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An Analysis on Exoplanets and How They are Affected by Different Factors in Their Star Systems

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Summary

Is there a correlation between star size, and the number of planets that star is likely to support? This paper goes in depth to discover any correlation there is between planets and their stars. We hypothesize that exoplanets are affected by their host stars' stellar classifications, and that these classifications impact the number of exoplanets that a star can support. We will analyze a dataset in the NASA Exoplanet Archive from August 2017, using a sample size of around 3,500 planets, and mathematical statistics to determine if these correlations are present in real star systems. Different elements of exoplanetary star systems were studied. First, we performed an analysis of all planetary systems in the database and identified how many planets were in those systems. Next, we analyzed the systems by stellar class, first considering individual planets regardless of multi-planet systems, then the number of these multi-planet systems per stellar class. In every case, we found, with high confidence, that there is a significant correlation between stellar class and the number of individual planets supported. Furthermore, there is a correlation between stellar class and multi-planet systems. Finally, we performed an analysis to determine the probability of planets existing in the habitable zone around their star. We found, with high confidence, that around 6% of all planets in our galaxy are in these habitable zones.

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Introduction

Extrasolar planetary research – or exoplanetary research – is the study of planets outside our own solar system, and exoplanets are the planets that exist beyond our solar system. The goal this research sets out to accomplish is to discover clues about why Earth came to be, and to search for life beyond our own planet (1). Fortunately, recent innovations in technology have unlocked different methods of discovery, such as transit and radial velocity, increasing exoplanet discovery to levels far beyond those in the previous decade (2). Transit and radial velocity are the two primary methods used to discover exoplanets. Transit measures the dimming of light as a planet moves in front of its star. Radial velocity measures fluctuations in the wavelength of light coming from stars as the gravity from their planets pulls them closer to and away from our planet. With these discoveries, patterns can be seen between different factors in planetary systems in space. Trends between the types of star and number of planets around those types of stars are the focus of this paper. Using the surplus of data found in NASA's exoplanet archive makes it easy to view any possible correlations between factors of planetary formation and the resulting planetary systems (3). It is because of recent innovations in discovery and NASA's database that we can test our hypothesis of whether the number and frequency of exoplanets is affected by their host stars' stellar classification.

Our research goal is to find and explain associations between factors in planetary systems, and to determine how they can be used to find more exoplanets in an easier and more effective way. Many of these correlations revolve around where to find multi-planet systems and what to look for when searching for them. The more planets there are, the more data can be recovered in the smallest amount of time. Correlations found here between stellar class and planetary frequency is very helpful when drawing conclusions about different protoplanetary discs. These conclusions are immensely helpful when creating and refining global models of planetary formations from stellar class (4). Also note our use of the phrase "planetary system." Our findings are applicable only when planetary systems are being analyzed. Fortunately, scientists believe that there is a high possibility of every star in the universe having at least one planet, so the theories here may be applicable to every star (5).

Stellar class will also be very important when analyzing different planetary systems. There are 7 different stellar classification types described in the standard MK classification scheme; O, B, A, F, G, K, and M (6). Stellar classifications are determined by a star's effective temperature, or the temperature calculated by the radiation it emits (6). O class is the largest and hottest star type on the scale, ranging from 30,000-60,000 degrees Kelvin (°K) (7,8). These stars give off blue light. B is the second hottest at 10,000-30,000 °K, shining blue-white light (7,8). Next is the A type, which burn at 7,500-10,000 °K, shining white (7,8). F burns from 6,000-7,500 °K, shining yellow-white (7,8). G, which is our suns stellar type, burns from 5,000-6,000 °K, shining yellow (7,8). K burns 3,500-5,000 °K and shines yellow-orange

(7,8). Finally, are the “red dwarf” or M type stars burning at less than 3,500 °K and shine red (7,8).

Ultimately stellar class can affect the birth of a planet through solar activity and the star’s protoplanetary disk. Protoplanetary disks are clouds of matter surrounding stars shortly after their inception. They are responsible for the creation of planets. Solar wind is the constant flow of charged particles from the sun, and solar flares are large ejections of these particles in a short burst. When stars are very young these disks are very violent fields of creation due to all the matter colliding and the powerful emissions from the star. The resulting shape of the system is dependent on the amount of matter around the star, as well as the size of the star itself. The size of the star is a significant factor in planet formation, because powerful emissions of particles from stars get more and more powerful the larger a star is. Large stars, such as those belonging to O or B class, have flares that can completely wipe their protoplanetary discs away, leaving little chance for planetary formation. Matter alone in the protoplanetary discs of stars is not the only factor in determining whether planets form. Certain metallicities may also be required to support certain Earth-sized and gas giant planets (9).

All of our studies showed that there are trends between star type and exoplanet presence, suggesting that G-type stars have over 50% of multi-planet systems in our galaxy. Our study, which also suggested that 6% of all exoplanets exist in habitable zones, can help scientists understand what parameters are important to consider. With a better understanding of how planets form, exoplanetary research can reach even greater outputs of relevant data. New information may provide answers to questions about why Earth is here and if there is life beyond planet Earth.

Results

All datasets used were acquired from the NASA exoplanet archive in August 2017 and consisted of 3,502 confirmed and 5,017 candidate planets (3). Since exoplanets are being confirmed continuously, numbers used at this date may differ from numbers used to recreate our analysis later. The goal of our first data analysis was to find the composition of planetary systems regardless of star type, or whether or not they contained habitable planets. The main question we asked was how many planets are typically in a planetary system?

Systems containing a planet are more numerous than any other multi-planet system (**Figure 1**). As the number of planets within a system goes up, the number of those types of systems continues to diminish. We next conducted a proportion hypothesis test to determine the percentage of single planet systems that make up all planetary systems. Understanding the frequency of having a single planet in a system can be important when making new models or assumptions about planetary development, such as with the amount of matter a star must have in order to make planets. Our hypothesis was that single planet systems make up more than 75% of all planetary systems in our galaxy. The numbers in the

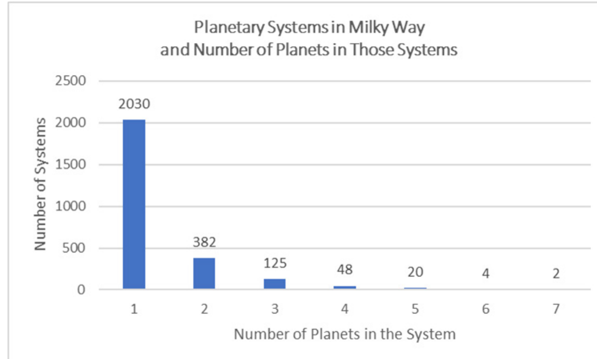

Figure 1: Most planetary systems are comprised of only one planet. A clear trend can be seen, as a planet is added to a system, the number of those systems diminishes steadily. The common number of planets in a system here is one but can go as high as seven.

database indicated that well over 50% of systems had one planet, so we checked 75% first. It tested to be true, so 80% was attempted next, but did not significantly support our findings, resulting in 75% being kept. Our statistical analysis implies that there is sufficient evidence at the α−level of .01, or 99% certainty, to conclude that over 75% of planetary systems in the Milky Way galaxy are single planet systems, suggesting that for every random draw of four planetary systems, at least three will only have a single planet (**Figure 2**).

Next, we evaluated how many multi-planet systems exist among each different type of star. Stellar class is important when analyzing planet formation because it provides an indication of the earliest conditions in which a planet was formed. Important conditions to consider include the strength of solar activity, the amount of matter around the star, and the metallicity, or the heavy metal contents, of the star. We analyzed the statistics based on type of star because any correlation found would provide insight to the early conditions of the stars, which can greatly help with modelling planetary formation.

Temperature is directly influenced by size; the bigger stars tend to be, the hotter. However, being the biggest or smallest is not always the best for harboring exoplanets. The largest and smallest stars tend to have the least number of planets while the ones in the middle have the most (**Figure 3**). Being bigger is worse for

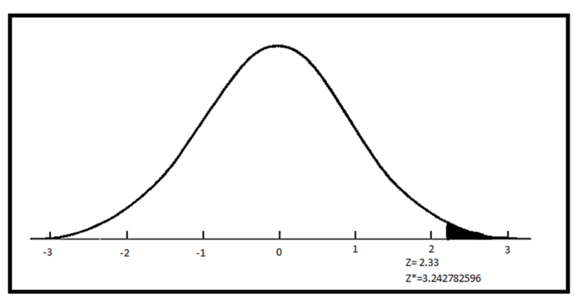

Figure 2: An illustration showing the results of the first hypothesis test. The hypothesis is that 75% of all planetary systems have only one planet, with a bell curve, showing that the hypothesis has a high probability of being correct (1% chance incorrect).

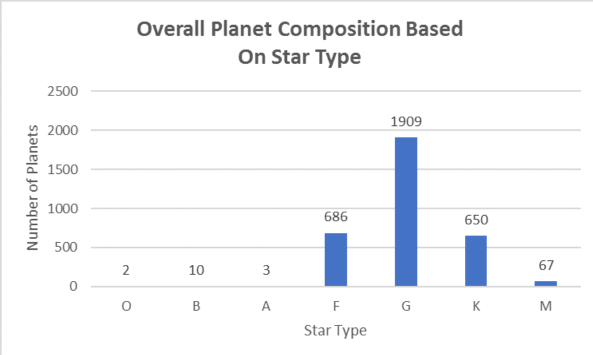

Figure 3: Most planets exist among G-Type stars, and the rest trickle down among the other types. O-Types have the least number of planets, and even the smallest M-type stars have few planets.

exoplanet maintenance because big stars typically blow their protoplanetary disks away due to their very large solar flares and intense solar wind, making the creation of planets highly unlikely. Similarly, smaller stars don't have much matter for this disk, making the creation of planets less common. M class stars also have intense solar activity during the protoplanetary disk phase of their lives. Intense solar activity during protoplanetary formation further reduces chances of planets, as well as life. Medium sized stars typically have a good amount of matter for a disk and don't pose as much as a threat to it as larger stars do, making them excellent candidates for planet creation. The mix between protoplanetary disk size and stellar class results in planetary formation favoring middle class stars, while the largest and smallest stars, such as O and M, have the most difficult time supporting planets (**Figure 3**).

Similar to the trend between stellar class and number of planets, the number of multi-planet systems, or stars with multiple planets, was favored by middle class stellar types (**Figure 4**). There were very little systems to show for the biggest and smallest star types; however, the medium sized stars, or F-K type, had an abundant amount of multi-planet systems. Of every star type, G had more systems than every other star type combined, sticking out as a nursery for exoplanets. The

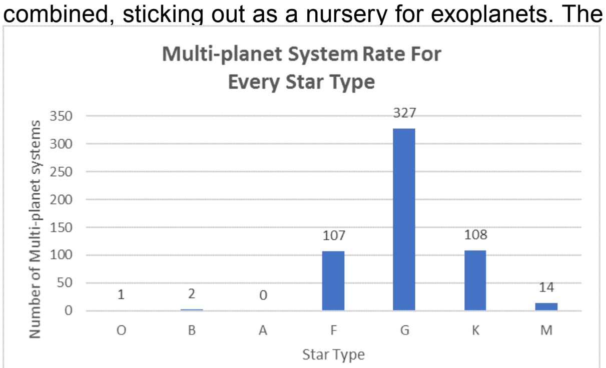

Figure 4: Building off planets compared to stellar class, comparing stellar class to the number of multi-planet systems analyzed for every star type. Each number recorded for a specific type of star represents a planetary system with more than one planet. Again, G-type stars have many more multi-planet systems than any other star.

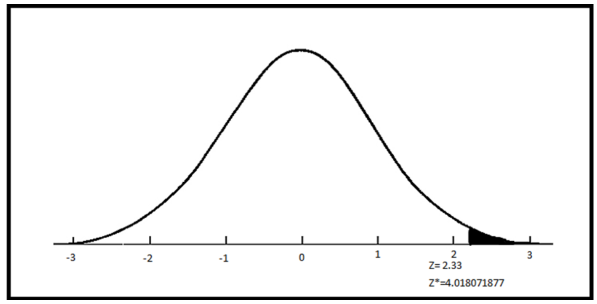

Figure 5: The bell curve illustrating the results of the second hypothesis test. The figure shows that the results were of a high probability of the hypothesis, over 50% of all multi-planet systems belong to G-type stars, being correct (1% chance incorrect).

hypothesis test aimed to evaluate whether over half of all multi-planet systems belong to a G-type star. This hypothesis is important when compared to the first one conducted on single planet systems. Showing that single planet systems are less common for G-type stars than the overall average for all systems shows that G-type stars are far more promising for producing a copious number of planets. Based off the number of multi-planet systems recorded around G-type stars, we decided to test whether 50% of systems comprised of more than one planet were around these types of stars. This tested to be true, so we analyzed 75% next which was not significantly supported. Our statistical analysis implies that there is sufficient data at the α−level of .01, or 99% certainty, to conclude that over 50% of multi-planet systems in our galaxy have a G-type star (**Figure 5**).

Next, we performed an analysis on G-type stars and the relationship between the number of multi-planet systems and single planet systems they have. Two different populations were used, those with single planets and those with multiple planets. The purpose of this test was to find out how often G-type stars have multi-planet systems. Knowing which stellar classes have the highest number of planets is useful for modeling the formation of planets around these stars. When conducting a statistical analysis on the set, 20% was found to be the largest probable number. Our statistical analysis implies that there is sufficient evidence at the α−level of .05, or 95% certainty, to conclude that for every five planetary systems with a G-type star, at most there will be one

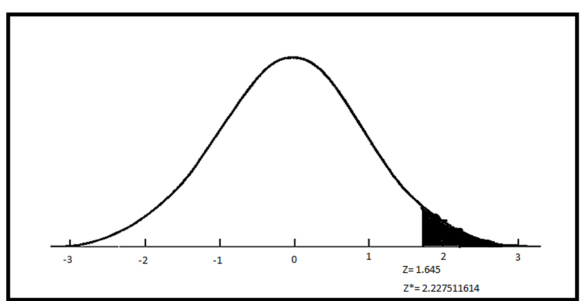

Figure 6: The third hypothesis tests bell curve. The figure illustrates that there is high confidence in the probability that 20% of all G-type star systems have more than one planet, being correct (5% chance incorrect).

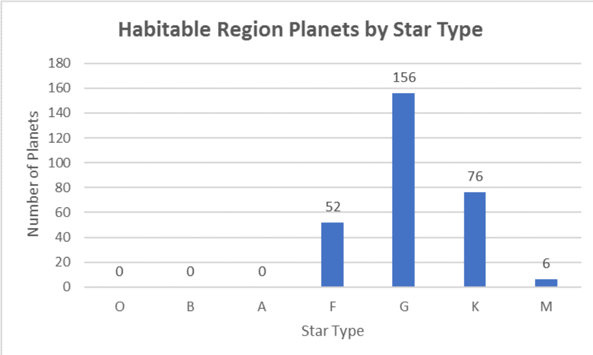

Figure 7: Habitable region planets by star type. Although the numbers are smaller than the rest of the planets in our galaxy, the amount of potentially habitable planets is very promising. Again, G-Type stars contain the greatest number of habitable region planets, with the rest of the stellar classes decreasing in number as different classes are analyzed.

multi-planet system (**Figure 6**). A trend can also be observed between potential habitable worlds and stellar type, where G-type stars have the largest number of this type of planet (**Figure 7**).

Finally, an analysis on potential habitable worlds was collected. The dataset used was from the Kepler Objects of Interest (KOI) program rather than the list of confirmed planets (3). This dataset had more diversity and depth, while the confirmed planet list had limited information with respect to planet size, stellar temperature, and temperature ranges on the planets themselves. The restriction for the KOI data was that the planets included had to either be confirmed or a candidate. False positives skewed the data because they were registered as a planet candidate at one point but were later proven to be something other than a planet. The restrictions put the number of planets in the dataset at 4,541. Of these, 290 were in the habitable zone. The habitable zone, in relation to carbon-based life forms, is the ideal distance from the sun in which liquid water can exist (10). It is also classified as the region where the planets equilibrium temperature is between 180-310 °K and has an insolation flux factor between 0.25 and 2.2. Equilibrium temperature is the theoretical temperature a planet would be if it were only being heated by its parent star. Insulation flux is the amount of energy per unit area that a planet receives as radiation from its star.

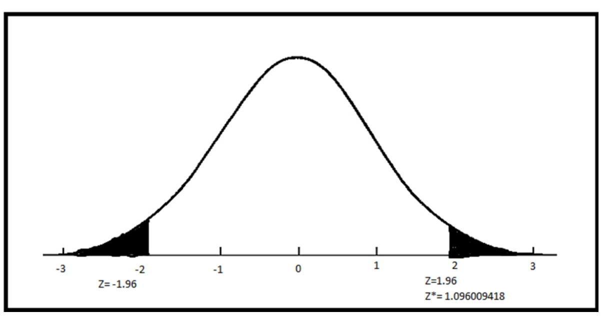

Figure 8: The bell curve supporting the fourth hypothesis test. The curve shows that the null hypothesis fails to be rejected, supporting the claim that 6% of planets in our galaxy are in habitable zones with a confidence of 95%.

We performed a test to determine how probable it is to discover a potentially habitable planet in our galaxy. When compared to the number of planets in the galaxy, any number above 1% was extremely promising. Our results can help reinforce the search for life in the galaxy, and can later be used in other analyses to identify which stellar classes have the highest probability to have a habitable planet, assuming this is not random. When testing the data in the KOI set, 6% of its planets were found to be the most probable candidates for life. The goal of the test was to determine what percent of planets in our galaxy are potentially habitable. Our statistical analysis implies, with a certainty of 95%, that out of all the planets in our galaxy, 6% of them are in a habitable region around their star (**Figure 8**).

Discussion

The hypothesis tests and analysis conducted aimed to determine whether there is a common trend between star type and exoplanets in our galaxy. The stark similarities in **Figures 3, 4** and **7**, support our hypothesis, that a correlation between stellar type and exoplanet formation exists. The largest and smallest star types have little to no planets, but the stars whose classification lie in the middle of the ranking have many more. Starting at O-type, there is little change until F-type is observed where there is a spike in the number of planets. Moving to G-type, the number of planets peaks. The K-type stars have numbers mirroring those of F-types. Finally, M-types drop back down again to levels slightly above those of the largest planets (**Figures 3, 4, 7**).

Explanations for the results of the four hypothesis tests rely heavily on early star and planet formation. When stars are very young their protoplanetary disks are very violent planes. All the matter within the disks are colliding and being impacted by large solar emissions. If it is a large star, there lies the chance for more matter in its disk, but its emissions may be too powerful to maintain the disk. The smaller stars have less matter to create planets in the first place, but their emissions are less likely to blow their disk away. The middle lies in a better ground for planet creation, plenty of matter to create planets with smaller emissions that do not pose a large threat to the young planets.

Finding 1, which concluded that 75% of stars in our galaxy have one planet, can be explained by availability of matter for most forming stars. Most stars in the universe likely have enough matter for a single planet with some left-over debris, especially the smaller stars such as the M class. The F, G, and K class stars are in a middle ground where they are large enough to support more massive protoplanetary discs while keeping violent particle ejections at safe levels. Larger stars like O, B, and A have larger solar flares that lower the probability of many planets forming. The resulting conditions combined between all stars reinforce our original hypothesis that three out of four planets in our galaxy are alone in a system.

Findings 2 and 3, which concluded that 50% of all multi-planet systems have G-type host stars, and of all systems with a G-type star 20% are multi-planet systems, have similar explanations. Since G-type stars appear to be the most favorable for creating planets, it is no surprise that they are superior in creating multi-planet systems. G-type stars have the perfect conditions for planetary creation, including a relatively calm solar activity and larger amounts of matter to create planets. This informed our original hypothesis that over half of multi-planet systems are orbiting around a G-type star. Since it had been suggested that these stars support most multi-planet systems in the galaxy, our analyses sought to determine just how common it is for a G-type to have multiple planets. We found that of all G-type star systems, 20% will have more than one planet.

The final finding, that 6% of all planets are potential candidates for supporting life, is different from the first three in that it seems to be more random in nature. For a planet to be habitable it needs to be at the perfect distance from its star, and this distance varies from star to star based on radiation and heat. This occurrence is not impossible. Humans would not be alive if habitable planets could not form; however, it is very difficult to meet every requirement for there to be life. As difficult as it is to achieve this, our analysis concluded that around 6% of planets are in this zone (**Figures 7, 8**). This is a great number when compared to all planets that exist in the galaxy. If true, there should be hundreds of millions of planets with the ability to support life, assuming the conditions of the planet itself are suitable.

Implementing this data can be done in one main way. Our hypotheses can be used with exoplanetary information to create a filter that only searches within a certain spectrum range to ensure that the highest output of exoplanet candidate systems with G-type or other stars are found. As this method could result in a high output of exoplanet discoveries, it would also neglect other types of stars and systems in the galaxy. In a sense, it would be a waste of good information and a deeper understanding of space. This method can be useful so long as it is not used exclusively.

In statistics there is always a concern that data may be biased, skewed, or inaccurate. The data we used in our study is exceptional, but not perfect. A major example of inaccurate data causing a problem happened back in 2015 when a team of astronomers discovered that around 54% of the "planets" the Kepler space telescope had discovered were not really planets but instead false positives, meaning that the telescope thought it saw a planet and that "planet" was researched and catalogued; however, it was either a star or a brown dwarf, which is essentially a small failed star (11). Since then these false positives have been removed, but there is still the small chance that some fake planets remain, or that there is another problem scientists have yet to notice and fix. As the NASA Exoplanet Archive data does have a chance of being inaccurate in some places, the only finding that has a chance of being affected is the percent of exoplanets that are in the habitable zone for carbon-based life (**Figure 8**). The only reason the data can be skewed is because the Kepler Objects of Interest data involving confirmed planets and candidates was used instead of the list of all confirmed exoplanets. Kepler Object of Interest (KOI) was used because it has more data and planets (290) that fit into that habitable zone, while the other dataset had only 8 planets. Regardless, the information in the KOI program has been sorted out since 2015, and the probability that enough planets in this sample turn out to be false positives that it affects our hypothesis test result is low.

Further risk for bias can be found in the method by which exoplanets are found. Radial velocity and transit, the two primary methods used for discovering exoplanets, have success in discovering planets with orbit periods ranging from nearly one Earth day to over ten thousand Earth days. In the very beginning of exoplanetary research, the tools used to find planets were supremely rudimentary and were only able to find the largest planets closest to the star. Bias towards distance and size of planets has been relieved since then. Today, with new space telescopes such as Kepler, that were designed specifically to discover planets, planets of all sizes and orbits are being found. Using these methods require accurate asteroseismology, or an analysis of the host star, and can give us information about the system's planets ranging from their density and mass to how far they are away from their star (12).

Despite our astronomical leaps in technology, the data on exoplanets is still potentially biased with respect to the size of stars. Smaller stars are affected much more significantly by their planets than larger ones. It is much easier to detect planets around stars of class F, G, K, and M. M class stars are the easiest for planets to effect due to their size, yet relatively few have been found around them when compared to F, G, and K (13). One reason could be because M class stars are dimmer since scientists targeted other planets thought to be more favorable (5). Another possibility is that there is a correlation between stellar mass and exoplanet creation. Even with the potential bias, there is an observable trend in which G class stars have the greatest number of planets. The increase in planets for G class stars is not because they are more common since smaller stars are more common. Small classes, such as M, can summarize the planetary structure of most of our galaxy due to their abundance (5). If the occurrence rate observed is accurate for M class stars, it would say a lot about the likelihood of a correlation being true. It is also less likely a result of ease of discovery, since there are more K and M class stars than G class and since they are easier to detect planets around due to their small mass. Our conclusion is that either the luminosity and mass of G class stars are biased toward detection, or more planets are found around them simply because they have more planets. If the latter is true, then the proposed correlation seems ever more probable.

Unfortunately, there will always be unavoidable discrepancies in datasets such as NASA's Exoplanet Archive. The greatest problem here is that every planet in a star system has not yet been discovered. There is a great chance of error occurring in at least one planetary system in the dataset because planets go unnoticed. Great trust is put into the methods of discovery and how thorough they prove to be, since unnoticed planets are nearly inevitable with current technological restraints. Another discrepancy in the data may occur with larger stars of the O, B, and A class. Transit and Radial velocity methods are poor at finding planets around larger stars. The lack of data points for large stars are most likely either due to bias or proof of the proposed correlation between stellar class and planet number. The support of the existence of correlation is based on the proof of the F, G, K, and M stars in the previous paragraph. It is also very difficult to compensate for the possibility that these smaller stars are remnants of once large ones with their planets remaining, which requires more trust in the accuracy of the dataset.

As time goes on and technology evolves, the data about exoplanets will change and evolve. This will either bring about changes in what scientists currently believe, or reinforce what they already know. The very difficult thing about space research is how unpredictable the universe can be.

Methods

Using the tools found in NASA's exoplanet database, it is easy for anyone to collect large amounts of planetary information to analyze, ranging from planet size to the amount of radiation it gets from its star. Finding planetary systems is done easily by typing the letter "B" in the planetary letter tab and seeing how many data points appear. Finding multi-planet systems is done by typing "C and above" in the tab, depending on how many planets you are looking for in a system. Finding stellar class by effective temperature can be done by entering different temperatures. Temperatures related to class are mentioned earlier in the introduction portion of the paper. Finding every datapoint required is easy and makes conducting statistical review convenient, especially with these large sample sizes.

<u>Hypothesis</u>

H_o: $p \leq 75\%$

H_a: $p > 75\%$ (claim)

<u>Data</u>

n= 2611 x= 2030 $\hat{p} = \frac{2030}{2611}$ p= .75 q= .25

<u>Hypothesis Test</u>

$$Z^* = \frac{\hat{p}-p}{\sqrt{\frac{pq}{n}}} = \frac{(\frac{2030}{2611} - .75)}{\sqrt{\frac{(.75)(.25)}{2611}}} = 3.242782596$$

α–level: .01

Above is the proportion hypothesis test for the claim that single planet systems make up more than 75% of all planetary systems in our galaxy. The final decision in this hypothesis test was to reject the null hypothesis, ultimately accepting the alternative (**Figure 2**).

<u>Hypothesis</u>

H_o: $p \leq 50\%$

H_a: $p > 50\%$ (claim)

<u>Data</u>

n= 559 x= 327 $\hat{p} = \frac{327}{559}$ p=.5 q=.5

<u>Hypothesis Test</u>

$$Z^* = \frac{\hat{p}-p}{\sqrt{\frac{pq}{n}}} = \frac{(\frac{327}{559}) - .5}{\sqrt{\frac{(.5)(.5)}{559}}} = 4.018071877$$

α–level= .01

The hypothesis test above evaluated the claim that over half of all multi-planet systems belong to a G-type star. The final decision for this hypothesis was to reject the null hypothesis (**Figure 5**).

H_o: $p_1 - p_2 \leq 50\%$

H_a: $p_1 - p_2 > 50\%$

<u>Data</u>

$x_1 = 1100$ $x_2 = 327$ n= 1427 p= .5 $\hat{p}_1 = \frac{1100}{1427}$ $\hat{p}_2 \frac{327}{1427}$

<u>Hypothesis Test</u>

$$Z^* = \frac{(\hat{p}_1 - \hat{p}_2) - (p_1 - p_2)}{\sqrt{\bar{p}\bar{q}(\frac{1}{n_1} + \frac{1}{n_2})}} = \frac{\left(\frac{1100}{1427} - \frac{327}{1427}\right) - .5}{\sqrt{(.5)(.5)(\frac{1}{1427} + \frac{1}{1427})}} = 2.227511614$$

α–level: .05

The above test analyzed the claim that out of G-type star planetary systems, the probability of finding a multi-planet system is less than the probability of finding a single planet system by about 50%. For this hypothesis, the final decision was that there was enough evidence to reject the null hypothesis (**Figure 6**).

<u>Hypothesis</u>

H_o: $p = 6\%$

H_a: $p \neq 6\%$

<u>Data</u>

n= 4541 x= 290 $\hat{p} = \frac{290}{4541}$ p= .06 q= .94

<u>Hypothesis Test</u>

$$Z^* = \frac{\hat{p}-p}{\sqrt{\frac{pq}{n}}} = \frac{(\frac{290}{4541}) - .06}{\sqrt{\frac{(.06)(.94)}{4541}}} = 1.096009418$$

The final test above analyzed the claim that more than 6% of planets are potentially habitable. As figure eight shows, the final decision for this test was to fail to reject the null hypothesis. This means that there was not significant evidence at the α−level of .05 to conclude that the percentage of potentially habitable planets is not 6% (**Figure 8**).

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