Extrasolar Planets: An Amateur's Search

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A thesis submitted in partial fulfillment of the requirement
for a degree of Bachelor of Science in Physics
from the College of William and Mary in Virginia

by

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Accepted for: BS in Physics

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Williamsburg, Virginia
May 2008

Abstract

The first extrasolar planet was discovered in 1995 and since then over 200 new extrasolar planetary systems have been identified. While much is known about the formation of our own Solar System, theory varies as to the true nature of extrasolar planetary formation factors. Moreover, in the twelve years since the first discovery of an extrasolar planet, only just over 200 more have been discovered. This hardly matches conventional wisdom which suggests thousands of extrasolar planets throughout the universe. This study attempts to identify "planet forming factors" through a descriptive statistical analysis of the population of stars known to host extrasolar planets in comparison to a general population of stars. Moreover, observations are made to demonstrate the difficulty an amateur astronomer today would have in identifying a new planet hosting star if "planet forming factors" can be determined.

"The Milky Way is nothing else but a mass of innumerable stars planted together in clusters."
-Galileo Galilei

Acknowledgements

I would like to thank Professor Robert Vold for all of his good advice and help. I want to especially thank him for taking me out to observe the stars noted in this study – it was a very enjoyable trip. Without his support, I certainly would have completed a lesser project. To him I owe a debt of gratitude and thanks.

Contents

1 Introduction

The search for worlds beyond our own among the heavens has fascinated man for ages – that fascination continues today. Currently, there are 264 known extrasolar planets making up 226 extrasolar planetary systems (Schneider 2007). This paper presents a descriptive statistical interpretation of the search for extrasolar planets based on the properties of stars playing host to such planets. These properties are deemed “planet forming factors.” A description of the factors required for the formation of planets as well as the research design of this project are first presented. A series of distributions based on the important star forming factors from known extraplanetary hosts are presented in the findings chapter and compared to the same factors from stars in a randomly selected sample. First hand observations of stars are discussed in relation to these findings and the challenges of amateur extrasolar planet observation are outlined. Ultimately, conclusions on the validity of the planet forming factors analyzed, as well as prospects for amateur observation of extrasolar planets, are discussed along with future research prospects.

1.1 What is an Extrasolar Planet?

Before a systematic search for extrasolar planets can be understood, a working definition of what constitutes a planet is required. The definition used in this work is as follows:

> Objects with true masses below the limiting mass for thermonuclear fusion of deuterium …that orbit stars or stellar remnants are "planets" (no matter how they formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same as that used in our Solar System. (WGESP 2003)

While there are a series of other substellar objects and free-floating objects with some conventional properties of planets, these are not considered when searching for extrasolar planets or planetary systems (WGESP 2003).

In 1961, Frank Drake of the SETI Institute devised an equation which he purported would give an accurate probability of life beyond planet Earth provided the correct variable values being used. The Drake Equation is given by:

$$N = R \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$

Where N is the total number of communicative civilizations in the galaxy, R is formation rate of stars with suitable life zones, f_p is the fraction of those stars with planets due to discrete planet forming factors, n_e is the number of Earth-like worlds per planetary system, f_1 is the fraction of those on which intelligent life develops, f_i is the fraction of those on which intelligent beings develop technology, and L is the lifetime of a civilization with an ability to communicate (Ford 2003). It is extremely difficult to choose values which might satisfy this equation accurately. The best estimate for R is about 10^{11} stars have come into existence over about the 10^{10} year life of the galaxy; therefore, between 1 and 10 might be acceptable in value (Clark 1998). For f_p, simplistic assumptions such as only single stars will form planets set the number around .5 (Clark 1998). However, this number guess must be taken with a grain of salt as it has been shown that up to triple star systems may be able to support stable planets (Konacki 2005). All of the other variables are essentially guesses between 0 and 1 with the exception of L, which is a hotly debated factor due to the seemingly self destructive nature of "intelligent" civilizations (Clark 1998).

In the case of this study, a modified version of the Drake Equation modeling only those variables important to extrasolar planet formation is required. Such an equation models the rate at which new extrasolar planets might be forming. It follows as:

$$N_p = R_p \cdot f_p$$

Only two factors, the formation rate of suitable stars for planets, R_p, and the fraction of those stars actually with planets due to planet forming factors, $f_{p,}$ dictate the fraction of stars with extrasolar planets forming. N_p in this case is the total number of extrasolar planets in the galaxy that form or formed per Earth year. Thus, using best estimated values given above, there should be approximately 5 extrasolar planets formed per year in the galaxy. Ultimately, researchers should be able to find far more than just the known 264 extrasolar planets; in fact, there should be many millions in the galaxy – some of which might even resemble Earth. Thus, those seeking new planets have a long way to go in locating and identifying them all.

Unfortunately, amateur astronomers cannot themselves identify new extrasolar planets due to the limited instrumentation available widely to the public. It is important to note that given current limitations in even the best instrumentation, no planets smaller than .4 times the radius of Jupiter have been identified outside of our solar system (Clark 1998). This limitation in measurement greatly lessens the number of planets which might be presently discovered outside of our solar system. For example, if an observer using present techniques took aim at our Sun from a great distance, planets such as Mars and Venus could not be observed using current methods. Professionals use a range of techniques for determining the existence of extrasolar planets. Radial velocity (Doppler) measurements, the oldest technique, were used to find a number of the earliest known extrasolar planets (Perryman 2000). Other detection methods include positional (astrometric) displacements, gravitational microlensing, and pulsar timing (Perryman 2000). All of these methods are out of reach for the casual astronomer or his equipment; however, professional astronomers today have become the Galileo of the past in the search for new planets and use these advanced methods regularly.

Understanding that current measurement techniques for finding extrasolar planets are limited, if one could better know what stars to observe with these methods, the likelihood of finding such planets might increase. Thus, the importance of this study in understanding the planet forming factors of stars.

1.2 Planetary Formation and Planet Forming Factors

There has been significant study of planetary formation, especially in our solar system[1]. Following the 'solar nebula theory,' planet formation is the extension of star formation as particles left over from star development aggregate to create a planet around the new star. This is often used to describe star formation within our own solar system (Perryman 2000). While there are a number of theories regarding the formation of planets and stars, none is entirely satisfactory across all situations (Woolfson 2000). Thus, even when many astronomers and astrophysisists feel somewhat comfortable describing the evolution of our Solar System, there is much unknown about just how extrasolar planets form. A better understanding of the stars around which extrasolar planets have been found could be a useful step not in just finding new extrasolar planets, but also in better understanding the conditions under which planets form.

[1] See Woolfson 2000

In the case of this study, a series of star factors are evaluated in determining around what types of stars one might find a future extrasolar planet. These are called the "planet forming factors" of stars and they include:

- Mass
- Radius
- Fe/H Ratio
- Luminosity

The mass and radius of a star represent a common measurable physical characteristic of stellar bodies and directly reflect the size of a star. The Fe/H ratio is the ratio between the heavy element iron and the light element hydrogen which is the primary full of a young star. As stars age, they fuse together lighter elements to create heavier elements, thus Fe/H also represents, in some ways, a star's age. Finally, the luminosity of a star is the total energy radiated from the star. [2]

Each of these is analyzed in this study to better determine which, if any, are significant to extrasolar planetary formation, and consequently what types of stars might be good candidates for future observation with regard to extrasolar planets.

[2] It was once thought that binary stars and triple star systems could not play host to planets due to the complicated orbits a planet would be required to perform in such a star system. However, it has been shown that in fact binary and triple stars can host planets even though it is less common (Konacki 2005). Multiplicity was explored as a possible fourth planet forming factor for this study, however, uncertainty over the multiplicity of many stars proved to make this factor untestable at the current time.

2 Research Design

2.1 The Search for Extrasolar Planets - Design

Utilizing each of the four identified planet forming factors of stars, this study completed a series of descriptive statistical distributions designed to summarize the number of stars exhibiting each of the factors. The fifth factor, multiplicity of a star system, is described in quantitative terms due to the binary nature of that data.

Three sets of distributions are presented for each of the four factors being analyzed in this way. The first set of distributions show the respective factor distributions for all 226 stars known to play host to extrasolar planets counting each planet each star hosts. It is important to note however that holes in the data for each extrasolar planetary host stars caused the N of each distribution to be less than 226. This first set of data is presented in this chapter to provide a base for later analysis. The second set of distributions describe the same factors once again, but count only on the stars hosting extrasolar planets, not the number of planets circling a star with such features. A sample size of 100 stars was used for each of these distributions, but again, due to holes in the available star data from public sources, the N values for each of these distributions is less than 100. Finally, the last set of distributions shows the same four factors measured across 100 randomly selected stars within the radius of the outermost star known to host an extrasolar planet. This is the control set and contains stars known to have no planets, as well as a handful of stars that do play host to extrasolar planets. These distributions as well, while based on an N of 100, register a lesser total of stars due to data gaps. The first two sets of distributions are compared to show consistency among the star factors which host planets, regardless of the number of planets hosted. The second two sets of distributions are compared to determine what factors, if any, measured in this study might possibly be significant to the formation of extrasolar planets.

While the data regarding test stars' mass, radius, and Fe/H ratio was readily available in internet star databases and catalogues, for the purposes of this study the luminosity of each star used in distributions had to be calculated given the available public information using the equation:

$$L_{star} = 0.0813 \cdot D_{star}{}^{2} \cdot 10^{-.04 m_{star}} \cdot L_{Sun}$$

Thus, the unknown luminosity of a star could be found in terms of the Sun only knowing the distance, D, and magnitude, m, of the star in question. This equation was used constantly across all planet forming factor distributions.

There are two star databases being used in this study. The first is an SAO catalogue which has been cut down to only those stars hosting extrasolar planets by the Extrasolar Planet Encyclopedia (EPE) administered by Jean Schneider. This database provided the required physical data on stars hosting extrasolar planets for the distributions presented in this study. The second and more general star database utilized in this study is the Internet Stellar Database (ISD) administered by Roger M. Wilcox. This is a hybrid collection of star catalogues which focuses primarily on stars within 75 light years of Earth, but also contains a majority of other "noteworthy" stars beyond this range. The ISD provided the star information for the sample of random stars which was used to create the control set of distributions. Random stars were chosen through a series of ISD searches based on coordinates from known planet hosting stars. Through comparing the data found in the EPE and the ISD, this study attempted to isolate planet forming factors unique to stars known to have extrasolar planets.

2.2 Amateur Observations

The other important mission of this study was to show the difficulty presented amateur astronomers who might show interest in finding an extrasolar planet of their own. To demonstrate the difficulty of this aim, a Meade LX200 GPS 10” F10 telescope along with a Canon Xti Digital Camera were utilized to photograph a series of well known stars formations. Unfortunately, the night of viewing, April 18th, 2008, proved to be replete with light pollution mainly due to the almost full Moon. However, a sample photograph showing the limitations of even a high end amateur telescope was achieved. This is used to demonstrate the difficulty of detecting faint and small objects, like extrasolar planets, with tool available to the general public.

3 Findings

3.1 Descriptive Distributions of Planet Forming Factors

Key to carrying out this study is possessing accurate baseline data describing the physical properties of stars known to have extrasolar planets. The planet forming factors of each star known to possess an extrasolar planet or planetary system were determined utilizing the database of star information provided by the Extrasolar Planets Encyclopedia.[3] The EPE provided a complete listing of this data and allowed for the creation of distributions which would be useful in analysis. Meanwhile, the ISD provided accurate data on a set of random stars which act as a control set in each of the following descriptions. In each subsection, with the exception of the distance section, the respective distributions for an individual factor by distribution set is introduced and compared across the other distributions.

3.1.1 Distance from Earth

When analyzing the available data on extrasolar planets, of particular interest is most stars with planets of which we are aware are found particularly close to Earth. This, of course, is an artifact of limited observational techniques and instrumentation; however, it suggests that given our current abilities, it may not be worth looking too far beyond 650pc (about 21000 light years) as we are unlikely to observe extrasolar planets at that distance even where they do exist. The volume of the sky in which planets are being evaluated in this study is determined by this distribution of known stars hosting extrasolar planets and is set at 650pc. No sample stars for any distribution were taken beyond the

[3] Again, one will notice that the total number of planets measured per histogram of star forming factor varies. This is a result of an incomplete dataset due to the instrumentation limitations. Despite this fact, the data provided by the Extrasolar Planets Encyclopedia is the best to date for extrasolar planetary statistics.

21000 light year mark. Practically, for an amateur astronomer attempting to discover or even catch a glimpse of a known extrasolar planet, despite the majority of host stars being reasonably close to Earth, it is a very difficult thing to see an object the size of a planet even 256 light years away, the mode distance shown in Figure 3.1.

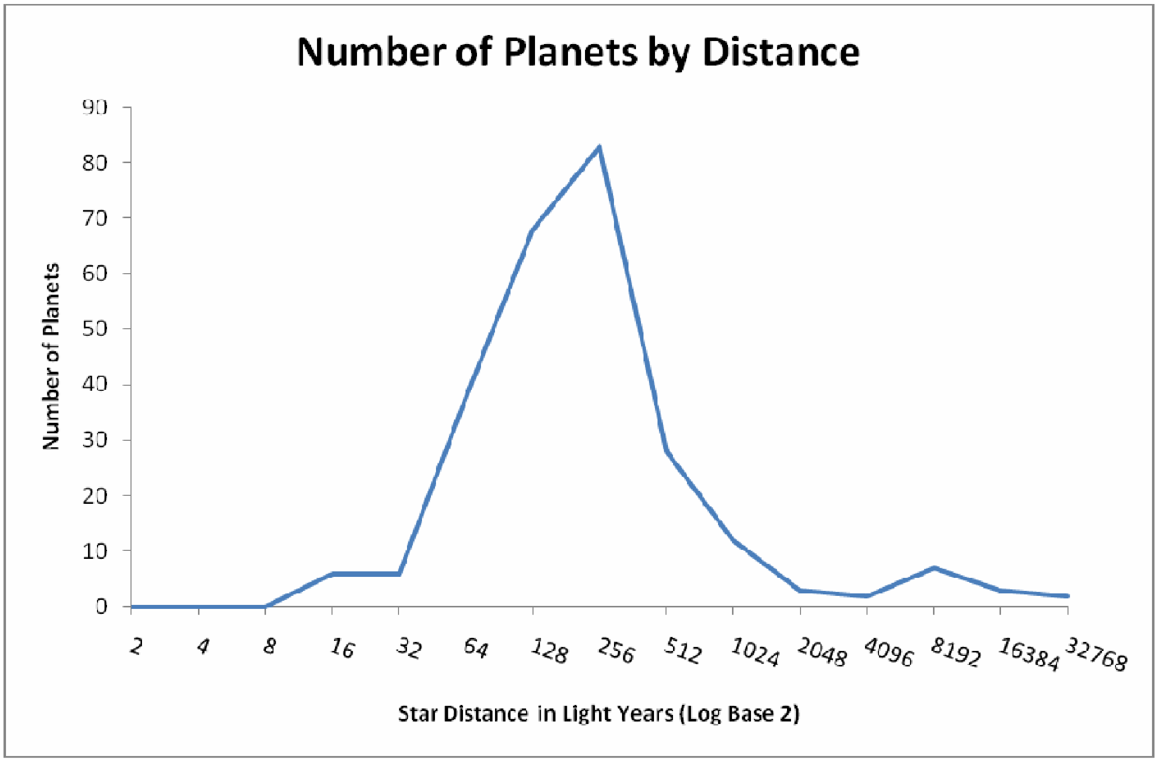

Figure 3.1 – The number of planets found by the distance of their host star from Earth
N 258 planets Source Data: Schneider 2007

3.1.2 Mass and Radius

Mass and radius may play a role in the likelihood of a star playing host to an extrasolar planet. A causal glance shows that most stars hosting extrasolar planets are approximately the same size as our Sun in both mass and radius. A deeper analysis of these results however shows that mass of a star may have a subtle influence on the likelihood of finding an extrasolar planet, but that the radius of stars may not have such an influence.

Figure 3.2 shows the number of planets by star mass for those stars hosting extrasolar planets. This distribution closely matches that of Figure 3.3, which simply maps the number of stars hosting extrasolar planets. Thus, it is safe to use Figure 3.3 in a more general comparison with a sample star population as it accurately reflects the star masses experienced by all extrasolar planets.

In closely examining Figures 3.2 and 3.3, it is clear that the majority of stars which have extrasolar plants are between .8 and 3.2 times the size of the Sun. Extremely small and extremely large stars do not seem to have planets orbiting them. In this regard, however, it is important to remember that limited observational techniques may be skewing the data in these figures to the large end and that there may in fact be many small stars hosting plants. That being said, it is still a safe claim that the majority of stars with extrasolar planets seem to be about the size of our own Sun given available data.

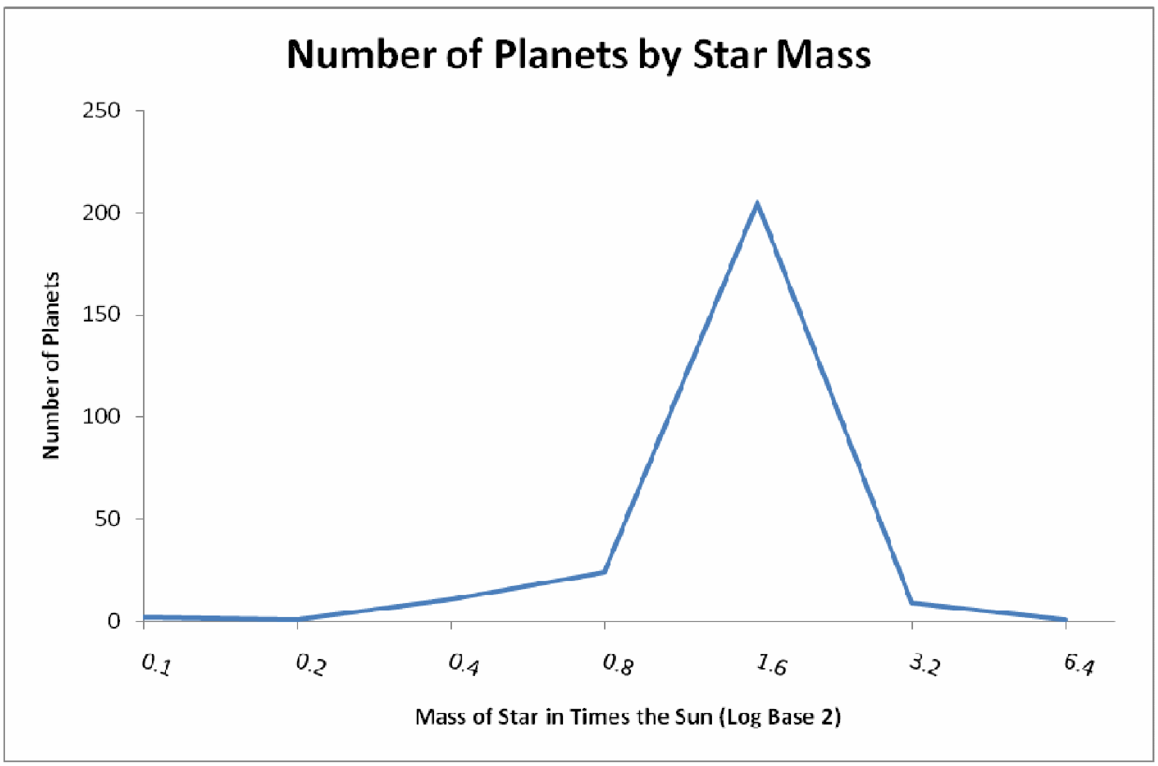

Figure 3.2 – The number of planets found by the mass of their host star
N 253 planets Source Data: Schneider 2007

Comparing Figure 3.3 to Figure 3.4, the general sample of stars, there is a slight suggestion in the distributions that stars bearing planets tend to slightly more massive than the average star in the sky. Most stars hosting a planet are clumped around 1.6 times the mass of the Sun, however, the general sample shows a more even distribution of star masses ranging from .4 to 1.6 times the size of the sun. This study cannot determine if this is a statistically significant difference; yet, it does suggest that stars with planets tend to be about the size or slightly larger than the Sun and this tends to be slightly larger than a population of random stars.

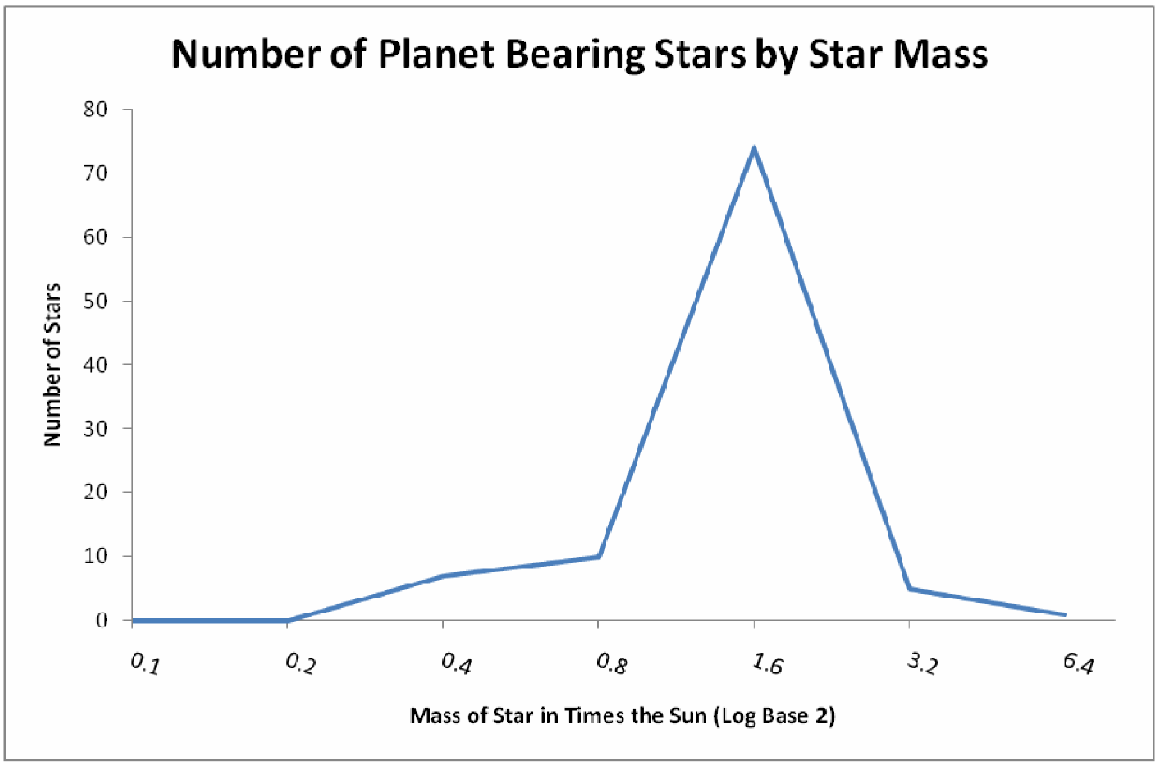

Figure 3.3 – The number of stars hosting extrasolar planets distributed over their mass
N 97 stars Source Data: Schneider 2007

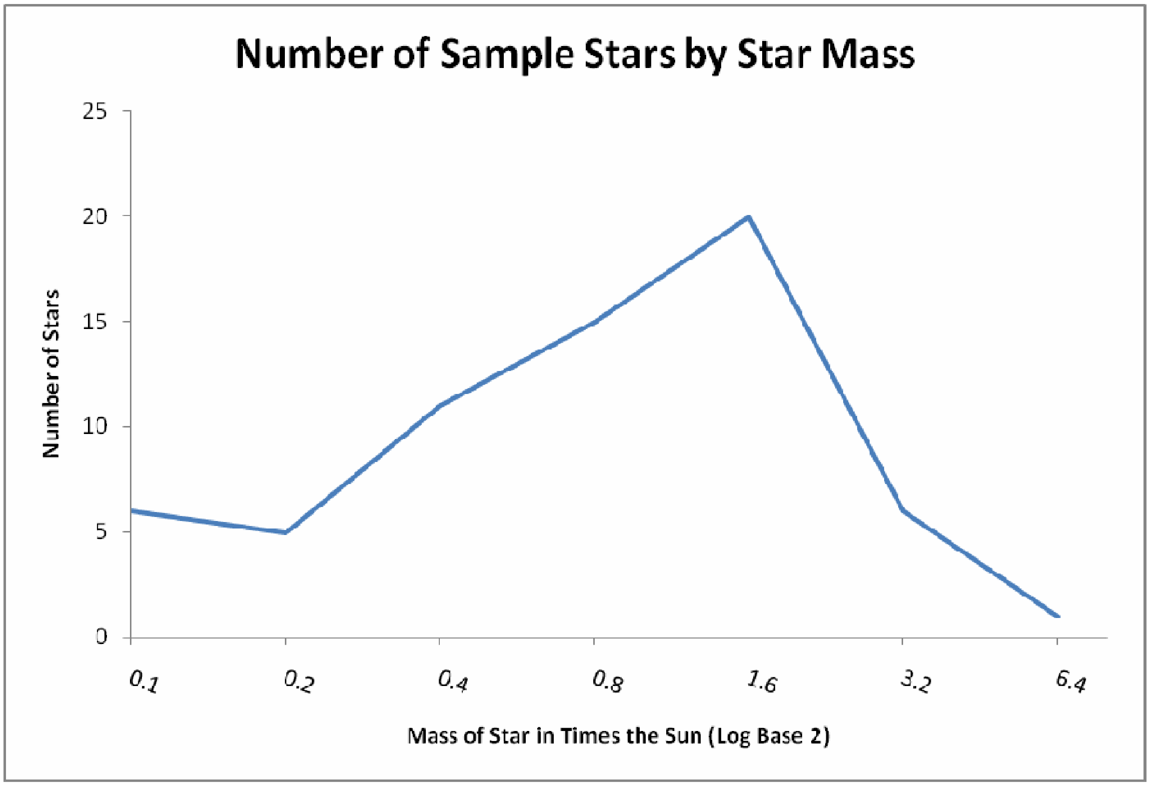

Figure 3.4 – A random sample of stars distributed over their mass
N 64 stars Source Data: Wilcox 200

Similar to mass, the radius of a star is also of particular interest in this study. In comparing figures 3.5 and 3.6, it is clear that the distributions of each closely match. Thus, Figure 3.6 simply maps the number of stars hosting extrasolar planets. It is therefore safe to use Figure 3.6 in a more general comparison with a sample star population in Figure 3.7 as it accurately reflects the star masses experienced by all extrasolar planets.

There appears to be no significant difference in the distributions between Figures 3.6 and 3.7. Stars hosting extrasolar planets seem just as likely to be 1.6 times the size of the sun as do stars of the general population. There is apparently no meaningful or significant relationship between the radius of a star and the likelihood that it will host an extrasolar planet. Radius as a planet forming factor

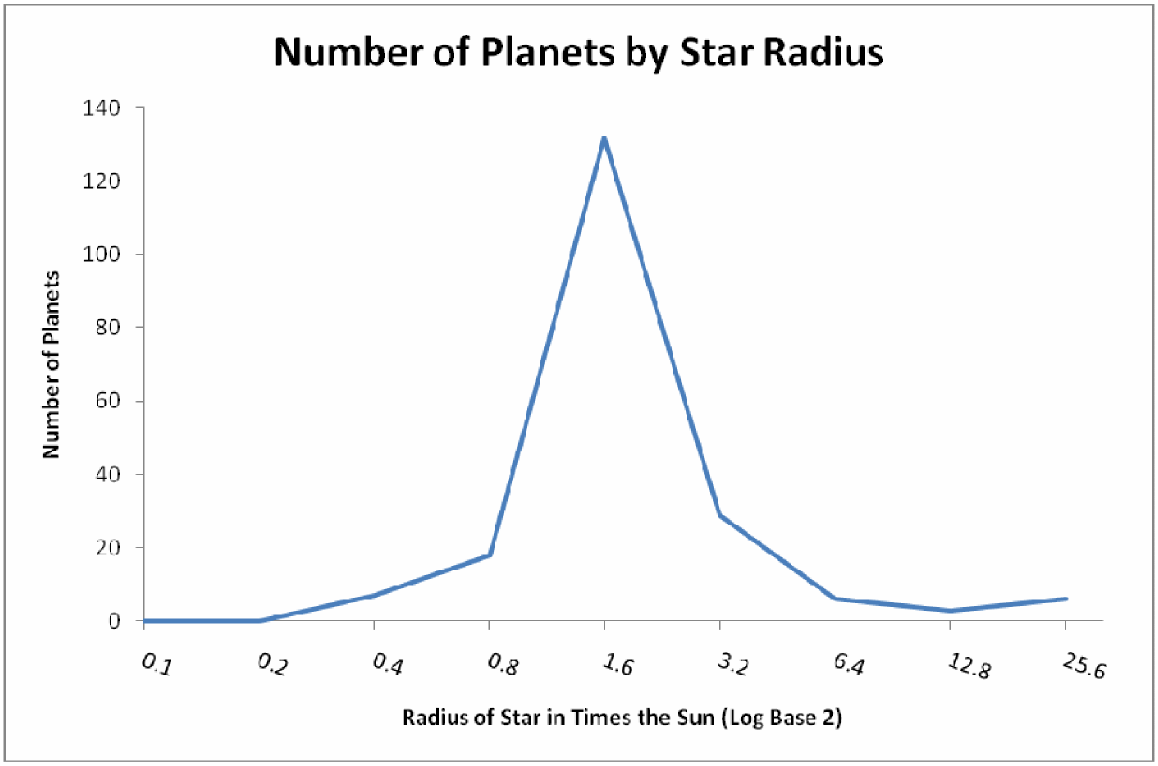

Figure 3.5 – The number of planets found by the radius of their host star
N 201 planets Source Data: Schneider 2007

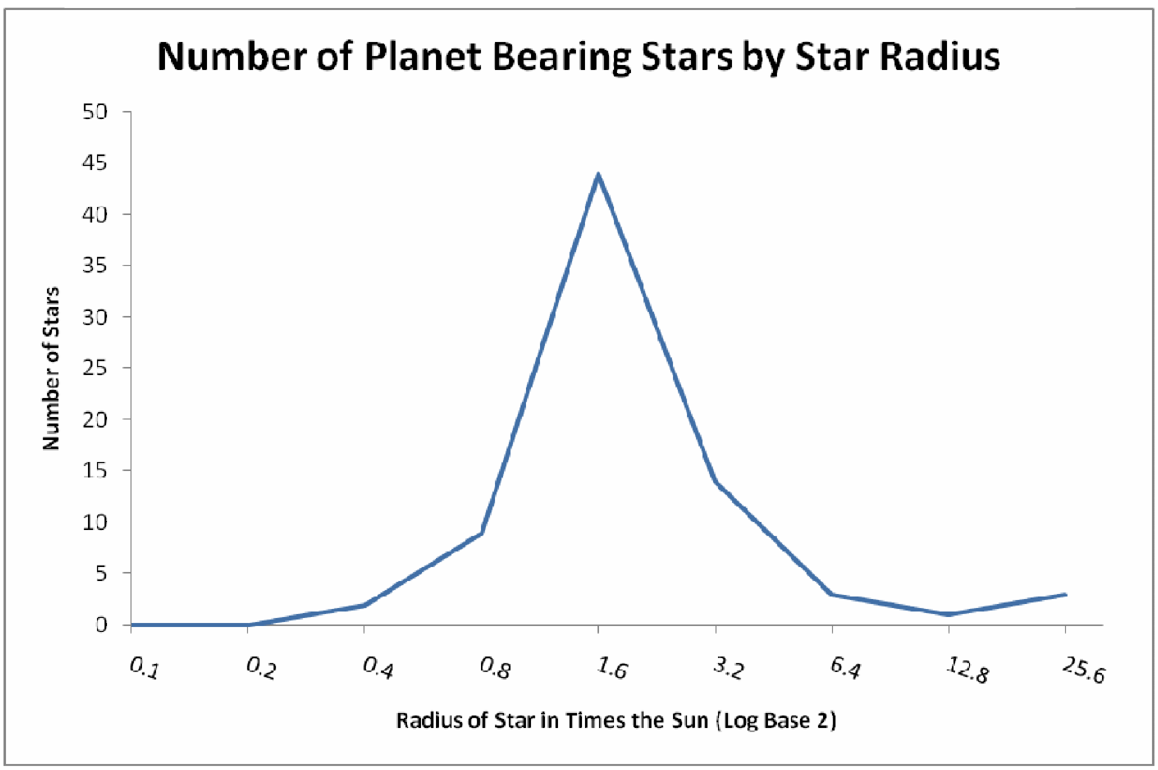

Figure 3.6 – The number of stars hosting extrasolar planets distributed over their mass
N 76 stars Source Data: Schneider 2007

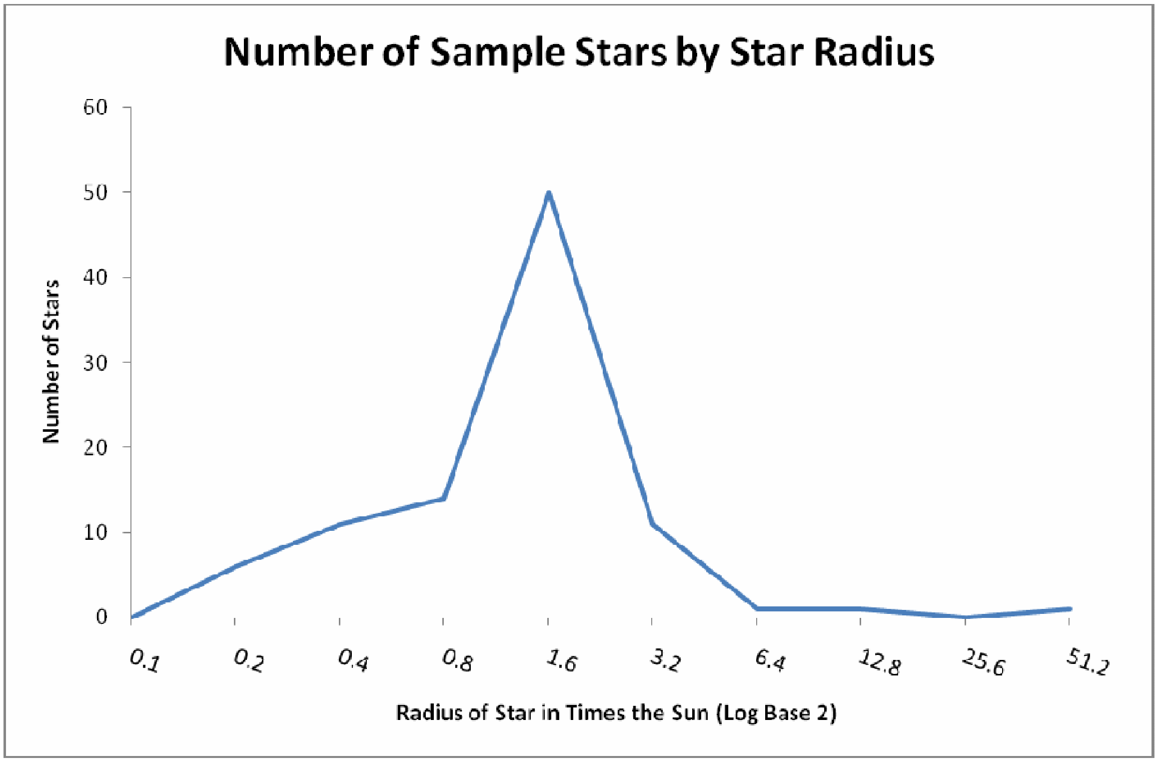

Figure 3.7 – A random sample of stars distributed over their radius
N 64 stars Source Data: Wilcox 200

3.1.3 Fe/H Ratio

As stars age, the process of nuclear fusion causes the hydrogen gas of a star to fuse into elements of higher mass. One measure of a star's age is its iron to hydrogen ratio, or more generally its heavy elements ratio. In the case of extrasolar planets, it appears that stars with heavy elements ratios similar to or greater than that of our own Sun are often host to extrasolar planets. In Figure 3.8 below, most planets have host stars with the same or greater Fe/H ratio as our Sun. Thus, one is led to believe stars with heavier elements are most likely to play host to extrasolar planets.

In comparing Figures 3.8 and 3.9, it is clear that generalizing the Fe/H ratio experienced by extrasolar planets around their stars to the population of stars hosting extrasolar planets is a safe assumption. Consequently, the stars hosting extrasolar planets

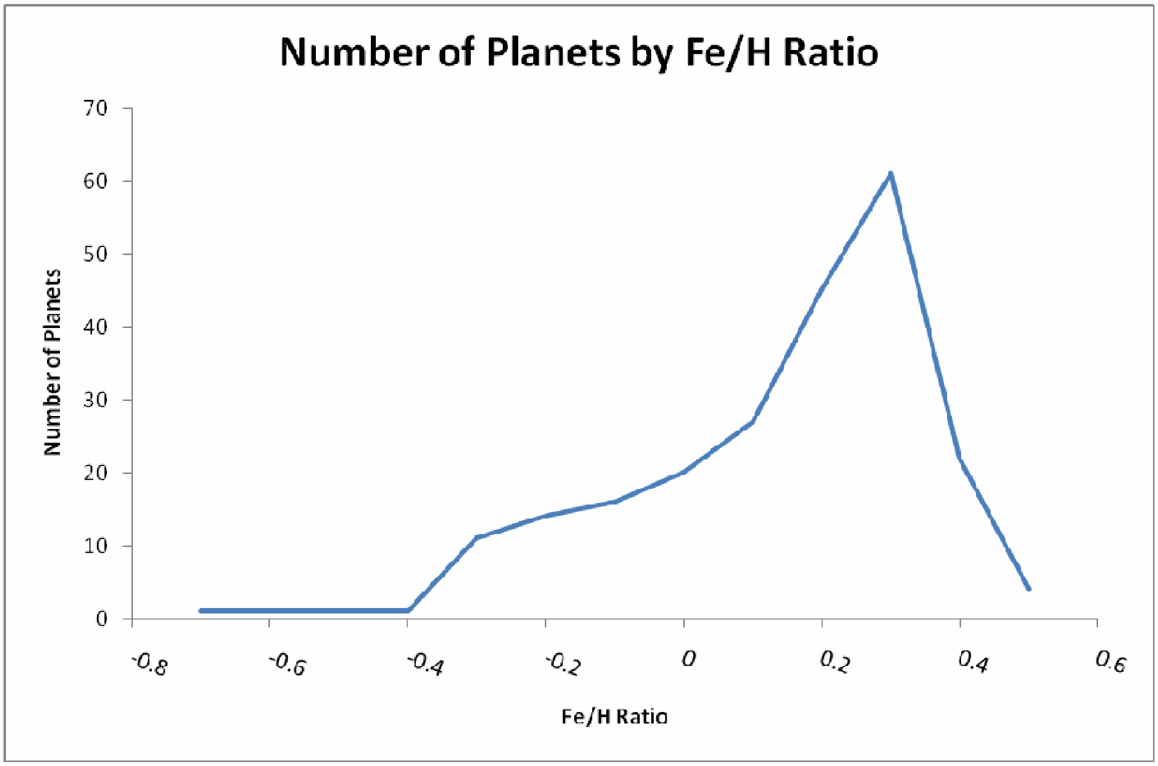

Figure 3.8 – The number of planets found by the Fe/H of their host star
N 228 planets Source Data: Schneider 2007

may be compared to sample of random stars and their heavy elements ratio show in Figure 3.10.

Figure 3.10 shows a very inconsistent picture of heavy element presence in a random collection of stars. There is no discernable pattern other than that most stars seem to share the same heavy element ratio observed in our Sun. However, upon comparing Figures 3.9 and 3.10, it appears that stars hosting extrasolar planets consistently tend to have heavy element ratios as high, or in many cases higher than, that of our Sun. Most stars with planets in fact have a heavy element ratio, specifically Fe/H, three times greater than that of our Sun. This in no way is an analogue of what is seen in the random control sample of stars. Therefore, while this study does not claim statistical significance, it certainly suggests that the planet forming factor of Fe/H ratio may provide clues to finding future extrasolar planets.

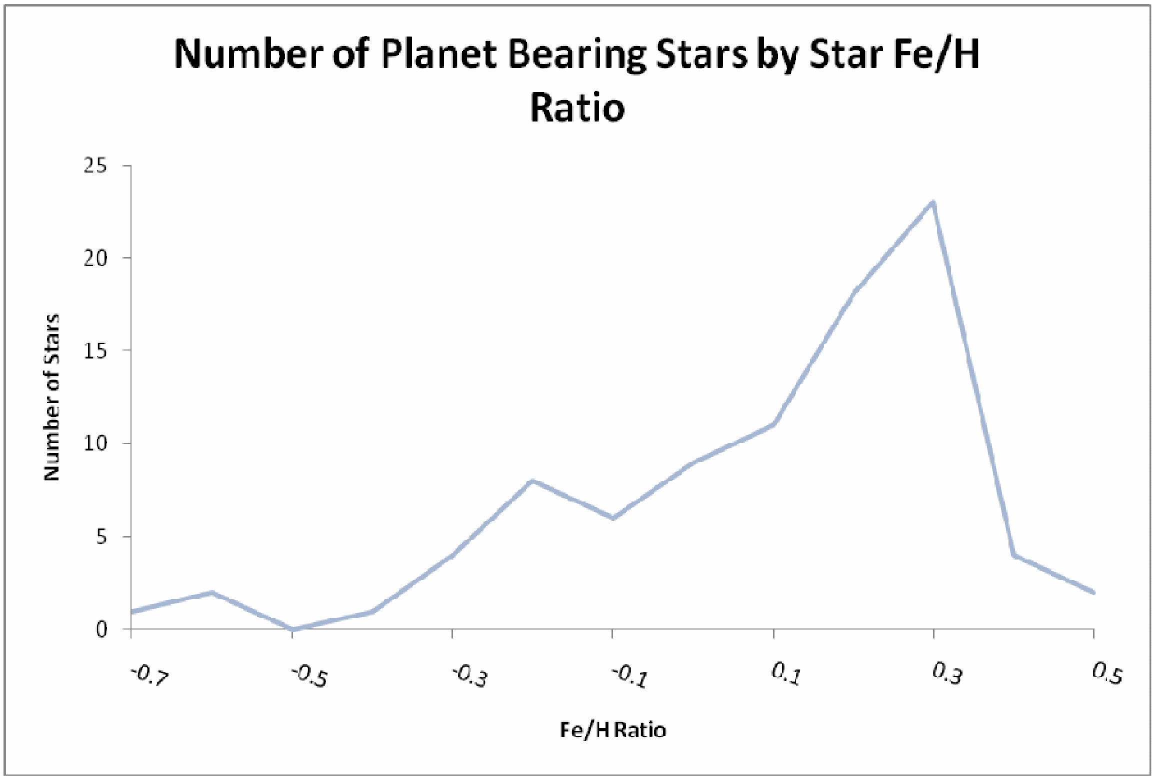

Figure 3.9 – The number of stars hosting extrasolar planets distributed over their Fe/H ratio
N 89 stars Source Data: Schneider 2007

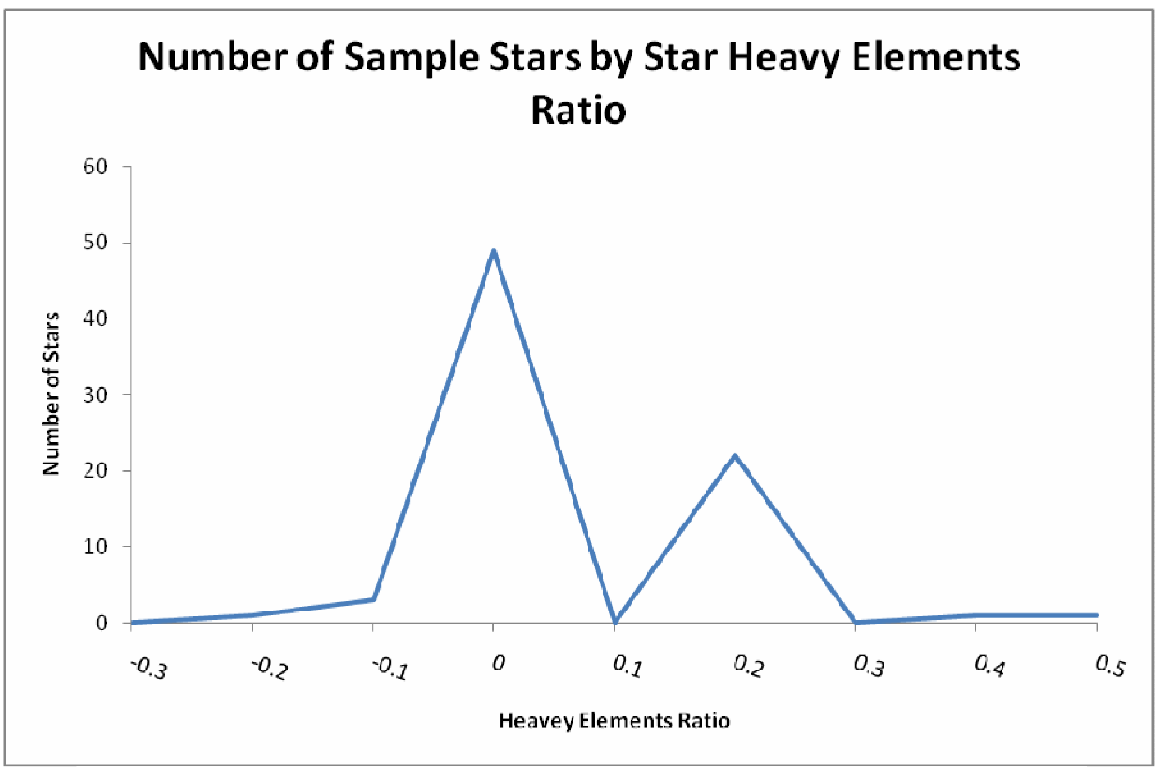

Figure 3.10 – A random sample of stars distributed over their heavy elements ratio
N 77 stars Source Data: Wilcox 2008

3.1.4 Luminosity

The luminosity of a star has particular appeal as a potential planet forming factor due to it measuring the energy which as star emits into its surrounding environment. For those interested in seeking planets with alien life, it may of be even more appeal. However, it appears that luminosity of a star does not play a large part in the formation of extrasolar planets, at least when compared to a random sample of stars.

In comparing Figures 3.11 and 3.12, it is clear that generalizing the luminosity experienced by extrasolar planets to the luminosity emitted by their host stars is an accurate and acceptable procedure. Thus, one can compare the distributions found in Figures 3.12 and 3.13. In these, it is clear that the luminosity of most stars with extrasolar planets is approximately 1 to 10 times that of our Sun; however, this same pattern is observed in the random sample as well. It appears that the distribution shown in figure

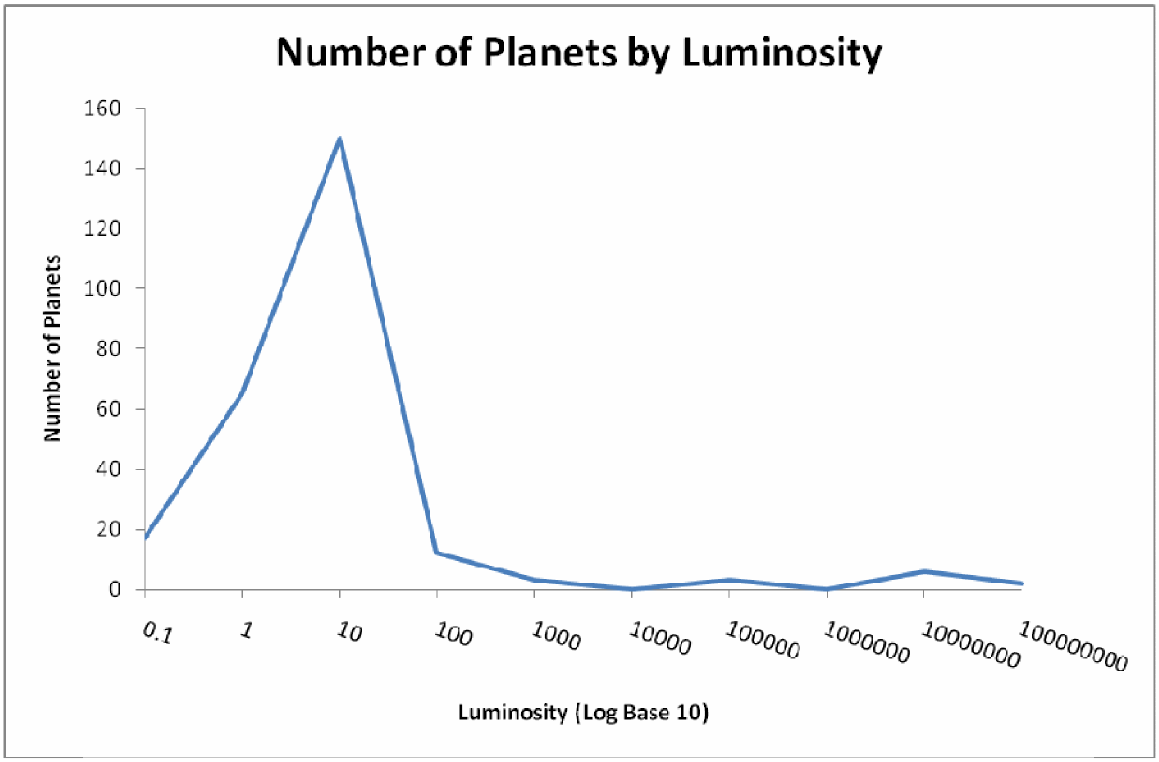

Figure 3.11 – The number of planets found by the luminosity of their host star
N 255 planets Source Data: Schneider 2007

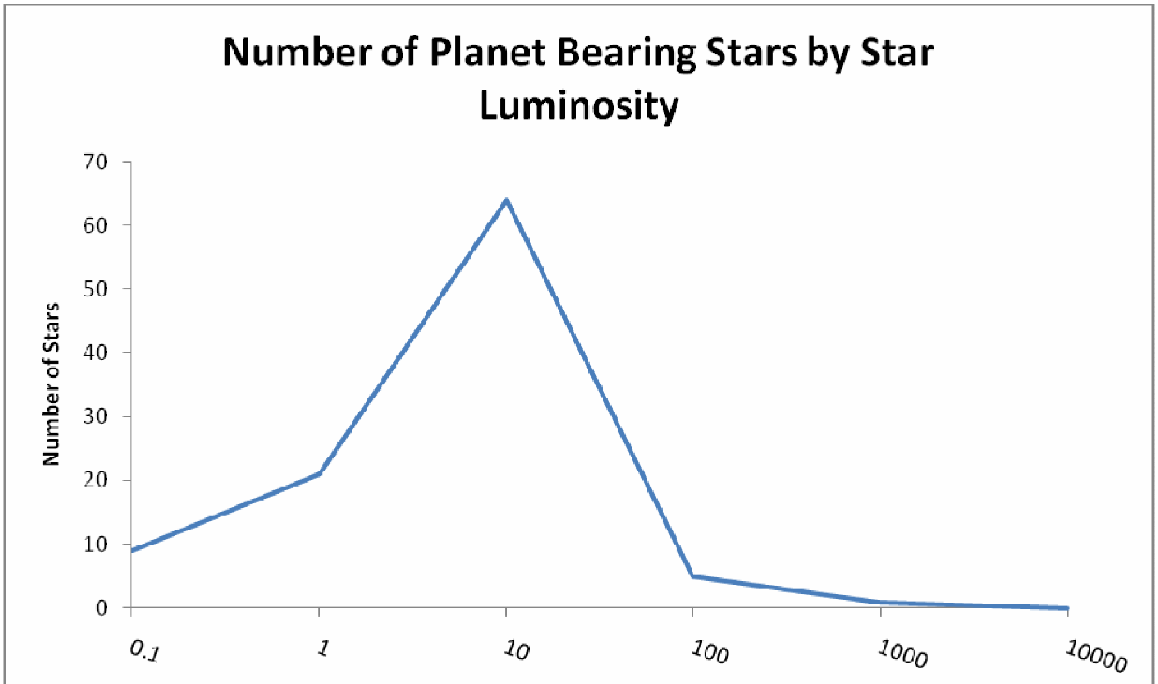

Figure 3.12 – The number of stars hosting extrasolar planets distributed over their luminosity
N 100 stars Source Data: Schneider 2007

3.12 is simply an analogue of the general distribution for the luminosity of stars. Thus, luminosity is not a worthwhile planet forming factor in the pursuit of extrasolar planets. The energy emitted from a star does not seem to having a meaningful impact on the chance of an extrasolar planet.

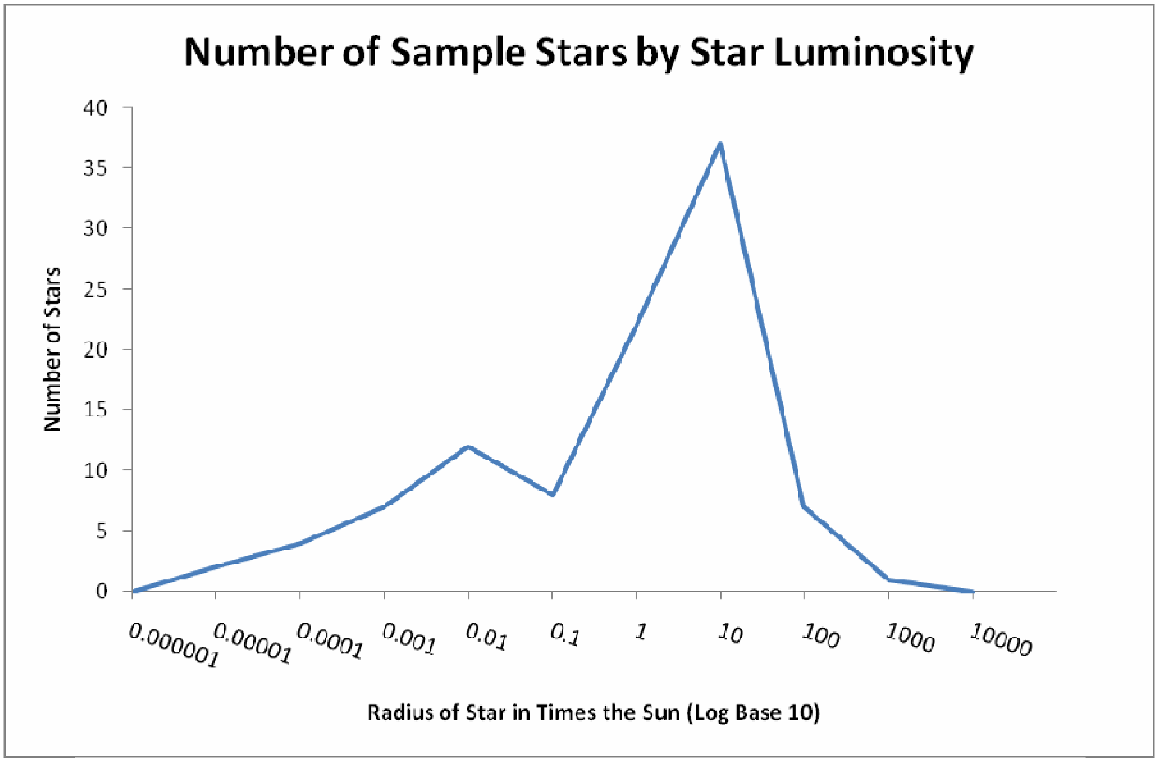

Figure 3.13– A random sample of stars distributed over their heavy elements ratio
N 100 stars Source Data: Wilcox 2008

3.2 Observations

While the variety of suggested star forming factors have been explored, understanding the technical difficulty facing an amateur astronomer in finding an extrasolar planet should be explored. In particular, it is important to understand that even with some of the most advanced commercially available equipment, amature astronomers are hard pressed for the ability to observe objects such as extrasolar planets, even when they know where the are located. This section will examine this idea in more detail as well as discuss specific technical challenges noted while taking first hand photographs of stellar objects.

Figure 3.14 shows a image of HD 118203b taken from the astronomy catalogue provided by Starry Night Pro +. HD 118203b is a star known to host at least one extrasolar planet. However, the Figure 3.14 shows an image that might be obtained using a particularly powerful amateur telescope. The star is 290 light years away and has a magnitude of 8.03, a mass of 2.1 M_J, and a major axis of .07Au. Using this information, one might calculate the angular separation between the star and its extrasolar planet. Specifically:

$$Star - PlanetAngularSeparation \approx \frac{Major\_axis}{dis\tan ce} = \frac{(.07AU \cdot 1.49x10^{8} m / AU)}{290Ly \cdot 9.46x10^{15} m / Ly} \approx 7.8x10^{-7} arc - \sec$$

Most amateur equipment has a field view limit of approximately 1 arc-sec. Thus, it is clear the difficulty one faces as an amateur attempting to locate an extrasolar planet.

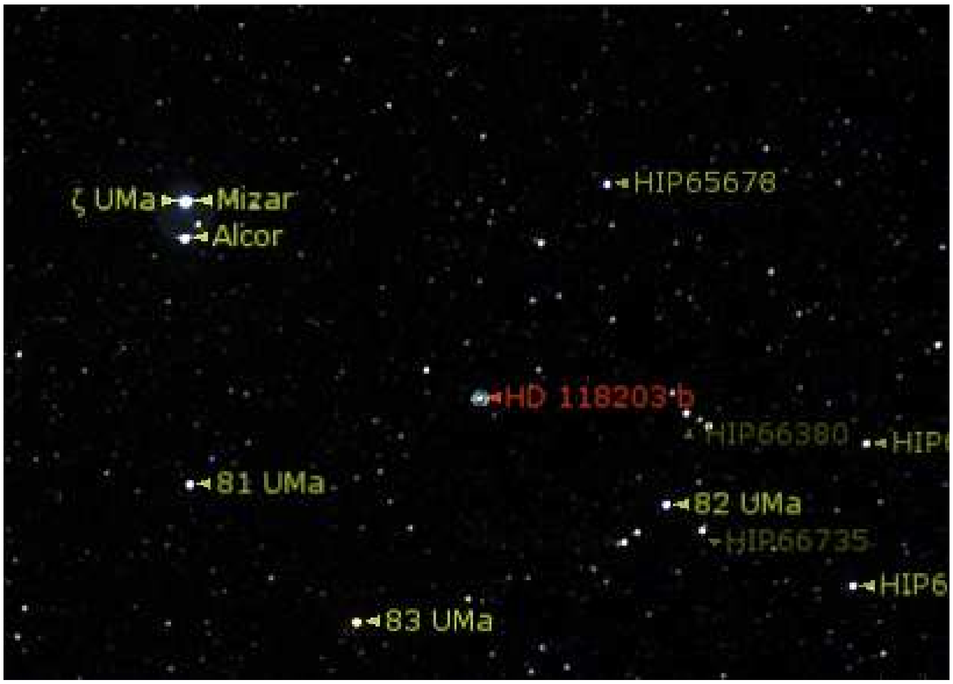

Figure 3.14– Image of HD 118203b taken from Starry Night

Source Data: Starry Night Pro +

Observations made in this study further illustrate this point. Using a Meade LX200 GPS 10" F10 telescope along with a Cannon Xti digital camera, a photograph of the binary stars Alcor and Mizar was taken. Figure 3.15 shows the image taken by this study while Figure 3.16 shows the image of the same stars taken from Starry Night Pro +. Mizar has a magnitude of 7.6, Alcor a magnitude of 3.96, and their binary partner TYC3850-257-1 has a magnitude of 7.56. The angular distance between Mizar and

TYC3850-257-1 is 14” and the angular distance between Alcor and TYC3850-257-1 is just less than 10”. These distances are approximately 10^7 times larger than the distance between HD 118203b and its known planet! Taking into account that a high end and reasonably powerful telescope was utilized to take the picture in Figure 3.15, it is clear to see the difficulty and near impossibility for an amateur to view an extrasolar planet, let along discover a new one even given the best planet forming factors as a guide.

Figure 3.15– Stars Mizar (upper), Alcor (lower), and TYC 3850-257-1

Source Data: 15 s exposure w/ Cannon Xti Meade Lx200 GPS 10” F10
4/18/2008 ~ 10 PM EST

Figure 3.16– Stars Mizar (upper), Alcor (lower), and TYC 3850-257-1

Source Data: Starry Night Pro +

4 Conclusions

This study set out to determine what, if any, planet forming factors could be isolated using the descriptive statistics of stars known to host extrasolar planets. It was shown through comparing distributions of each factor that the Fe/H ratio, as well as, albeit in a lesser way, the mass of a star may be related to the likelihood that a star will play host to an extrasolar planet. The radius and luminosity of stars were each shown to have little, if any, relationship between a star and its likelihood for having an extrasolar planet. Thus, future astronomers seeking extrasolar planets should pay careful attention to the Fe/H ratio of the stars they observe as well as their mass and aim to study stars with Fe/H ratios and masses similar to stars already known to host extrasolar planets. While this study succeeds in suggesting these factors may be related to extrasolar planets, it did not prove this in a statistically rigorous fashion. Such a rigorous proof is a particularly good direction for future research, as would be the evaluation of even more potential planet forming factors.

The second goal of this study was to demonstrate the difficulty which an amateur astronomer would experience while attempting to observe an extrasolar planet. While many amateur telescopes can achieve a field of vision equivalent to 1 arc second, many planets are much closer to their host star than such a field of vision would discern. Moreover, even utilizing a quality optical device to take photographs of objects many arc seconds apart is challenging and often ridden with obstacles, as is noted in this study's observations of Alcor and Mizar.

Potential sources of error in this study include a measurement bias introduced to the extrasolar planetary system data due to limited measuring techniques used to identify extrasolar planets. This error may have biased data being analyzed in such a way that larger and brighter stars occurred in the dataset more often than they are represented in reality. Related to this source of error was the small sample size for both random stars, as well as stars known to host extrasolar planets. With just over 200 star systems known to host planets, the pool of data begins very small. After some data points are dropped out during different descriptive statistics because there is insufficient information on a star, the dataset is further limited. Moreover, detailed physical data on a wide range of random stars is not widely available to the public and often requires certain values to be backed out from what little existing data is available. While these sources of error may have skewed the results of this study to some degree, the overall message and findings of this paper hold despite their interference.

Ultimately, this project sought to provide a novel method for determining where to point the telescope in the search for new planets through utilizing a descriptive statistical analysis of the stars already known to possess extrasolar planets. Planet forming factors which could help future extrasolar planet searchers identify promising targets were successfully evaluated and noted for future research. Moreover, this study showed the difficulty in observing extrasolar planets without specialized equipment. In the end, only the mass and the Fe/H ratio of stars may have an impact on a star’s likelihood to host an extrasolar planet, but future research in this field may find more promising factors.

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