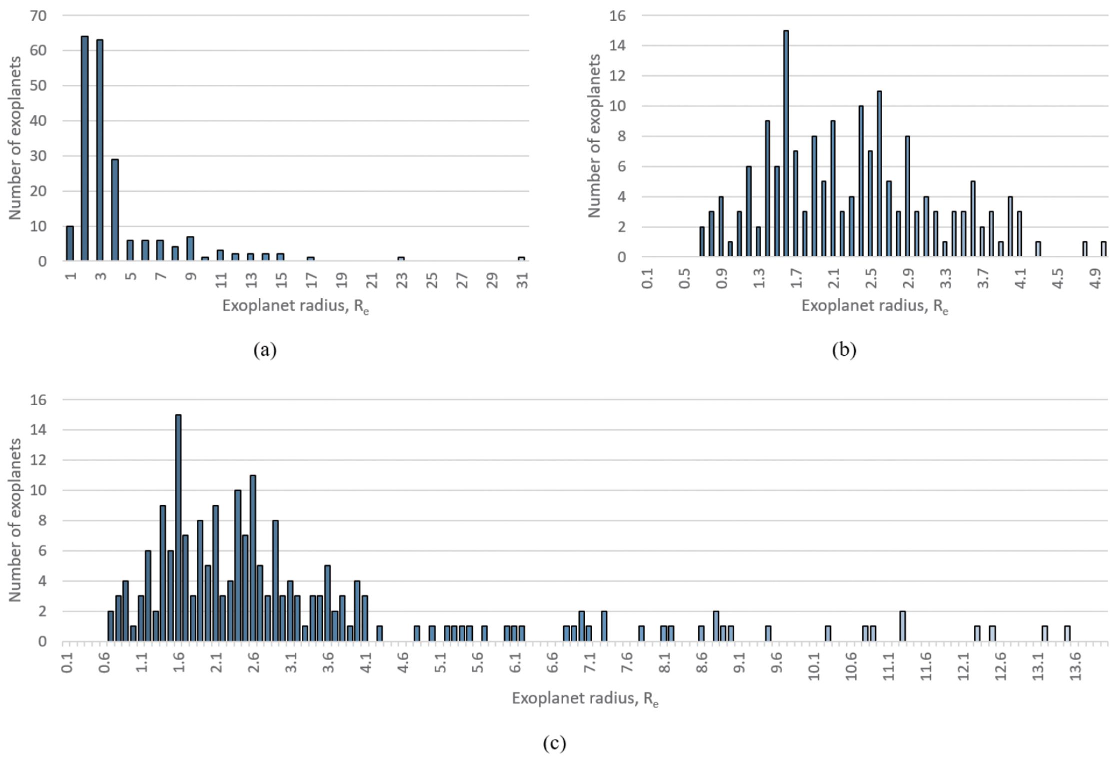

Figure 5. Distribution of exoplanets by radius: (**a**) for all considered exoplanets (the radial step is equal to 1 Earth's radius, R_e, which gives the general appearance of the distribution); (**b**) for exoplanets in the range close to the "Fulton gap" (the range of radii is from 0.1 to 5 R_e, in increments of 0.1 R_e, which allows seeing the features of the distribution); (**c**) radius for exoplanets in the range from 0.1 to 14 R_e (the distribution step is 0.1 R_e, which allows seeing in more detail).

3.6 Distribution of Exoplanets by Orbital Radii

Regardless of the type of host star, the discovered exoplanets are mainly located in orbits with a small radius, as can be seen in Figure 6.

At distances greater than 0.5 AU single planets are located. Basically, exoplanets are located at tenths of an AU, as can be seen from Figure 6b. Moreover, the largest number of planets (112) is in the interval from 0.01 to 0.13 AU This distribution applies both to systems with planets of only one type, and to systems in which several types of exoplanets are located. Also in this distribution, exoplanets have different classes of host stars. The close location of exoplanets in multiplanetary systems to their host stars does not depend on the type of exoplanet or the class of the host star. This may be partly because planets at small orbital radii are easier to detect. Or it may be caused by the peculiarities of the formation of exoplanets in multiplanetary systems. From Figure 6a and 6b it also follows that for very small masses and/or radii of exoplanets, as well as for very large orbital distances, the determination of exoplanets is difficult, and may affect the results of the analysis.

A comparison with the Solar system, in which the distance to Earth is 1 AU, shows that only two planets are located closer to the Sun - Mercury and Venus, and further away the other 5—Mars, Jupiter, Saturn, Uranus and Neptune. In this regard, the Solar system, as a multiplanetary system, differs from those considered in the sample; it is not characterized by the close position of the planets to the host star.

3.7 Distribution of Exoplanets Depending on Orbital Periods

The exoplanets considered were characterized by short orbital periods (less than 30 days). Moreover, most of the exoplanets have a period of 10–10.5 days (see Figure 7). This may be because planets with short orbital periods (as well as small orbital radii) are easier to detect since exoplanets with short orbital periods have more frequent transits that are easier to observe, allowing for faster planet confirmation. This may also be because more exoplanets probably are born closer to the star than at further distances from it. multiplanetary systems may form in such a way that they are "compressed" towards the host star compared to the Solar system. This can be seen from the obtained distributions over orbital radii and orbital periods. Even gas giants are often found at fractions of an AU, which is not typical for this type of planet, for example, in the Solar system. Other types of exoplanets are also characterized by a close location to the host star. This does not depend either on the class of the host star, on the number of planets in the system, or on their types.

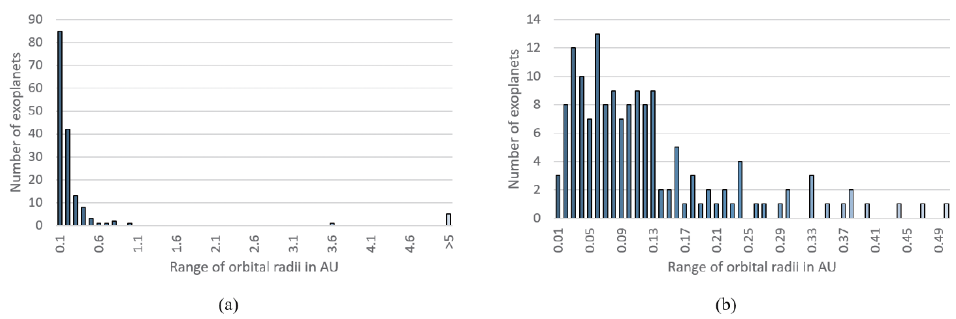

Figure 6. Distribution of exoplanets by orbital radii: (**a**) for all considered planets; (**b**) for the range from 0.005 to 0.5 AU.

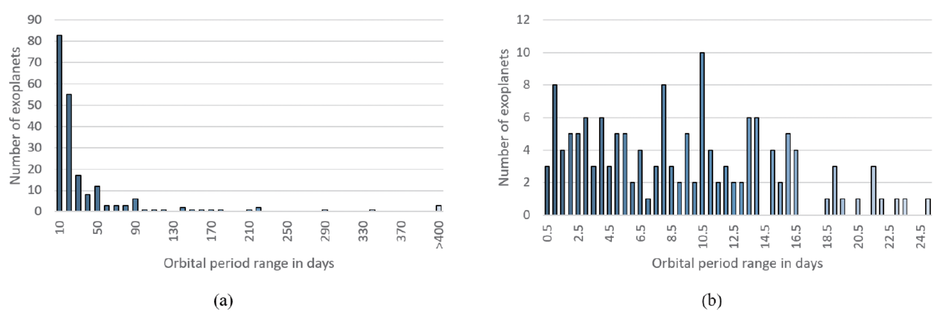

Figure 7. Distribution of exoplanets by orbital periods: (**a**) for all considered planets; (**b**) for the range from 0.05 to 25 days.

4. Discussion and Conclusions

Zhu and Dong [14] stated that there are inner and outer exoplanets in multiplanetary systems and found correlations between them. Nasralla [20] described several theories of planetary formation: from planetesimals, from the core-instability model beyond the ice-line, or from alternative the disk's gravitational instability in a case when the gravitational energy is larger than the rotational and thermal energy. In the outer disk the pebble-accretion theory is suggested. There are different regimes of planet migration. However, Pichierri [17] stated: "We still do not know with enough accuracy the final configuration obtained by multi-systems migrating in a disc of gas."

The characteristics of 100 multiplanetary systems with single central stars of different spectral classes were examined. For 293 planets from these systems masses, radii, orbital radii, orbital periods, and types of exoplanets were analyzed.

The number of planets in each system included in the sample was considered. The number of systems with the same class of host star was analyzed. A larger number of multiplanetary systems were discovered around stars of classes G, K, F, and a smaller number for stars of classes M, A.

Analysis by planet type showed that super-earths and Neptune-like ones are more often located in systems, accounting for 81.9% of all planets considered. The fewest terrestrials are 3.8% of all planet. The most common are super-earths –44.7%. Neptune-like 37.1%, and gas giants 13.3%.

The prevalence of exoplanet types was considered for each multi-planet system. The rarest type in such systems were terrestrial planets and after them the gas giants. Most of the exoplanets belonged to the type of super-earths.

The distribution of the number of planets in a system showed that systems with many exoplanets are less common than those with a smaller number. There are 52 systems with two planets, 27 with three, 15 with four, and only 8 systems with many planets. The system with the largest number of exoplanets in this sample is TRAPPIST-1 (7 planets) were there are four super-earths and three rocky planets around an M-class star.

In multiplanetary systems, the mass distribution of exoplanets was obtained. In general, systems contained both low-mass rocky super-earths and gas giants with a mass greater than the mass of Jupiter. In multiplanetary systems, most exoplanets are with mass from 1 to 2.5, and from 3.5 to 6 M_e, which may be a consequence of the peculiarities of the formation of systems with several exoplanets. Most gas giants have masses less than Jupiter's mass, which can be associated with a smaller amount of matter that was used for their formation in multiplanetary systems.

Exoplanets in multiplanetary systems were mainly of radii from 1.1 to 2.9 R_e. The planets with radii from 1.6 to 1.8 and from 1.9 to 2 R_e were less than exoplanets in neighboring radius ranges. (The Fulton gap range is from 1.5 to 2 R_e). As we showed here, the interval from 2.2 to 2.4 R_e contains more than two times fewer exoplanets than the neighboring intervals. Regardless of the type of host star, the discovered exoplanets were mainly located in orbits with a small radius. At distances greater than 0.5 AU there were single planets. Basically, exoplanets were discovered at tenths of an AU. Moreover, the largest number of planets (151) is in the interval from 0.01 to 0.5 AU. This distribution applies to both terrestrial and giant planets.

Accordingly, the exoplanets considered were characterized by short orbital periods (less than 30 days). Moreover, most such exoplanets have a period of 10–10.5 days. It is possible that multiplanetary systems form in such a way that they are "compressed" towards the host star. This can be seen from the obtained distributions over orbital radii and orbital periods. Even gas giants are often located at a fraction of an AU away.

For comparison, the Solar system is a system of eight planets around a G type star. There are no such number of planets among the multiplanetary systems considered in this work. Multiplanetary systems around G-class stars are common. There are three types of planets in the Solar system—terrestrial planets, Neptunes and gas giants. The distance to Earth in the Solar system is one astronomical unit, only Mercury and Venus are closer, and the other planets are further away. In the systems considered, exoplanets are generally located much closer to the host star at distances of fractions of astronomical units. The orbital periods of the exoplanets in the sample are significantly shorter than the periods of planets in the Solar system. Multiplanetary systems are characterized by periods of several days, and for the Solar system the minimum orbital period of Mercury is 88 days. Thus, the Solar system occurred to be not typical for the considered multi-planet systems.

Author Contributions

Conceptualization, Elza Buslaeva; methodology, Elza Buslaeva; formal analysis, Elza Buslaeva; investigation, Elza Buslaeva and Elena Belenkaya; writing - original draft preparation, Elza Buslaeva and Elena Belenkaya; supervision, Elena Belenkaya; project administration, Elena Belenkaya. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Acknowledgments

We would like to thank the anonymous reviewers as well as the editors for their constructive and helpful comments that led to the improvement of this article.

Data Availability Statement

Data are available in a publicly accessible repository that does not issue DOIs. Publicly available datasets were analyzed in this study. This data can be found here:

(1) https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=PS

(2) https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

Conflict of Interest

The authors disclosed no conflict of interest.

References

[1] Otegi, J.F., Dorn, C., Helled, R., et al., 2020. Impact of the measured parameters of exoplanets on the inferred internal structure. Astronomy & Astrophysics. 640, A135.
DOI: https://doi.org/10.1051/0004-6361/202038006

[2] Martínez, R.R., Martin, D.V., Gaudi, B.S., et al., 2023. A comparison of the composition of planets in single-planet and multiplanet systems orbiting M dwarfs. The Astronomical Journal. 166(4), 137.
DOI: https://doi.org/10.3847/1538-3881/aced9a

[3] Fatheddin, H., Sajadian, S., 2023. Detecting multiplanetary systems with gravitational microlensing and the roman space telescope. The Astronomical Journal. 166, 140.
DOI: https://doi.org/10.3847/1538-3881/aced8b

[4] Udry, S., Santos, N.C., 2007. Statistical properties of exoplanets. Annual Review of Astronomy and Astrophysics. 45, 397–439.
DOI: https://doi.org/10.1146/annurev.astro.45.051806.110529

[5] On the Question of Gravitational Instability of the Protoplanetary Disk of the Sun. Part I. Statement of the Problem. Preprint, Inst. Appl. Math. [Internet] [cited 2024 Jan 20]. Available from: https://library.keldysh.ru/preprint.asp?id=2014-34 (in Russian).

[6] Some Models of Proto-Planet Disk of the Sun at an Initial Stage of it Evolution. Preprint, Inst. Appl. Math., The Russian Academy of Science [Internet] [cited 2024 Jan 20]. Available from: https://www.keldysh.ru/papers/2006/prep70/prep2006_70.html (in Russian).

[7] Belenkaya, E., Khodachenko, M., 2012. Accreation and current disks controlled by strong magnetic field. International Journal of Astronomy and Astrophysics. 2, 81–96.
DOI: https://doi.org/10.4236/ijaa.2012.22012

[8] Williams, J.P., Cieza, L.A., 2011. Protoplanetary disks and their evolution. Annual Review of Astronomy and Astrophysics. 49, 67–117.
DOI: https://doi.org/10.1146/annurev-astro-081710-102548

[9] Bartram, P., 2021. Pushing the envelope of exoplanet evolution modelling [Ph.D. thesis]. Southampton: University of Southampton. Available from: https://eprints.soton.ac.uk/456719/1/PeterBartram_thesis_unsigned.pdf

[10] Cridland, A.J., Rosotti, G.P., Tabone, B., et al., 2022. Early planet formation in embedded protostellar disks disks-Setting the stage for the first generation of planetesimals. Astronomy and Astrophysics. 662, A90.
DOI: https://doi.org/10.1051/0004-6361/202142207

[11] Heller, R., 2019. Formation of hot Jupiters through disk migration and evolving stellar tides. Astronomy and Astrophysics. 628, A42.
DOI: https://doi.org/10.1051/0004-6361/201833486

[12] Dawson, R.I., Johnson, J.A., 2018. Origins of hot Jupiters. Annual Review of Astronomy and Astrophysics. 56, 175–221.
DOI: https://doi.org/10.1146/annurev-astro-081817-051853

[13] Winn, J.N., Fabrycky, D.C., 2015. The occurrence and architecture of exoplanetary systems. Annual Review of Astronomy and Astrophysics. 53, 409–447.
DOI: https://doi.org/10.1146/annurev-astro-082214-122246

[14] Zhu, W., Dong, S., 2021. Exoplanet statistics and theoretical implications. Annual Review of Astronomy and Astrophysics. 59, 291–336.
DOI: https://doi.org/10.1146/annurev-astro-112420-020055

[15] Wright, J., Upadhyay, S., Marcy, G., et al., 2009. Ten

new and updated multiplanet systems and a survey of exoplanetary systems. The Astrophysical Journal. 693,1084.
DOI: https://doi.org/10.1088/0004-637X/693/2/1084

[16] Marov, M.Y., Ipatov, S.I., 2023. Migration processes in the Solar System and their role in the evolution of the Earth and planets. Physics Uspekhi. 66, 2–31.
DOI: https://doi.org/10.3367/UFNe.2021.08.039044

[17] Pichierri, G., Batygin, K., Morbidelli, A., 2019. The role of dissipative evolution for three-planet, near-resonant extrasolar systems. Astronomy and Astrophysics. 625, A7
DOI: https://doi.org/10.1051/0004-6361/201935259

[18] Helled, R., 2023. The mass of gas giant planets: Is Saturn a failed gas giant? Astronomy and Astrophysics. 675, L8.
DOI: https://doi.org/10.1051/0004-6361/202346850

[19] Fulton, B.J., Erik, A.P., 2018. The California-Kepler survey. VII. Precise planet radii leveraging Gaia DR2 reveal the stellar mass dependence of the planet radius gap. The Astronomical Journal. 156, 264.
DOI: https://doi.org/10.3847/1538-3881/aae828

[20] Nasralla, M., 2020. Fundamental properties and evolution of exoplanets and their host stars [Master's thesis]. Manchester: The University of Manchester.

Appendix A

Table A1. Some characteristics of multiplanetary systems used in the work.

Multiplanetary System	Star Class	Total Number of Exoplanets	Distance to Solar System in PC	Discovery Method	Discovery Year
Kepler-51	F	3	783,831	Transit	2012
Kepler-102	K	5	107,796	Transit	2013
WASP-47	G	4	264,78	Transit	2015
Kepler-595	K	2	643,009	Transit	2020
Kepler-406	G	2	364,03	Transit	2014
HD 137496	G	2	155,317	Transit	2021
TOI-2134	K	2	22,6202	Transit	2023
KOI-3503	F	2	887,064	Transit	2021
Kepler-100	G	4	304,645	Transit	2014
K2-138	G	6	202,585	Transit	2017
Kepler-107	G	4	525,997	Transit	2014
EPIC 220674823	G	2	244,59	Transit	2016
Kepler-462	A	2	596,625	Transit	2016
Kepler-11	G	6	646,346	Transit	2010
Kepler-450	F	3	455,982	Transit	2015
KOI-55	B	2	1231,02	Orbital Brightness Modulation	2011
K2-3	M	3	44,0727	Transit	2015
Kepler-50	F	2	250,11	Transit	2012
Kepler-30	G	3	914,221	Transit	2012
Kepler-36	F	2	527,956	Transit	2012
TOI-4010	K	4	177,504	Transit	2023
HD 3167	K	4	47,2899	Transit	2016
Kepler-56	K	3	912,994	Transit	2012
Kepler-53	G	3	1366,07	Transit	2012
TOI-1260	K	3	73,5977	Transit	2021
TRAPPIST-1	M	7		Transit	2016
TOI-238	K	2	80,5407	Radial Velocity	2024
Kepler-407	G	2	338,368	Transit	2014
HIP 29442	K	3	68,192	Radial Velocity	2023
GJ 806	M	2	12,0445	Transit	2023
Kepler-109	G	2	474,861	Transit	2014
K2-233	K	3	67,5062	Transit	2018
Kepler-29	G	2	832,532	Transit	2011
Kepler-126	F	3	237,401	Transit	2014
Kepler-94	K	2	191,904	Transit	2014
Kepler-177	G	2	1435,44	Transit	2013
Kepler-139	G	4	391,038	Transit	2014
Kepler-92	G	3	477,992	Transit	2013
Kepler-57	K	2	644,14	Transit	2012
K2-36	K	2	109,749	Transit	2016
TOI-5398	F	2	130,855	Transit	2023
Kepler-9	G	3	628,257	Transit	2010
Kepler-52	K	3	321,542	Transit	2012
TOI-836	K	2	27,5024	Transit	2023

Table A1 continued

Multiplanetary System	Star Class	Total Number of Exoplanets	Distance to Solar System in PC	Discovery Method	Discovery Year
K2-285	K	4	154,961	Transit	2018
Kepler-1972	G	2	287,339	Transit	2014
K2-19	G	3	289,827	Transit	2016
Kepler-113	K	2	262,351	Transit	2014
LP 791-18	M	3	26,4927	Transit	2023
LP 890-9	M	2	32,4298	Transit	2022
Kepler-129	G	3	408,845	Transit	2014
KOI-1783	G	2	865,73	Transit	2020
PDS 70	K	2	113,064	Imaging	2019
Kepler-10	G	3	185,506	Transit	2011
K2-38	G	2	192,69	Transit	2016
Kepler-323	F	2	454,883	Transit	2014
Kepler-18	G	3	433,047	Transit	2011
HD 206893	F	2	40,7583	Imaging	2021
HD 22946	F	3	62,7792	Transit	2022
HD 80653	G	2	109,86	Transit	2020
K2-199	K	2	107,518	Transit	2018
Kepler-65	F	4	303,728	Transit	2012
Kepler-103	F	2	494,832	Transit	2014
TOI-1386	G	2	146,858	Transit	2024
TOI-178	K	6	62,699	Transit	2021
KOI-1599	G	2	1131,64	Transit	2019
EPIC 249893012	G	3	321,296	Transit	2020
TOI-1470	M	2	51,9503	Transit	2023
Kepler-82	G	5	904,326	Transit	2012
Kepler-97	G	2	400,907	Transit	2014
TOI-561	G	4	85,799	Transit	2020
Kepler-131	G	2	228,678	Transit	2014
Kepler-324	K	4	501,574	Transit	2021
Kepler-289	F	3	704,438	Transit	2014
Kepler-418	G	2	1002,53	Transit	2014
GJ 367	M	3	9,41263	Transit	2021
Kepler-138	M	4	66,8624	Transit	2014
KOI-142	G	3	376,863	Transit	2013
Kepler-1514	F	2	397,292	Transit	2016
Kepler-79	F	4	1020,72	Transit	2012
Kepler-58	G	4	969,252	Transit	2012
K2-146	M	2	79,3002	Transit	2018
HR 8799	F	4	41,2441	Imaging	2010
TIC 279401253	G	2	285,584	Transit	2023
Kepler-1513	G	2	349,247	Transit	2016
TOI-544	K	2	41,1166	Transit	2022
CoRoT-24	K	2	591,555	Transit	2014
HD 73583	K	2	31,5666	Transit	2022
Kepler-93	G	2	95,9115	Transit	2014
K2-141	K	2	61,8736	Transit	2018

Table A1 continued

Multiplanetary System	Star Class	Total Number of Exoplanets	Distance to Solar System in PC	Discovery Method	Discovery Year
Kepler-48	K	5	306,738	Transit	2012
CoRoT-7	K	3	159,906	Transit	2009
GJ 9827	K	3	29,661	Transit	2017
Kepler-1705	F	2	1633,49	Transit	2021
K2-111	G	2	200,394	Transit	2017
Kepler-106	G	4	444,322	Transit	2014
Kepler-19	G	3	218,562	Transit	2011
Kepler-968	K	3	290,324	Transit	2021
WASP-84	K	2	100,588	Transit	2023
Kepler-419	F	2	1011,36	Transit	2014
TOI-4600	K	2	216,056	Transit	2023