Occurrence Rate of Super-Earths Around Binary Star Systems

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ABSTRACT

The Planetary Habitability Laboratory at the University of Puerto Rico cataloged 60 exoplanets as habitable, 36 of which are Super-Earths or Mini-Neptunes. According to the Kepler survey, the occurrence rate of super-Earths around Sun-like stars is approximately 30%. This rate is significantly higher in the vicinity of less massive M stars. In addition, binary or higher-order multiple systems are detected in 70% of massive early-type stars, 50%–60% of solar-type stars, and 30%–40% of M-stars. Chemical composition of the exoplanet along with its distance from the stars enables us to draw conclusions about its habitability. Our research seeks to conduct a comprehensive analysis of the occurrence rate of Super-Earths around distinct binary star systems, as well as deduce other correlations with their host stars, in order to learn more about their nature and habitability.

INTRODUCTION

Following the discovery of the first exoplanet in 1988 [1] new technologies and surveys have uncovered numerous more exoplanets. Within these discovered worlds are two categories of planets that do not exist in our solar system, Hot Jupiters, a type of Gas Giant, and Super-Earths. Jupiter-type planets, on the other hand, are very uncommon, with only around 10% of stars housing gas giants [2,3]. A gas giant is a massive planet that is largely made up of helium and/or hydrogen. These planets, like Jupiter and Saturn in our solar system, contain swirling gases atop a solid core rather than hard surfaces. Exoplanets that are gas giants can be considerably larger than Jupiter and far closer to their stars, which is unlike anything witnessed in our solar system [4]. Hot Jupiters are gas giant planets with orbits that last less than ten days. Because of their brief period, Hot Jupiters are indeed very close to their host stars, typically less than 0.1 AU, or one-tenth the distance between the Earth and the Sun [5]. Neptune-like exoplanets are similar in size to our solar system's Neptune or Uranus. Neptunian planets' atmospheres are generally dominated by hydrogen and helium, with cores of rock and heavy metals [6]. Super-Earths are a type of planet that is unlike any other in our solar system. They are larger than Earth but lighter than ice giants like Neptune and Uranus, and they can be formed of gas, rock, or a mix of the two. They range in size from twice the size of Earth to ten times its mass [7]. Statistical models, on the other hand, have found that 33–50% of all stars host super-Earths within a 100-day period [8]. As a result, super-Earths are the most common type of planet [9]. Terrestrial, or rocky, planets in our solar system include Earth, Mars, Mercury, and Venus. Terrestrial planets are those planets that lie between half the size of Earth to a radius that is twice as large as Earth's. Others may be much smaller. Exoplanets twice the size of Earth and greater may also be rocky, although they are referred to as super-Earths [10]. While a handful of binary star systems have been discovered to have exoplanets, those systems are relatively uncommon when compared to single star systems. According to Kepler satellite telescope observations, most single stars of the same kind as the Sun contain many planets, but just one-third of binary stars do, making investigating exoplanets in binary star systems much more intriguing. The term binary was first used for star systems by Sir William Herschel in 1802. He hypothesized that binary stars are held together by their mutual gravitational attraction to one another and that any two stars that are mutually coupled constitute the binary sidereal system [11]. The vast majority of solar-type stars [12] are found in binary systems. In reality, up to 70% of all star systems in our galaxy may not be single-star systems but multi-star systems [13], with Binary Stars being a major component of them. Binary stars, according to the currently accepted definition, are stars that revolve around a common center of mass [14]. The brighter star in the system is referred to as the primary component, while the other is referred to as the secondary component. Planetary orbits around a binary star system can be divided into two main categories: (1) S-Type orbits, which are associated with planets that orbit one of the binary star system's components while the other component acts as a perturbator, and (2) P-Type orbits, which are related to planets that orbit around both components of the binary star system [15]. The planetary formation and its stages after the huge explosion of big bang and completely accepting the nebular hypothesis. This hypothesis is mostly accepted explanation for how the sun and the planets and solar system may have formed. The mostly accepted was “The Big Bang”, that is the universe started out as a hot and dry mass [45].

METHODOLOGY

We acquired data from the NASA Exoplanet Archive [16], NASA Exoplanet Catalog [17], The Extrasolar Planets Encyclopaedia [18], Catalogue of Exoplanets in Binary Star Systems [19], Open Exoplanet Catalogue [20], and ExoKyoto [21]. To avoid mistakes, data from these databases were collected and cross-matched. We gathered all available information on 315 Binary Star Systems with 428 exoplanets from these databases.

Our primary objective is to determine the rate of occurrence of Super-Earths in Binary Star Systems. In addition, we graphically evaluate data on exoplanets in Binary Star Systems in general and draw crucial findings and inferences, with an emphasis on Super-Earths. Our paper is divided into three primary sections. The first part examines various occurrence rates, such as Super Earth occurrence rates in Binary Star Systems and observations on eccentricity, orbital radius, and time-period. In the second section, we present graphs linked to the stellar type of the host star in Binary Star Systems, and in the third section, we look at the relationships between exoplanets and their habitability in Binary Star Systems.

OCCURRENCE RATES

A number of initiatives, including radial velocity programs [22], transit discoveries [23], and direct imaging surveys [24, 25], have searched for planets in and around Binary Stars, resulting in the discovery of a number of planets in both S-type and P-type orbit. It has been discovered earlier that more massive host stars are more frequently found in binary configuration, and that planet-containing stars in multiple systems are typically seen to be the most massive component of stellar binaries. According to studies by Bonavita and Desidera, Giant planets were solely found to be populating multiple star systems [26]. About 70% of massive early-type stars [27, 28] and 50%–60% of solar-type stars [29, 30] have been detected in Binary or Multiple Star Systems. Approximately 44% of FGK stars have been found in multiple systems, 33% in binary systems, and 11% in higher-order structures [30]. As a result, about half of prospective planet hosts are in multiple-star systems, implying that the percentage of large planets orbiting a star of a Binary Star System is unlikely to be insignificant [31].

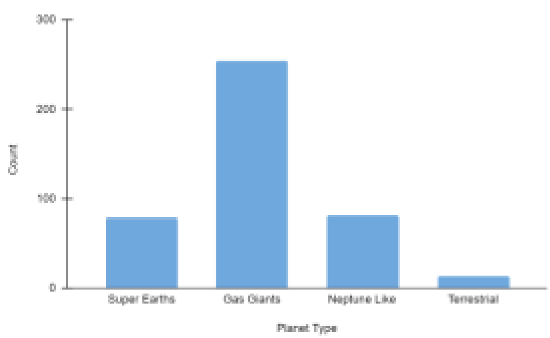


FIGURE 1a. *Number of Planets belonging to each type*

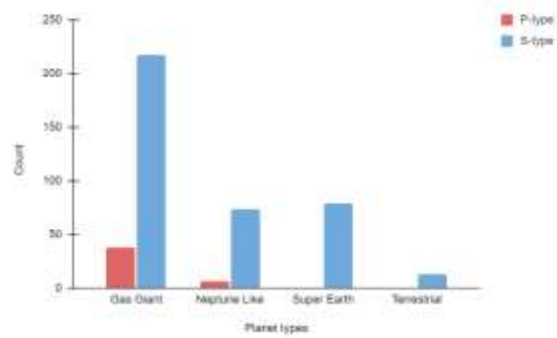


FIGURE 1b. *Number of Planets belonging to each type with orbit type*

Binary Star Systems with one exoplanet have the greatest number of exoplanets, which is much more than the number of exoplanets in systems with more than one exoplanet, which might be owing to the fact that exoplanets become more difficult to detect the farther they are from their host star. The proportion of Gas Giants in systems with one exoplanet is ~75.8%, which is much greater than the proportion of any other planet type.

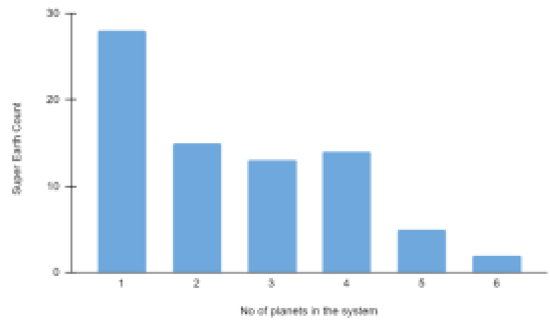


FIGURE 5. *Number of Super Earths versus the number of exoplanets in a Binary Star System*

Binary Star Systems with one exoplanet has the greatest number of Super-Earths. The fraction of Super-Earths remains nearly constant in Binary Star Systems with two, three, and four exoplanets, and it reduces drastically in systems with more than four exoplanets.

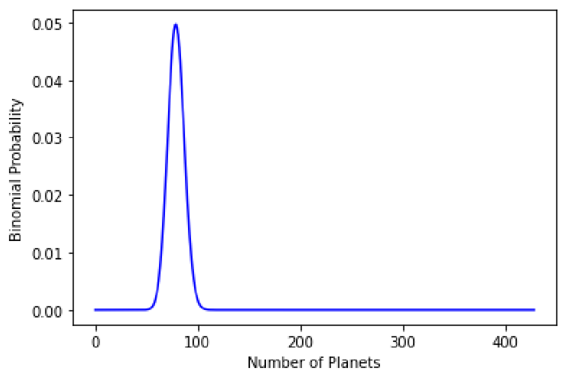


FIGURE 6a. *Probability of Super-Earths with 18.4579% occurrence rate among 428 planets*

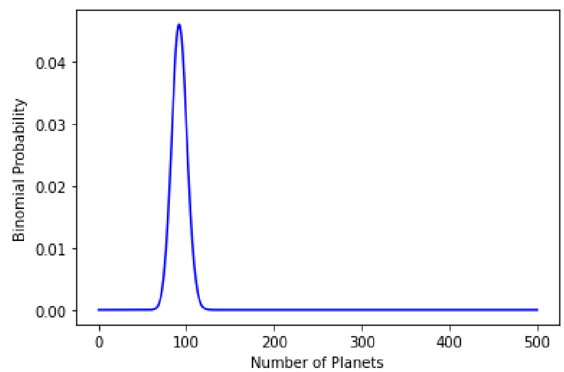


FIGURE 6c. *Probability of Super-Earths with 18.4579% occurrence rate among 500 planets*

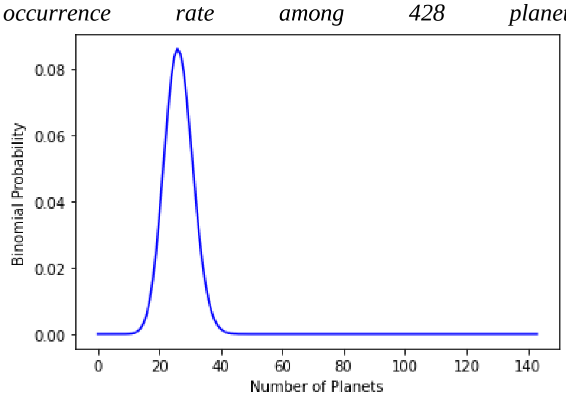


FIGURE 6b. *Probability of Super-Earths with 18.4579% occurrence rate among 143 planets.*

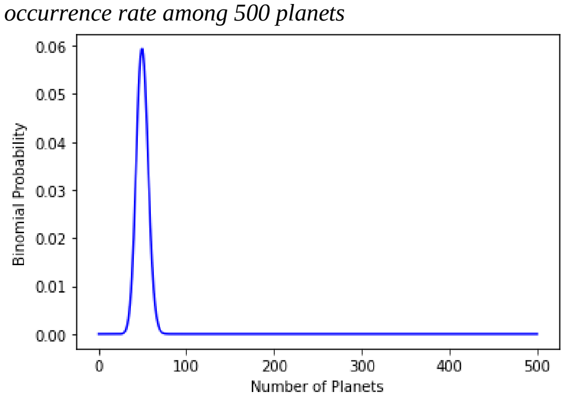


FIGURE 6d. *Probability of Super-Earths with 10% occurrence rate among 500 planets*

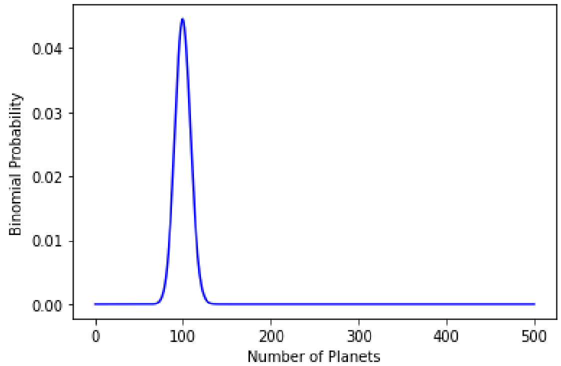


FIGURE 6e. *Probability of Super-Earths with 20% occurrence rate among 500 planets*

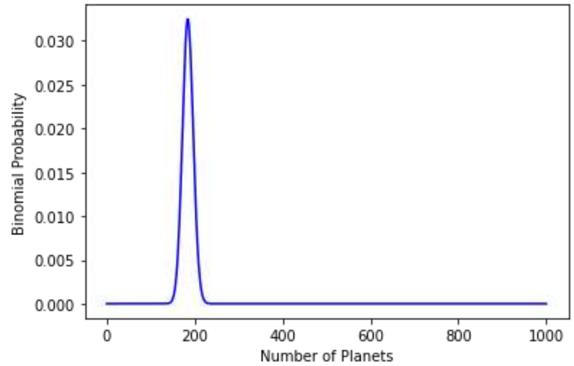


FIGURE 6g. *Probability of Super-Earths with 18.4579% occurrence rate among 1000 planets*

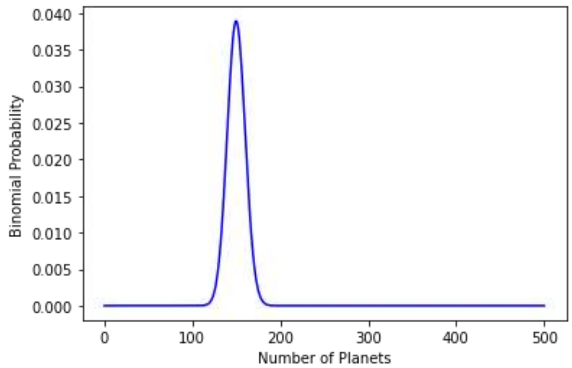


FIGURE 6f. *Probability of Super-Earths with 30% occurrence rate among 500 planets*

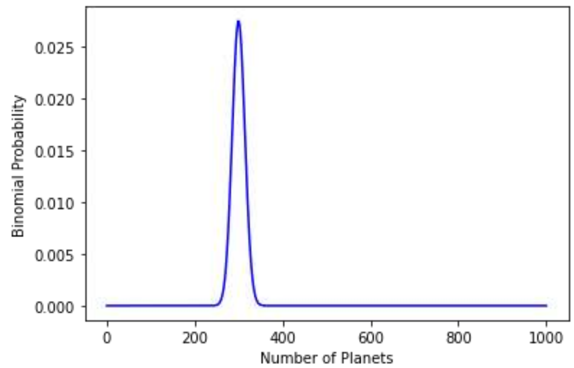
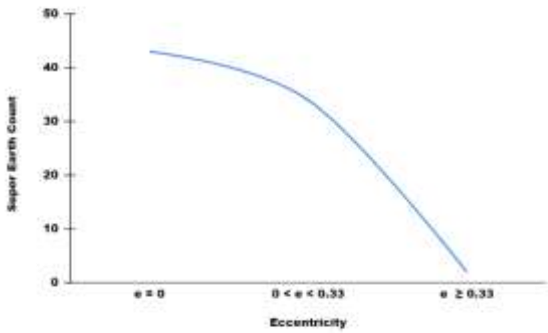


FIGURE 6h. *Probability of Super-Earths with 30% occurrence rate among 1000 planets*

We attempted to provide a range of probabilities for the occurrence rate of Super-Earths in Binary Star Systems from FIGURE 6a to FIGURE 6h. The occurrence rate of Super-Earths is 18.4579% based on data from TABLE I., which comprises 428 exoplanets. If we take an occurrence rate of 18.4579 percent, the probability of 79 Super-Earths in 428 exoplanets in Binary Star Systems is 0.049651049893918296. (FIGURE 6a.). Astronomers had discovered 143 planets around Binary Stars as of July 2019. When the number of Super-Earths in that system is 26, we discover that the maximum probability of occurrence of Super-Earths in that sample is 0.0858956524391321 when the occurrence rate is the same (FIGURE 6b.) From FIGURE 6c through FIGURE 6f, we attempted to model future possibilities by assuming a total of 500 exoplanets in Binary Star Systems. Using the same occurrence rate, we find a maximum probability of 0.04597470731947923 when the number of Super-Earths is 92 in FIGURE 6c. In FIGURES 6d, 6e, and 6f, we investigate occurrence rates of 10%, 20%, and 30%, respectively, and find that the probability of occurrence is highest (0.05937067027042826) when the occurrence rate is 10% and decreases as the occurrence rate increases. We modeled the situation when there are 1000 exoplanets in FIGURES 6g and 6h. If the occurrence rate is 18.4579%, the number of Super-Earths with a maximum probability of 0.032506216914481786 is projected to be 184. The greatest probability is 0.02752100382127235 if the incidence rate is 30%. In FIGURES 6f. and 6h., we used a 30% occurrence rate since, as of 2020, 30% of the 4000 exoplanets found by the Kepler Space Telescope are Super-Earths [36].



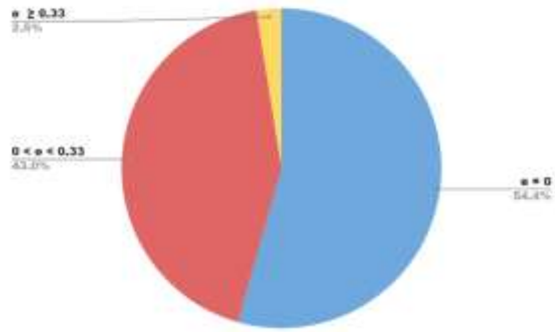
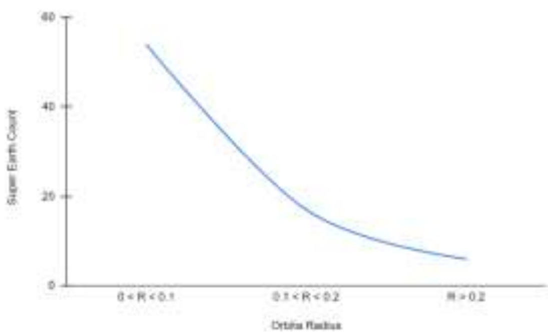


FIGURE 7a. *Number of Super Earths versus eccentricity* ***FIGURE 7b.*** *Number of Super Earths versus eccentricity*

Approximately 54.4% of Super-Earths observed in binary star systems have an orbital eccentricity of zero, indicating that their orbits are totally circular. A circular orbit implies that the planet will have more or less constant climatic conditions throughout the year because the planet is equidistant from its star. It should be emphasized that this is an unusual event, as most exoplanets rotate in an elliptical orbit around their star. In the binary system, the eccentricity range of 43.0% of the Super-Earth populations is 0 - 0.33. Only 2.5% of Super-Earths have eccentricities larger than 0.33. As a result, only a very tiny fraction of Super-Earths has elongated orbits.



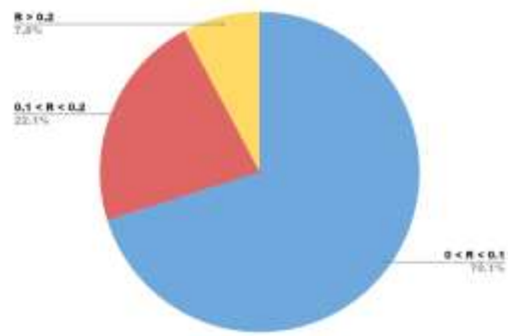
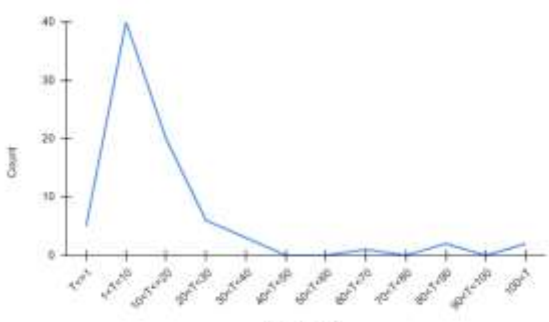


FIGURE 8a. *Number of Super Earths versus orbital radius (in AU)*

FIGURE 8b. *Number of Super Earths versus orbital radius (in AU)*

Almost ~70.1% of all the Super-Earths found in Binary Star Systems are observed to have an orbital radius of 0 - 0.1 AU.



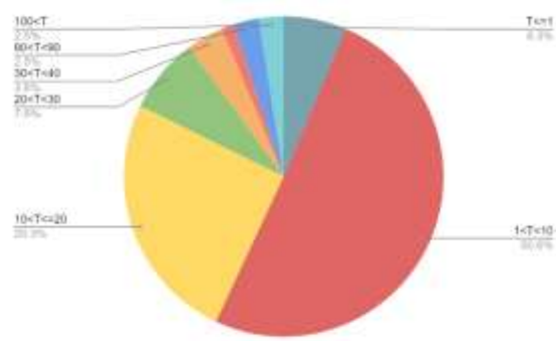


FIGURE 9a. *Number of Super Earths versus orbital period (in days)*

FIGURE 9b. *Number of Super Earths versus orbital period (in days)*

A major proportion of Super-Earths (~50.6%) have orbital periods ranging from one to ten days. Around 25.3164% of Super-Earths have orbital periods ranging from ten to twenty days, and the frequency of Super-Earths with longer orbital periods reduces significantly after that.
Considering the Figures from FIGURE 7a. to FIGURE 9b., it is possible to conclude that most Super-Earths in Binary Star Systems revolve in circular or near-circular orbits relatively close to their Host Star. Because they are near to their Host Star, there are fewer gravitational disturbances, which may explain why most Super-Earths in Binary Star Systems have circular orbits.

BINARY STELLAR TYPES AND PLANETS

Angelo Secchi, an Italian astronomer, identified four major spectral types of stars in the 1860s. During the creation of the Henry Draper Catalogue of stars at Harvard College Observatory in the 1880s, more kinds were differentiated and were assigned by letter in alphabetical sequence based on the intensity of their hydrogen spectral lines. The kinds were reorganized in a nonalphabetic sequence as the investigation continued to put them in order by surface temperature. The stellar kinds are listed in the following order, from hot to cool; O, B, A, F, G, K, M [37].

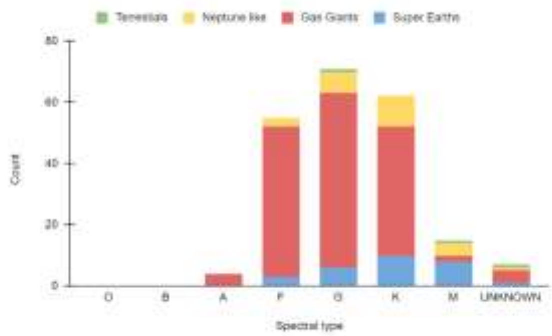


FIGURE 10. *Number of exoplanets with host star of each spectral type with planet type*

The majority of Binary Star Systems with only one exoplanet have Spectral Type G, which is consistent with the findings of Quintana [12]. According to NASA, the proportion of K-type stars is 13% [38], yet according to FIGURE 10, the percentage of K-type Host stars of exoplanets in Binary Star Systems with just one exoplanet is 28.9719%. While Gas Giants are found to be the sole residents in the vicinity of A spectral type Host Stars, they are substantially less prominent in the vicinity of M-type stars. M-type stars, as seen in FIGURE 10., are mostly populated by Super-Earths. It has been shown that F-type stars have the same number of Super-Earths and Neptune-like planets. A similar phenomenon is observed with K-type stars.

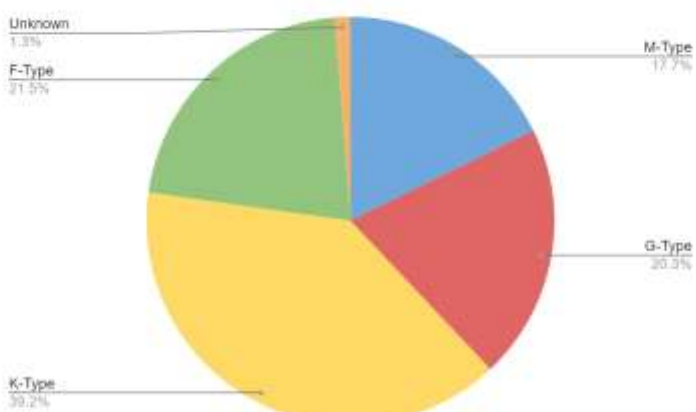


FIGURE 11. *Number of Super-Earths with host star of each spectral type*

According to FIGURE 11, most Super-Earths in Binary Star Systems are most noticeably found around K-type Host

Stars. K-type stars can be found on the main sequence for an extremely long time (18 to 34 billion years, compared to 10 billion for G-type stars like the Sun). [39] They, like M-type stars, have a relatively tiny mass, resulting in an extraordinarily long lifespan with plenty of time to form orbiting Earth-like planets [40], which might explain why the greatest number of Super-Earths have been discovered near K-type stars.

HABITABILITY OF PLANETS IN BINARY STAR SYSTEMS

In general, a circumstellar habitable zone is considered to be the region where the presence of liquid water on the planet's surface is conceivable. [41]. Prior studies on habitability have mainly concentrated on Binary Star Systems which primarily consist of stars of spectral type F, G, K, and M because their lifetimes are long enough to allow the development of life on the planets, or their satellites present in the habitable zone [42].

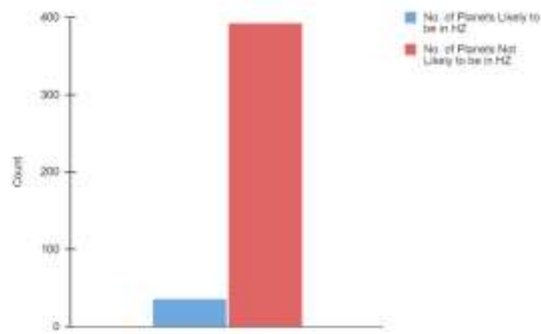


FIGURE 12. *Number of planets likely or not likely to be in the habitable zone*

Only ~8.41% of the planets in Binary Star Systems were found fully or partially in the habitable zone.

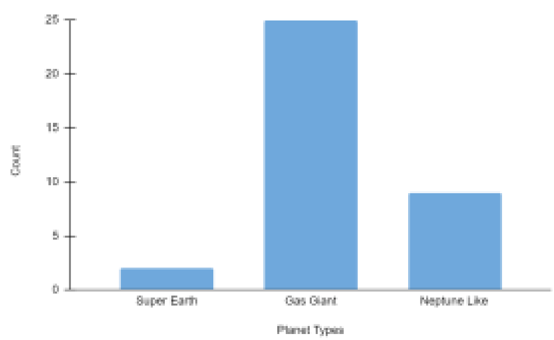


FIGURE 13. *Number of exoplanets in the habitable zone according to planet type*

Despite popular belief that Super-Earths are strong candidates for habitable exoplanets, the graph shows that relatively few Super-Earths are in the habitable zone. Despite the fact that Super-Earths and Neptune-like exoplanets have almost identical occurrence rates in Binary Star Systems (18.4579% and 18.9252%, respectively), the number of Neptune-like planets inhabiting habitable zones is significantly larger than that of Super-Earths. It has been discovered that the transition of a Super-Earth from a rocky planet to a gaseous one occurs at just twice the mass of the Earth. If they are twice the mass of Earth and receive the same amount of energy from their star, they will be able to hold onto a significant hydrogen-and-helium envelope of gas, creating atmospheric pressure hundreds or even thousands of times greater than what we have on Earth's surface [43]. Gas giants have been discovered in every zone of their planetary systems, and according to FIGURE 13, a significant percentage of them are also located in the habitable zone. Gas giants in the habitable zone can have habitable satellites with rocky surfaces, even if they cannot support Earth-like life since they lack a solid surface and are largely made up of hydrogen and helium, as opposed to carbon-based life forms on Earth. None of the Terrestrial planets in Binary Star Systems were discovered to be in the habitable zone of their host star, which is consistent with the findings of Menou and Tabachnik [44], who investigated the influences of other planets on Terrestrial planets and concluded that a substantial chunk of the identified exoplanetary systems is unable to harbor habitable terrestrial planets.

DISCUSSION AND CONCLUSIONS

The primary objective of our investigation was to find the occurrence rate of Super-Earths around binary star systems. Our investigation and observations are based on 315 Binary Star Systems containing 428 planets (TABLE I.). In our initial studies, we find that 18.457% of the total exoplanets around Binary Star Systems are Super-Earths, although 30% of the 4000 exoplanets discovered by Kepler till 2020 were Super-Earths. Interestingly, all the Super-Earths that have been found, are orbiting around one of the stars of the binary system, which further signifies that none of the Super-Earths has a P-type orbit. In our further investigations, we include various parameters like eccentricity, orbital radius, orbital time-period, stellar type, and habitable zone to determine the occurrence rate of Super-Earths.

In our study based on the eccentricity of Super-Earths, we found that around 54.4% of the Super-Earths have eccentricity equal to '0' which signifies that orbit of these Super-Earths are circular. 43% of the orbits of Super-Earths are found to have significant elliptical orbits with their eccentricities not exceeding the value of 0.33. Only 2.5% of Super-Earths are found to have highly elliptical orbits with eccentricities of more than 0.33.

From our studies based on orbital distances, we found that most of the Super-Earths (70.1%) are present in regions having a distance less than 0.1 AU from their host stars. A significant number of Super-Earths (22.1%) are found to be present in regions having a distance between 0.1 AU & 0.2 AU from their host stars. Only 7.8% of Super-Earths are found to be in the region having a distance more than 0.2 AU from their host stars.

K-type host stars are found to have the maximum number of Super-Earths around them (39.2%). Also, F-type, G-type, & M-type host stars are found to have 21.5%, 20.3% & 17.7% of the Super-Earths around them respectively. More than half (50.6%) of the Super-Earths are found to have an orbiting time period between 1 day to 10 days which suggests that most Super-Earths form and orbit very close to their host stars. This has a profound effect on their habitability.

Through our investigation based on habitability, we found that most of the Super-Earths are unlikely to be present in the habitable zone around their host stars. Only 2.531% of the Super-Earths are found to be present inside the habitable zone of their respective host stars. However, 8.411% of the total planets are found to be inside the habitable zone which is 3.323 times more than that of Super-Earths.

After investigating different parameters regarding Super-Earth, we simulate future conditions with the occurrence rates of Super-Earths around the binary star system and found that with an occurrence rate of 10%, we get the maximum probability for the occurrence of Super-Earths, around 0.05937067027042826 when the number of exoplanets is 500. We also found that the probability may decrease with the increase in the rate of occurrence.

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AUTHORS' CONTRIBUTIONS

Sanjana Gupta, Ishan Kaushal and S. Majal Shiny have contributed equally to the paper. Rishab Gupta has supervised and guided the team.

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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