5-1-2018

DETERMINING THE HABITABILITY OF EXOPLANETS IN TRIPLE STAR SYSTEMS

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by

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Presented to the Faculty of the Honors College of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

HONORS BACHELOR OF SCIENCE IN PHYSICS

THE UNIVERSITY OF TEXAS AT ARLINGTON

May 2018

ACKNOWLEDGMENTS

First and foremost, I would like to acknowledge the support and guidance from my mentor, Dr. Cuntz. Without his help I would not have been able to complete this paper and get a good head start on my research.

I would also like to thank my family. Mom and Dad, my heroes, you have always supported me through everything and a son could not ask for anything better. I owe all this success to you. I cannot believe I made it this far!

I also have to include those close friends that stuck with me through the years. It was through their support I was able to handle college and partially keep my sanity.

To all, thank you for helping me get this far.

May 11, 2018

ABSTRACT

DETERMINING THE HABITABILITY OF

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STAR SYSTEMS

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The University of Texas at Arlington, 2018

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Understanding the habitability of exoplanetary bodies in triple star systems begins by observing the formation timeline of all involved objects and their interactions with one another. If an exoplanet is to flourish in a system with multiple stellar components, it must possess favorable characteristics (i.e. prominent magnetic field) that can withstand the early formation and evolution of those components. Using the parameters of habitability known for Earth, habitable zone models, and a recently constructed Triple System Exoplanet Catalogue (TSEC), we can determine regions where single and combined stellar radiation do not inhibit biological growth. Using a previous definition for a hierarchical system, results show approximately 38% of discovered triple systems are hierarchical in nature. Circumbinary orbits make up approximately 8% of exoplanet orbits, S-type binary

orbits account for 21%, and single S-type orbits account for 71%. Furthermore, exoplanets in the habitable zone of a K-type single star or those in a circumbinary orbit around a binary of similar stellar radiation are thought to be the best candidates for habitability. This preliminary research integrates current studies with the TSEC to provide new insights into the overall picture of how habitability establishes itself in the system. It also highlights the need for further research over specific topic areas covered in the paper.

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CHAPTER 1

INTRODUCTION

There are several conditions that must be met for an exoplanet to be considered habitable, as outlined by numerous previous studies (Bowing & Housh, 1991; Kaltenegger 2007; Airapetian 2016). Unfortunately, there are even more conditions to be satisfied when we specify that this habitability must coincide with a triple star system. As emphasized by Toonen et al. (2016), understanding triple systems heavily relies on merging three-body dynamics and stellar evolution. While numerous works have combined these two components (Kratter & Perets, 2012; Perets & Kratter, 2012; Hamers et al. 2013; Shappee & Thompson, 2013; Michaely & Perets, 2014; Naoz et al. 2016), the overall study of such systems is lacking compared to those of single and binary systems. However, it is from these observations of simpler systems that we have been able to distinguish basic parameters for habitability and outline the most prominent conditions that have allowed life on Earth to not only form but have enough time to grow complex as well.

Although we have a better understanding of how these conditions are vital for a planet to survive and to support life, such conditions become more complex with the addition of stellar components in the system. As stated before, there is not an abundant amount of research material available that combines three-body dynamics and the evolution of each stellar component for a triple system. Thus, there is much more research needed to validate observations made over triple systems (hence, the production of this early Triple System Exoplanet Catalogue [TSEC]). Despite this setback, we can use the fact that exoplanets in triple star systems orbit their stellar components in such a way that it is possible where they are only majorly affected by either one or two components. Thus, data gathered from single stars and binary systems can be used to infer the type of relationship between the possible exoplanet and the stellar component(s). In a three-star system an exoplanet can possibly be habitable if it receives just enough energy to sustain itself but also enough to not have its ability to sustain life stripped away by the stellar flux. Such in-depth discussions will be left for Section 3.1, but before delving into the habitable conditions that must be present we must attempt to understand the composition of the system that could provide such conditions. Focusing on the history of all components in the system is the first step toward understanding how a three-body problem is affected by the evolution of each stellar component and what effects such a combination has on habitability in a system.

CHAPTER 2

FORMATION

It is crucial to understand the very beginning of the formation timeline for stellar objects, and how the formation affects the space environment around the forming star(s) as well. The evolution of single and binary star systems has been studied much more extensively than triples, and there is a consensus over the dominant physical processes that govern the evolution (Postnov & Yungelson, 2014; Toonen et al. 2014, 2016). These studies have shed light on how habitability eventually becomes plausible but only after the components of the systems undergo radical changes to become more stable. For example, in a single system such as that of our Solar System, the early Sun (approximately 100 million years ago) was thought to possess far-UV and X-ray emissions as much as 30 – 50 times and 100 – 500 times, respectively, higher than today (Guinan et al. 2003). To compensate for such intense stellar radiation, early Earth must have possessed a magnetic field for protection (Grießmeier et al. 2004). However, not all objects can protect themselves as we see with Venus and Mars. Venus succumbed to the Sun's high magnetic activity, which has led it to being hot, dry, and inhospitable (Kulikov et al. 2006); while Mars lost its geomagnetic field approximately 3.5 gillion years (Gyrs) ago and has now become too cold and dry for life to exist on the surface (Fairén et al. 2010). This example demonstrates how one stellar component can affect neighboring planets very differently and how properties during formation drastically effect the future of a possible habitable exoplanetary body.

2.1 Three Body Stellar Components

According to Hut & Bahcall (1983), triple systems tend to be hierarchical in nature with a distant star in orbit as the center of mass of an inner binary. For a large majority of such systems, they can be treated as a combination of a binary and single (Valtonen et al. 2008), due to the vast distances between components and we can apply the Lidov-Kozai (LK) mechanism (Toonen et al. 2016). Introducing more stellar components into the system increases the chances of developing instabilities, and systems that are highly unstable eventually dissolve into lower order systems on dynamical timescales (Georgakarakos 2008). Even systems that begin in stable configurations can develop into stages of unstable orbits (Van der Berk et al. 2007). Thus, a prominent topic of triple system formation is stability. But it was quickly found out that a three-body system is a much more difficult problem to solve compared to a two-body; and while various criteria have been established to deal with certain situations over large timescales (Georgakarakos 2008), it can be hard to establish a stable/unstable state, due to the sheer unpredictability of space and the amount of time processes take. One way of modeling stability is using the criteria established by Mardling & Aarseth (1999) (Appendix C).

Using this criterion, Perets & Kratter (2012) show that triple evolution leads to instability in the form of close encounters and collisions between the stellar components (see publication for definition of variables). As noted by Toonen et al. (2016), this equation is based on the consequence of chaos and overlapping resonances. In the inner binary of the triple, the two components can vastly affect each other via stellar winds and mass transfer as the triple begins to evolve (Kiseleva et al. 1994; Iben & Tutukov, 1999; Freire et al. 2011; Portegies Zwart et al. 2011).[1] As noted by Toonen et al. (2016), Lidov-Kozai cycles cause angular momentum to be exchanged between the inner and outer binary. As a result, the orbital inner eccentricity and mutual inclination vary periodically. This is but one way the inner binary can affect the overall system. For more information regarding the orbital inclination affecting stability in triples (such as inner binary mass stability, stability of p-type orbits, and LK cycle effects that cause initially circular orbits to become highly eccentric) see Georgakarakos (2013). Winds and mass transfer in the inner binary can potentially influence the outer star depending upon the stability of the relationship between the inner components. If mass transfer is limited and stable, the outer orbit remains unchanged (Toonen et al. 2016). If the mass transfer is enhanced for the inner binary, the outer star is affected depending upon the mass lost from the inner binary (Toonen et al. 2016). Also, depending upon the spectral types of the inner binary, the star may be more willing to initiate mass transfer (as stars with extended envelopes are more likely to engage in mass transfer). Evolutionary aspects of stellar components that could affect the evolution of triples such as supernovas, neutron stars, and white dwarfs have been studied by Pijloo et al. (2012), Cordes et al. (1993), and Camacho et al. (2014), respectively. In Tokovinin's catalogue of multiple star systems, approximately 20% of the systems contain an outer star that is more massive than the inner two stars. But more studies are needed regarding mass transfer occurring from the outer component of the hierarchical triple and how it can potentially affect the inner binary.

[1] There are numerous mass transfer scenarios in which the transfer is stable and unstable. Circumstances include angular momentum loss if accretor star is not capable of accreting the mater conservatively, the donor star loses envelope, the effects of tides on each component, Common Envelope (CE) phase etc. For a complete reference consult Toonen et al. (2016).

Up until this point the focus has been on hierarchical triple systems of structure "2-1," in which an inner binary is orbited by an outer component that may initiate mass transfer or remotely affect the inner binary. But of the 24 triple systems with exoplanet components, approximately 38% follow a hierarchical orbit of this definition. The majority are found to follow a "1-2" orbit configuration in which an outer binary orbits the center of mass of a primary component. If the primary component is massive enough and the outer binary consists of considerably lower mass stars, it can be assumed it will consume the binary and complete its stellar evolution over large timescales. As noted by Darwin (1879), there is no solution for stability in systems containing components of large mass ratios. The TSEC reflects how in exoplanetary triple systems all stellar components either decrease in stellar type or remain the same for all three components. This is a prime example of how systems form differently, and with further research it could point to how such differing formations affect the evolution of exoplanets as well as the possible physical structure of the expected exoplanet. However, more studies are needed to understand why the presence of exoplanetary bodies cause the system to form in a "1-2" hierarchy as opposed to a "2-1" formation more often, and how such bodies affect the overall formation of the system (as we will discover later, the presence of Jupiter may have very much affected the evolution of all planets in the Solar System). These studies will be aided by the fact triples are becoming more commonly observed, as seen with the research conducted by Duchêne & Kraus (2013) detailing how the fraction of triple systems increases with rising stellar types with approximately 50% of spectral B types being in such systems (Remage 2016). The prevalence of stars in triple systems is further elaborated with the research conducted by Moe & Di Stefano (2016), who detail how 10% of low mass stars are in triple systems.

As expressed before, the evolution of the components is important to detail when considering a three-body problem. We have considered how all three components affect each other and the results of different scenarios. Understanding the environment caused by the stellar components allows us to gauge the parameters the planetary object must possess to survive through the early formation process of one or multiple stellar components. The planet must contain some sort of lengthy "relationship" (i.e., Earth-Sun) with the stellar component so conditions of habitability can form. In-depth discussions regarding inclinations, angular momentum conservation amount stellar components, tidal friction, Roche Lobe overflow, and differing configurations of orbits have been reserved for previously mentioned papers. This paper sheds light on using the TSEC to conduct preliminary studies on how formation is related to stellar evolution combined with a three-body dynamic. There will be more focus on how habitable locations transform throughout the stellar evolution and how the complexity of a three-body problem affects these locations as well in Section 3.1.1.

2.2 Earth & The Solar System

Prior to discussing the formation of exoplanets, a short review on how the Earth was formed might be relevant. It also allows us to examine what initial conditions were present that eventually led to the origin of life. Knowing this information will help us distinguish possible habitable Super-Earths and exoplanets that could possess formation characteristics like that of primordial Earth. This will only cover the formation aspect, as results discussing the biochemistry of Earth's habitability can be seen in Section 3.2.

We know Earth formed approximately 4.5 billion years ago (Manhes et al. 1980; Dalrymple 1991, 2001), and the oldest material in the Solar System is dated to be 4.5672

± 0.0006 Byr (Bowring & Housh, 1995). Planet formation begins during star formation, where planets are born from the circumstellar disk around a forming star (Safronov 1972). In early stages, protoplanetary disks consist of 99% gas and 1% dust grains or ice particles (Williams & Cieza, 2011). Utilizing nebular theory, planets form from accretion, and primordial Earth formed in approximately 10 – 20 Myrs (Télouk et. al 2002). Earth's thermal and volatile beginnings (as well as those of Venus) were researched by Franck & Bounama (1995), who used the information to determine scaling laws for mass-dependent Super-Earths (rocky planets from one to ten Earth masses with the same chemical and mineral composition as the Earth) (Valencia et al. 2006). The formation of terrestrial planets and the early Solar System is discussed in the works of Izidoro & Raymond (2018) in which the formation process of terrestrial and gaseous planets is analyzed under several differing models. It is also discussed how a possible chain of events highlights why our Solar System differs more than 99% of other observed systems. Some of the following differences and notes are as follows: a lack of Super-Earths, a wide-orbit gas giant on a low-eccentricity orbit, early Solar System formation models suggesting Jupiter prevented the other gas giants from invading the inner Solar System, and how the stability between Jupiter and Saturn may have been prevented the destruction of the terrestrial planets during the early stages of formation. We can utilize Solar System constraints by inputting the masses and orbits of terrestrial planets into the Angular Momentum Deficit (AMD) and the Radial Mass Concentration (RMC) equations. (Laskar 1997; Chambers 2001) (Appendix C). The AMD is a diagnostic of how well simulated terrestrial planetary systems match the real terrestrial planet's level of dynamical excitation, while the RMC measures a planetary's system's degree of radial concentration (Izidoro & Raymond 2018). Such constraints can help us with formation models of observed systems and help us distinguish certain events that would be plausible in early Solar System situations.

As previously stated, Earth's formation was occurring about the same time as the Sun. The early yellow dwarf constantly bombarded Earth's magnetic field with far-UV and X-ray emissions as much as 30 – 50 times and 100 – 500 times compared to today. Work by Güdel et al. (1997) shows that zero-age main-sequence (MS) stars rotate over 10 times faster than today's Sun, and it is quite possible the Sun may have had strong magnetic events as well as relatively quiet times during its evolution. This would account for the Sun's prominent magnetic dynamo and high energy emissions during its early age, and it showcases the impact the stellar object had on its space environment (Guinan & Ribas, 2002; Airapetian 2017b). This initial stage of the Sun varied the habitable zone (HZ) in the Solar System from today, and the effects on various planets in the Solar System was discussed earlier and through works by Stevenson et al. (1983) and Sleep (2000) [with specific attention to the thermal evolution of the Sun affecting the inner planets of the Solar System]. Diffey et al. (1991) has completed lengthy analysis of the relationship between Earth and the UV effects of the Sun. Such a relationship details the importance of considering stellar evolution for habitability in a triple system. While a three-body problem encounters a whole range of issues a single does not, it is important to note we have a better understanding of how a single star system interacts with planets through formation. If an exoplanet eventually becomes habitable after the formation process, it is through our studies of the Sun's evolution that we can begin to parameterize the conditions the stellar component imposes upon the planets of the Solar System. It serves as the only model we have thus far of how an evolving stellar component directly affects habitable conditions on a system. The only issue here, compared to our study, is the lack of a three-body problem.

2.3 Exoplanets

As noted in Izidoro & Raymond (2018), our system seems to have formed atypically compared to others. Some of these effects in which our system operated differently have already been discussed (i.e., Jupiter possibly preventing gas giants from entering inner system, stability between Jupiter and Saturn). Unlike Earth, exoplanets generally form within a few million years of their star forming (Télouk et al. 2002; Rice & Armitage, 2003; Mamajek 2009). The general formation of exoplanets follows those processes listed in Section 2.3 and those detailed in the work of Izidoro & Raymond (2018) (for terrestrial exoplanets). Kepler data has found a correlation between the stellar components metallicity and the presence of exoplanets; thus, stars with higher metallicity are more likely to have planets (particularly giant planets) than stars with lower metallicity (Wang & Fischer, 2013). Methods of detection will be discussed further in Chapter 4.

As of April 1 2018, there are 3,758 confirmed planets in 2,808 systems, with 627 systems having more than one planet (http://exoplanet.eu/catalog/). Utilizing the TSEC, we find that most of the masses lie with approximately 1000 $M_\oplus$ (see Figure 2.1).

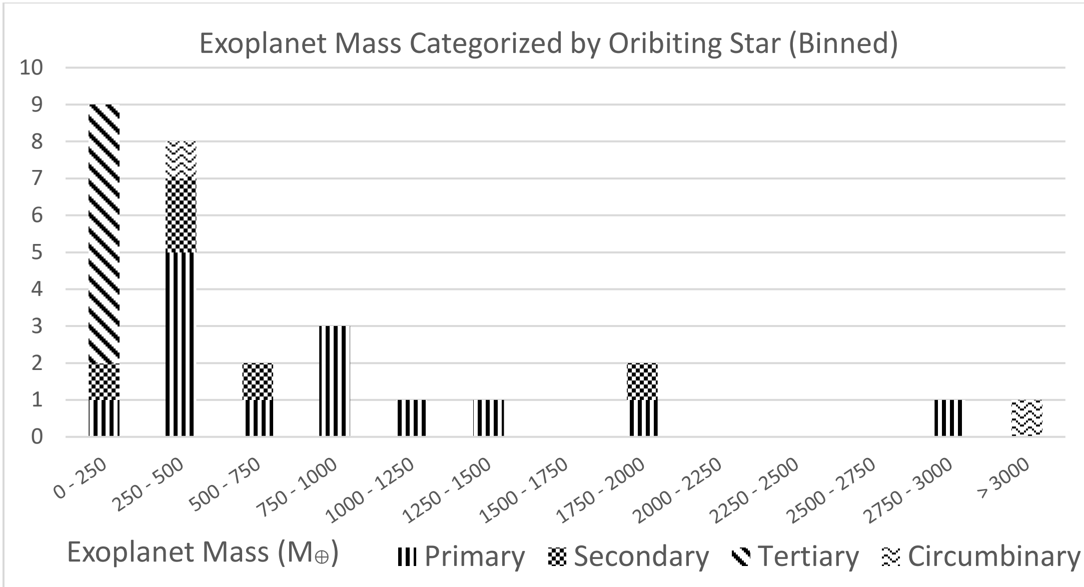

Figure 2.1: Exoplanet Mass Categorized by Orbiting Star (Binned)

In Appendix B we can see characteristics of the exoplanets such as distance from Earth, Earth mass, Earth radius, and effective temperature. These values are a part of the TSEC we will be utilizing throughout the paper.

CHAPTER 3

HABITABILITY

Being the only location we know of capable of supporting complex life, Earth serves as an prime example of what a habitable planet could look like. Many of the conditions we impose upon possible exoplanetary candidates come from the set of parameters we have developed observing Earth's interaction with its space environment over time. However, these parameters we impose upon other objects cannot account for conditions that we do not find in our Solar System (and it is unfortunate due to some atypical aspects of our Solar System as discussed before). Despite this set back, we understand there are underlying conditions that make life more probable in certain locations and it is productive to explore such areas with an attempt to compare observations with already established criterion for habitability. By understanding the processes that have enabled habitability on Earth, namely those of the Sun and the Earth itself, we can attempt to understand and characterize possible habitable worlds in similar as well as more complex systems.

3.1 Habitability – Stellar Components

While it is assumed that most, if not all MS stars can support extreme forms of life, it is the habitable conditions needed for complex forms of life to develop and evolve that piques our interest most. When a possible exoplanet candidate is found, a main priority is determining the architecture of the system around it. Namely, the relationship between the possible candidate and the stellar components of the system (if there are any). Detection methods, which will be discussed in further detail in Chapter 4, allows us to determine basic information (i.e. luminosity, stellar age) of the stellar components that affect the habitability of the space environment. Using this information, we can acquire the identity of stellar components and therefore infer habitability conditions. The search for habitable locations centers around F-M type MS stars, as the nuclear evolution timescale for more massive stars evolves much faster and their lifespans are much shorter compared to F-M types, which can sustain themselves for extended periods of time (see Salaris & Cassisi, 2005; Eker et al. 2015; Toonen et al. 2016). Theoretical HZs have been studied for those stars of higher spectral class (O-A), but there are so many hindrances to the formation of life (stellar winds, short stellar lifetime, radiation, effective temperature, etc.), it is not promising to search for life around such stars. Studies over F type stars and their habitability have been completed by Meynet et al. (1993), Cockwell (1999), Mowlavi et al. (2012), and Sato et al. (2014). Out of the F-M type group, F-types suffer an extreme disadvantage for habitability, as they evolve from the MS much faster than the other lower mass stars. This consequently results in any chance of habitability to be highly improbable but not impossible. Conditions of habitability are already widely known for G-types, as our Sun has been under much research in several regards (Durney 1972; Skumanich 1972; Guinan & Ribas, 2002). K-types have been discussed and apart of research as well, especially regarding the search for astrobiology (Cuntz 1998, 1999; Cuntz & Guinan 2016; Kaltenegger 2017). These orange dwarfs possess some of the best characteristics to support life; however, exoplanetary bodies orbiting a K-type component are subjected to high levels of X-ray and UV irradiances, while the star is young, similar to the early environment Earth was subjected to (as discussed previously in Section 2.2). Perhaps the most researched are M-types, which is more than likely attributed to accounting for 75% of the MS stars in the solar neighborhood (LeDrew 2001). Papers studying physical characteristics of M-types, as well as their capability to provide habitable conditions, include Cuntz (1998, 1999), Tartar et al. (2007), Tabataba (2016), Guinan et al. (2016), Airapetian et al. (2017a), and a plethora of references throughout Cuntz & Guinan (2016).

Regarding HZs, I will be adopting notation from Cuntz & Guinan (2016), as well as the varying definitions of HZ criteria established in the same paper. Research over finding a stable HZs around a single star system has been conducted by Kasting et al. (1993) and Kopparapu et al. (2013, 2014), while higher-order systems (such as a binary and multiple systems) have been studied by Cuntz (2014a, 2015). General HZ (GHZ) account for the greenhouse effects, which gives inner and outer limits to HZs and have been measured for differing stellar components ranging from F-M types. Studies conducted by Grießmeier et al. (2005) and Güdel & Náze (2009) demonstrate how active low mass MS stars have high XUV fluxes comparable to the Sun at age 0.7 Gyr-old Sun (with the latter specifically outlining K, M, and G-type stars) (Airapetian et al. 2016). Models used by Cuntz & Guinan (2016) also demonstrate X-ray and far UV irradiances for G0 V thru M5 V stars over a range of ages. Like Earth, any exoplanetary body would have to have an established magnetic field that could protect it from the early formation of a stellar component. Of course, interdependencies are a bit more complex when a higher order system contains stellar components comprising of different spectral classifications that form and affect the primordial exoplanet differently. As discussed in Section 2.1, triple systems form being comprised of a binary and a single component. Therefore, exoplanets in orbit of one component in the system may follow HZ models as laid out by the work of

Kasting et al (1993). Likewise, those in circumbinary orbits can be treated as orbiting one stellar component (except when the two components eclipse one another) depending on the distance the exoplanet is from the binary and the spectral types of the components. With the background of formation alongside habitability studies of differing stellar components, we can now look at specific triple systems, and distinguish whether the spectral components of the systems inhibit or provides habitability.

Of the currently cataloged triple star systems, most components are of either K or M-type, which shows that the majority of the triple star systems found will contain stellar components of smaller mass and lower luminosities as expected. Of the 24 catalogued exoplanetary triple systems alongside four quadruple systems, those components of which we know the spectral type can be used to calculate the expectation values using already obtained information found from observing the solar neighborhood. These expectation values are listed in Table 1 below using information from Bennet & Shostak, 2016.

Expectation Values Table			
Spectral Type	# of Stars	Frequency	Expect Value
A	4	1%	0.57
F	7	2%	1.14
G	14	7%	3.99
K	11	15%	8.55
M	21	75%	42.75

Table 3.1: Expectation Values

Using the information from Table 1, we created a bar graph (Figure 3.1) detailing the number of stars in each spectral type. This graph highlights which spectral types dominate component groups. For example, we can see that the primary components of triples occupy all spectral classes, but the majority is focused on later spectral types such as A, F, and G. Likewise, tertiary components are mostly smaller M-types. The overall trend details how spectral class lowers with each progressing star; therefore, the stellar components decrease in mass, radius, and effective temperature as we progress from the primary to tertiary component.

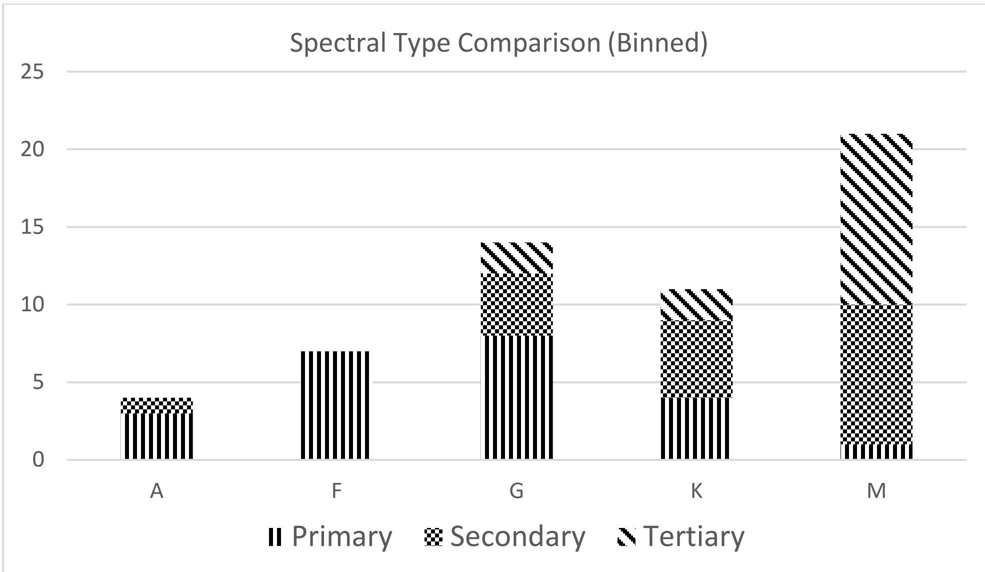

Figure 3.1: Spectral Type Comparison (Binned)

Those exoplanets with a G-type or lower primary component are more likely to be in a habitable system, as the rest of the components would be of lower spectral class. Depending upon the stability of the lower-class components, these systems could provide the best chances of life. Studies completed by Tabataba (2016) detail flare activity around M dwarfs stars, and further research regarding super-flare activity on exolife in general has been completed by Segura et. al (2010) and Kasting et. al (2014). Generally, flare activity is considered incredibly harmful and preventative of habitability, but recent work by Airapetian et al. (2016) has identified how super-flares can have favorable outcomes to kick start biology on G and late K-type stellar components. This will be taken into consideration when considering exoplanet habitability in Section 3.2. All information thus far would suggest the best spectral type for habitability would be K-type. This is due to the fact it is less prone to flares than M-types, has a longer lifetime than G-type stellar components, and is less prone to tidal locking during formation.

In future research we can utilize the TSEC and combine previous research conducted by Cuntz & Guinan (2016) over HZ calculations as well as UV irradiance for G, K, and M dwarfs stars over time to determine HZs around the most stable stellar components of the system. Those exoplanets within their stellar components HZ can retain liquid water on their surface and therefore be habitable. This is, of course, using a standard model set by the previous research of one team. Subsequent models formed from different research must be used in conjunction with the TSEC to validate the HZ and GHZ values used. Those exoplanets within the primary component's HZ require further research and criteria to establish their habitability. When further research is completed and results are validated, the combined research efforts of differing spectral types, HZ calculations for single and binary systems, and the TSEC can help us distinguish habitable conditions in triple star systems. This is due to the fact that most triples follow a hierarchical formation and they act as single and binary systems. However, not all triple systems follow this format. Those that follow different orbits, such as cases of unstable systems and exoplanets that orbit one component of a binary, are described in further detail in the following subsection.

3.1.1 Habitable Zone (HZ) Variation in Triple Systems

Established boundaries and formulas for HZs as well as GHZs have already been discussed for single and binary systems Section 3.1, but the addition of a third component in the system can either cause drastic or little variation in the system. As stated before, a hierarchical formation for a triple system is the most stable configuration that can provide a long lifespan to all relevant components. Triples that do not follow this hierarchical regimen are more likely to be unstable and even lose components due to erratic orbits. Studies conducted by Valtonen et al. (2008), using the stability condition for hierarchical stability (Eggleton & Kiseleva, 1995), showed how the energy of the system changed if a single component entered a binary formation. The role of orbital inclination in the stability of a system was studied by Georgakarakos (2013) and demonstrated how differing orbital angles can cause variations in the orbits resulting in stellar components being ejected from the system during the integration time. Approximately 8% of exoplanets fall into circumbinary orbits (P-type orbit), while 92% into S orbits. Of that 92%, 21% orbit one component of a binary pair (SB-type orbit) while 71% orbit one component (S-type orbit). Therefore, we can roughly treat 71% of exoplanets as a single system while the other 29% will be treated as a binary (depending upon circumbinary information). For the binary studies, habitability is greatly dependent upon the spectral class of the stellar components. In Table 3.2 I have listed such components for further discussion.

P & SB Systems					
System	Comp A	Comp B	Comp C	ToS	ToO
HW Virgins	M	M	---	"2-1"	P
KOI-2939	F	G	---	"2-1"	P
Formalhaut	A3V	K4Ve	M4V	"2-1"	SB
Psi1 Draconis	FV	G0V	K/M	"2-1"	SB
HD 126614	K0	MV	M4	"2-1"	SB
HD 2638/2567	G0	G5	M1V	"1-2"	SB
HD 4113	G5V	M0	T9	"2-1"	SB

Table 3.2: P & SB Systems

Using the table, we can see the first two encompass circumbinary orbits. While the spectral classes match accepted types for habitability, the presence of an M-type can hinder chances of probability. HW Virgins contains two M-types, which are susceptible to flares and high magnetic activity that have higher chances to hinder a planet's biological production. For KOI – 2939, a triple system where the binary is composed of two different spectral types, studies by Cuntz (2014b) and Moorman et al. (2018) would be of benefit to understand how the two different spectral classes causes variation in the orbit and HZ. The same paper can be applied to other cases in the table such as Formalhaut, HD 126614, Psi 1, and HD 4113. The last system contains a binary configuration in which the exoplanet is in a binary where the two stellar components are roughly the same spectral class. This is a much more stable configuration that can prevent the orbit from becoming too eccentric. In future papers we can use established HZ models to observe binary components in the triple systems and distinguish regions in which the flux would not be too little or too high for the exoplanet to thrive.

3.2 Habitability – Exobiology

Understanding the formation of Earth and the processes that allowed life to grow complexly, allows us to observe exoplanets that could be in similar circumstances around their parent stars. We now have come to understand that Earth was formed in an atypical system (see Section 2.2), but it is believed that the same conditions of habitability on Earth can be reached in other systems. While these conditions greatly minimize possible habitable exoplanets, each category helps to fine tune the wide range of objects observed in interstellar space. Such categories include formation, physical characteristics, and neighboring space environment. Turning to the biological and chemistry aspect of exoplanets, if they are to be habitable they should possess observable signatures of life that need to modify the atmosphere or surface (as well as other atmospheric components such as stellar irradiance, or atmospheric composition that determines climate, and orbital flux variations) (Kaltenegger 2017). If the exoplanet is biological active, atmospheric biosignatures should be detected (Kaltenegger 2017). If an exoplanet does lie within the HZ and its stellar component does not damage its surface, the next step is to closely monitor its progression and see if we can detect biological activity like that on Earth.

3.2.1 Earth Habitability

Despite our best efforts, the only signs of life detected have been on Earth. But as we know, life can form in the harshest of conditions (Kashyap 2018). During birth, Earth was covered in incandescent pools of magma and was constantly in battle with the prolific boulders colliding with its surface – some averaging 75 times the speed of sound (Hazen 2001). This war would sterilize the planet's surface for another half billion years, and the dense iron from the oceans of magma began to sink to form the metallic core of current Earth (Valley et al. 2002). Deep underground, the radioactive decay of elements produced heat at rates more than six times greater than they are today (John et al. 2002). But at some point, within a few hundred million years of this hellish age, microscopic life crafted from air, water, and rock appeared in abundance (Robert 2001). There is a general understanding that the first major component of life's origin started with carbon-based molecules that could make copies of themselves, and there are numerous papers discussing the advantages of carbon over other molecules as well (Goldsmith & Owen, 2002; Von Bloh et al. 2007; Airapetian 2017b). There have been attempts to recreate the environment of primordial Earth with only the known compounds available, such as Stanley L. Miller's famous experiment in the early 1950s, which attempted to the first chemical reactions on primitive Earth. This is possibly how intricate organic compounds could have formed from simple molecules present on the surface.

Current methodologies for detecting biological activity on exoplanets arise from the presence of chemical compounds that are out of chemical equilibrium due to the complex biochemistry of life (Seager 2013; Lovelock 1975). Common molecules in Earth's troposphere such as molecular oxygen, ozone, water vapor, carbon dioxide, nitrous oxide, and methane should be detectable on a biological active exoplanet (Kaltenegger et al. 2007; Berdyugina, 2016; Seager et al. 2016; Meadows et al. 2017). The ability for life to be sustained on Earth is due to several considerable factors such as: Earth forming in the HZ of its parent star, Earth developing liquid water as a solvent, and a domination of the carbonate-silicate cycle that maintains the long-term climatic stability of the planet (Von Bloh 2007). Its continued success as a habitable planet is quite apparent, with its abundant oceans, greenhouse atmosphere, global geochemical cycles, and life itself (Kaltenegger 2017). Although we are not able to observe Earth at different geological ages, rock records contain critical information for determining the atmospheric makeup of primordial Earth. We can also constrain the stellar irradiance on Earth as well, since we know the evolution of our Sun. It is assumed more massive planets (i.e. Super-Earths) convect in plate tectonics similar to Earth (Valencia et al. 2007), and biological active planets will retain several characteristics similar to that of Earth's early atmosphere depending upon their age (Cockrell 2002; Lyons et al. 2014; Airapetian et al. 2017; Reinhard et al. 2017).

3.2.2 Triple Star Systems

With this information, we can observe Earth's timeline and compare it to other exoplanets in different geological ages, which could possibly harbor life. As expected, this information is limited by the fact it derives from a system of one stellar component, but as we calculated earlier 71% of exoplanets can be treated as a single system in their triple orbit, while 29% can be treated as a binary or higher system. Further studies are needed to complete the analysis of habitability amongst the systems themselves. The TSEC can be used in conjunction with previous studies to determine the state of exoplanets relative to their stellar components and their formation. Information over the exoplanets in these systems can be found in Table 3.3 below:

Exoplanets				
Exoplanet Name	M	R	Temp(K)	Type
91 Aquarii Ab	1017			---
Prox Cent b	1.27			Terrestrial
Dagon Ab	953.7			---
HAT-P-8 Ab	425.98	16.45		Hot Jupiter
HD 178911Bb	2000			---
Psi1 Draconis Bb	486.4			---
WASP - 12 Ab	446.32	19.04		Gas Giant
Gliese 667 Cb	5.595			---
Gliese 667 Cc	3.8147			Terrestrial
Gliese 667 Cd	5.1			---
Gliese 667 Ce	2.702			---
Gliese 667 Cf	2.702			---
Gliese 667 Cg	0.461			---
16 Cygni Bb	534.07			---
Kelt - 4Ab	281.02	18.71		Hot Jupiter
51 Eridani b	2892.88	12.17		Jupiter-like
HAT-P-57 Ab	588.11	15.49		---
HD 126614 Ab	120.8			---
HD 132563 Bb	473.67			---
HD 196050 Ab	899.65			---
HD 2638 Bb	152.59	11.4		Hot Jupiter
HD 40979 Ab	1274.77			Gas Giant
HW Vir (AB)b	4545.95			---
Kepler 444 Ab		3.73		Terrestrial
Kepler 444 Ac		0.48		Terrestrial
Kepler 444 Ad		0.48		Terrestrial
Kepler 444 Ae		0.052		Terrestrial
Kepler 444 Af		0.66		Terrestrial
HD 4113 Ab	495.92			Gas Giant
Kepler - 13 Ab	1926.46	15.42	2750	Hot Jupiter
KOI-2939 (AB)b	483	17.54		---
HD 185269 Ab	298.82			---
HD 41004 Ab	807.46			---

Table 3.3: Exoplanets

Of the total triple star systems found, there are a total of 33 exoplanets among them. Exoplanets can be classified as either being a part of the jovian or terrestrial class. Out of the 33, approximately 15 can accurately be placed into one physical class. With 7 being terrestrial in nature and the other 8 being jovian. Using the TSEC we can also include the types of systems these exoplanets are in Table 3.4.

Exoplanet Types						
Exoplanet Name	ToS	ToO	M	R	Temp(K)	Type
Prox Cent b	"2-1"	S	1.27			Terrestrial
HAT-P-8 Ab	"1-2"	S	425.98	16.45		Hot Jupiter
WASP - 12 Ab	"1-2"	S	446.32	19.04		Gas Giant
Gliese 667 Cc	"2-1"	S	3.8147			Terrestrial
Kelt - 4Ab	"1-2"	S	281.02	18.71		Hot Jupiter
51 Eridani b	"1-2"	S	2892.88	12.17		Jupiter-like
HD 2638 Bb	"1-2"	SB	152.59	11.4		Hot Jupiter
HD 40979 Ab	"1-2"	S	1274.77			Gas Giant
Kepler 444 Ab	"1-2"	S		3.73		Terrestrial
Kepler 444 Ac	"1-2"	S		0.48		Terrestrial
Kepler 444 Ad	"1-2"	S		0.48		Terrestrial
Kepler 444 Ae	"1-2"	S		0.052		Terrestrial
Kepler 444 Af	"1-2"	S		0.66		Terrestrial
HD 4113 Ab	"2-1"	SB	495.92			Gas Giant
Kepler - 13 Ab	"1-2"	S	1926.46	15.42	2750	Hot Jupiter

Table 3.4: Exoplanet Types

With the exception of two systems, we can see that the majority of exoplanets are located in systems where they could be treated as a single component (classified as S under heading “ToO”). Also, it can be noted that all of the terrestrial class exoplanets lie in single systems. Therefore, for terrestrial planets, we can use conditions founded in our Solar System to make comparisons of habitability (assuming the binary component of the triple does not affect the exoplanet). Likewise, we can use information over the jovian planets in our Solar System to infer conditions of habitability of gas giants we find in S-type orbits in triples. What’s peculiar is how the two exoplanets with SB-type orbits are jovian in nature. With further study some light could be shed on how gas giants are more likely to form in these types of orbits and terrestrial planets are more likely to form in stable orbits regardless of the multiplicity of the system. Binary studies on gas giants will help distinguish habitable characteristics for exoplanets that find themselves in similar circumstances.

CHAPTER 4

DETECTING HABITABLE SYSTEMS

The majority of exoplanets studied are found using the transit method. As seen in Table 4.1, there have been a variety of methods used to detect exoplanets and their spectral information. This table details A detailed look into the various detection methods that have found the number of systems with planets and multiple planets as of October 14, 2017. As we can see, the main methods used are Primary Transit and Radial Velocity (exoplanet.eu).

Detection Methods	Systems	Planets	Multiple Planets
Radial Velocity	544	728	131
Pulsar	20	25	4
Microlensing	61	63	2
Imaging	81	88	5
Primary Transit	2059	2748	455
Astrometry	1	1	0
TTV	6	7	1
Other	13	14	1
Secondary Transit	0	0	0
TOTAL	2752	3672	616

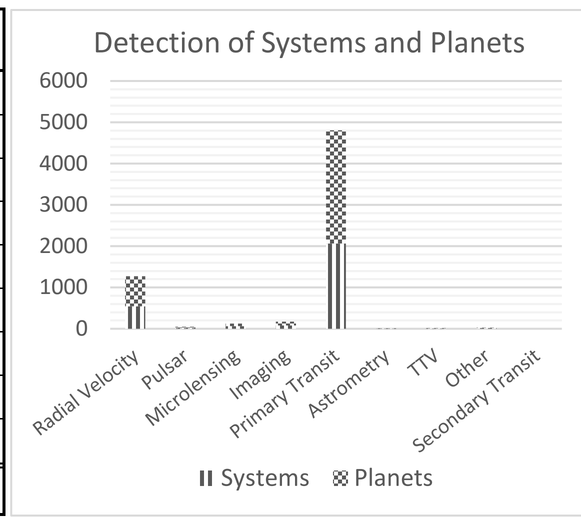

Table 4.1: Detection of Systems and Planets

As technology and telescopes become more sophisticated, we will be able to observe farther and more in depth. This will be vital to detect possible biosignatures through observing the spectra of exoplanets. As noted by studies of Snellan et al. (2015) and Stark et al. (2015), detecting major biosignatures from an Earth-like active planet around a Sun-like star is difficult with current telescopes and requires long exposures with high spectral, high contrast, and high spatial resolution coronographic instruments on ground-based telescopes. These elusive biosignatures can be indicative of the biological activity on the surface of an exoplanet, and they detail a plethora of information including atmosphere composition, magnetic field presence, and surface activity.

4.1 Atmospheric Biosignatures

When attempting to find exoplanets or exomoons that could possible harbor life, it is a key factor to try and detect atmospheric biosignatures that modify the atmosphere or surface. The term "biosignatures" is used to represent gases that are produced by life, accumulate in the atmosphere, are not readily mimicked by abiotic processes, and can be detected by space telescopes (Kaltenegger 2017). There are also multiple types of biosignatures one could detect, such as abiotic, biological, and technology-based (Kaltenegger 2017). It is crucial to be able to separate these signatures and understand each one when attempting to detect them. As noted in Section 3.2.1, the first forms of life on Earth did not rely on oxygen, but on carbon dioxide (e.g., Goldsmith & Owen 2002). Studies led by Sagan et al. (1993) studied the emergent spectra of planet Earth and detected copious amounts of oxygen and methane, which strongly suggest the presence of biology. But the mere detection of just one of these gases is not enough to conclude that it is a biosignature being observed because an individual gas could very well be produced abiotically and build up in the atmosphere without the presence of life (Kaltenegger 2017). In fact, oxygen alone was thought to be a tracer of life, but several teams of scientists have shown that oxygen can build up abiotically through photodissociation at the edges of or the outside of the HZ. Similar to oxygen, methane alone was also thought to be a possible tracer of life. With approximately one-third present day methane being produced via geological activity and the rest produced via human activity (Krüger et al., 2001). Only a small amount is produced abiotically, but the amount of methane depends on the degree of oxidation of a planet's crust and upper mantle (Kaltenegger 2017). Therefore, the detection of methane alone cannot be considered as a biosignature. However, if detected together as a pair, these two could allow for the formation of carbon dioxide and water, which are required for life to exist. Carbon dioxide and water also serve as vital greenhouse gases and could highlight possible concentrations of oxygen on the surface of the subject of study (Kaltenegger 2017). Detecting such signs of possible life from vast interstellar distances can be quite a challenge, and if a ground based telescope was to be used (like the ELT [Extremely Large Telescope] or similar telescopes), they would have to use high resolution spectra and detect the possible biosignatures via doppler-shifted lines caused from observing over some prolonged period of time (Kaltenegger 2017). Another type of biosignature that could be observed is called a technology biosignature such as CFCs (CCl_2F_2 and CCl_3F), which are not naturally produced but rather by technology on our planet. While these could be used to detect advanced civilizations, they are extremely hard to detect spectroscopically and their abundance on Earth is quite small (Kaltenegger 2017).

In regard to finding these elusive biosignatures, their effects on spectral features depends on the wavelength observing the effect. For example, on Earth the spectral features seen in reflected light (UV to NIR) is dependent on the abundance of a chemical as well as the incoming stellar radiation at that wavelength (Kaltenegger 2017). For detecting a biosphere similar to that of our Earth, the key pairing to look for would be a combination of oxygen and methane in the visible to NIR from 0.7 to 3 μm to include the 2.4-μm CH_4 or observations in the IR between 5 and 10 μm (Kaltenegger 2017). The UV wavelength range is extremely sensitive to even the smallest of molecular abundances, resulting in it being a poor candidate for searching for biosignatures. Remote direct detection of surface life in reflected life becomes possible when organisms modify the detectable reflection of the surface (Kaltenegger 2017). An example of this would be the vegetation of Earth. Vegetation requires photosynthesis, and this process adapts to the spectrum of light that reaches the organism. Therefore, any color from deep violet through the near-infrared could power photosynthesis (Nancy 2008). This means around hotter and bluer stars compared to our sun, plants would tend to absorb blue light and could look green, yellow, or even red. Around cooler stars, such as red dwarfs, planets would receive less visible light resulting in plants attempting to absorb as much visible light as possible making them look black (Nancy 2008). Vegetation is but one of the many surface features that life produces on Earth. An experiment conducted by S. Hegde in 2015 showcased the spectral characteristics of 137 phylogenetically diverse microorganisms containing a range of pigments, including ones isolated from Earth's most extreme environments (also known as extremophiles). This experiment used an integrating sphere that mimicked the observations of an exoplanets modeled as a Lambertian sphere. This provided high-resolution hemispherical reflectance measurements for the visible and NIR spectra for a subset of life known on Earth and is completely free and available at http://carlsaganinstitute.org/data (Kaltenegger 2017).

When observing any object for potential biosignatures it is always important to determine what stage the object is in in its life cycle. It has already been well established Earth has undergone drastic changes during its lifetime, but throughout its growth there are periods during its evolution where biosignatures are more prominent or just beginning to form. At the beginning of its 4.5 billion year lifespan, the Earth received a different amount of stellar radiation than it does today. This affected not only the temperature of the planet, but the spectrum, chemical makeup, and surface morphology over time. It was not until 2.3 billion years ago that the Earth first formed abundant amounts of oxygen and ozone that affected the atmospheric absorption of the spectrum. This rise in oxygen made the biosignature pairing with the reduced gas methane detectable in the IR and NIR (Kaltenegger 2017). This has resulted in Earth showcasing a strong infrared signature of ozone compared to methane for more the two billion years. Knowing this historical information of our planet, we can establish potentially habitable planets exhibiting a similar observed spectrum as that of our past Earth.

4.2 Locations for Habitability

K and M-types combined make up approximately 90% of the observed stars in the solar neighborhood (see Table 1). Despite the heavy presence of M-types in triple systems, the most probable location to find a habitable planet would be around a K dwarf star (see Section 3.1 regarding flare activity and M-type habitability references within). However, there have been drawbacks to this conclusion, such as planets becoming tidally locked to the K or M type star due to complicated orbital distances, or X-ray and EUV flare activity with occurrences up to 10-15 times per day (for young M dwarfs) (Cuntz & Guinan, 2016). Despite some of these drawbacks, it is entirely possible for life to find shelter on the subsurface of a planet. While this makes detection more of difficult task, it could show how intelligent life would take shelter from UV radiation underneath an ocean or soil layer of a planet.

There are several subjects under study for the search of life, and one such example is our closest neighboring star, Proxima Centuari. The active M5 flare star experiences intense flares every 10-30 hours, exposing the terrestrial exoplanet in its HZ Proxima Ab to 30 times more EUV than Earth and 250 times more X-ray radiation (Ribas et al. 2016). If the exoplanet does not have a strong planetary magnetic field, then its atmosphere would be thinner and therefore allow more UV radiation to affect the planet. If life was to be found on such a planet, it would show just how tenacious life can be and help reinforce that life can form in harsh environments. For those exoplanets in the catalogue that orbit M-type stars, habitability would likely be reduced to the termination line. Where the tidally locked exoplanet has one side that constantly faces the star and the other side is shrouded in darkness. In between these two areas is a small sliver (i.e. the termination line) that could possible possess the necessary conditions for liquid water to form. In future studies, data should be collected over exoplanets in S-type orbits around single stellar components of spectral class G-M. This is considered the best-case scenario for habitability in stellar triples. Once an abundant amount of information exists over this scenario, the next step would be to focus on collecting data for SB-type orbits in the binary of a triple.

CHAPTER 5

CONCLUSION

In conclusion, research yields that all observed triple systems are hierarchical in nature, with the majority of systems taking on a "1-2" type orbit (as opposed to the original definition of "2-1"). Possible exoplanetary bodies must possess a strong magnetic field capable of withstanding far-UV and X-ray stellar emissions as much as 30 – 50 times and 100 – 500 times, respectively, higher than today during the formation process of the stellar components (for a Sun-like star). Triple systems currently have but one observed formation that provides optimal stability, and this in the form of a hierarchical triple. We can use stability equations and Solar System constraints to determine the formation process of our Solar System and relate it to other systems as well as distinguish it from others as well. Those systems which contain higher spectral components (A-F) are more likely to cause instability within the system due to short life spans and stronger fluxes of magnetic activity. Likewise, exoplanets orbiting M-type stars are more susceptible to tidal locking and lower chances of habitability.

Utilizing the TSEC, we can obtain expectation values of the spectral types by using data collected over observing the solar neighborhood. The primary components of stellar triples contain the highest spectral type of all three stars, with most systems losing spectral class with each following stellar component. All triples in the catalogue are constructed of a binary and a single component; however, the old "2-1" model of hierarchical triples accounts for approximately 40% of components and is replaced by a higher percentage of

“1-2” orbits with approximately 60% of triples following this new hierarchy. K-type stars would provide the most productive search for habitable life, as the orange dwarfs are less prone to tidal locking and flares compared to M-types and have stellar lifetimes that would be less likely to inhibit triple stability, unlike higher spectral types such as A, F, and G-types. This preliminary study shows approximately 8% of exoplanets are in circumbinary orbits, while 21% are in SB-type orbits, and 71% are in S-type orbits with single stellar components. Exoplanets in single S-type orbits are mostly terrestrial in nature, and SB-type orbits observed belonged to gas giants. In future studies we can combine previous research over single and binary systems with data from the TSEC to determine which exoplanets lie within the HZ and GHZ of their parent star. Once an exoplanet has been classified as possibly habitable, any presence of biology should be indicated by observed atmospheric biosignatures with the most likely indicator being in the form of a combination of methane and oxygen.

If future studies conclude the same calculated orbital percentages for the P, SB, and S-type orbits within the triple, this will accomplish several things: (1) The habitability of exoplanets in triple systems will be distinguished much quicker, as most components in triple systems would then follow a S-type orbit around a single component much like that of our heavily researched Solar System. (2) The structure of exoplanet orbits in triples would have a foundation stating the majority should orbit only one component (3) Exoplanets would be approximately three times more likely to have an SB-type orbit compared to a P-type, and there would be a higher chance of the planet being jovian. (4) Finally, exoplanets could only orbit in one of three configurations if the system intends on maintaining long term stability. All four statements have heavy implications, but all touch on the fact more research is needed to verify such conclusions. Should these statements hold true, future studies can begin discussing more complicated aspects of habitability such as SB-type and P-type orbits around stellar components comprised of two different spectral types in triple systems.

APPENDIX A

TSEC DATA: STELLAR COMPONENTS

For the following catalogue, there is a specific notation used to designate the origin of the data. Superscript A defines information that was pulled from an exoplanet catalog that can be found at openexoplanetcatalogue.com/. Superscript B defines information that was pulled from an exoplanet catalog that can be found at http://exoplanet.eu/.

If the column has a superscript of A or B, then all information below it is from that source unless otherwise specifically noted elsewhere. Superscripts next to star names indicates the information in that row comes from a different catalogue than that which is referenced in the table headings. Data with a superscript indicates only that piece of information came from the opposing catalogue. All information pertaining to the stellar components and exoplanets is retrieved from these two catalogs. The graphs and tables throughout the paper are of my own creation based upon the data I have reconciled from the catalogs.

TSEC DATA – STELLAR COMPONENT A

Star Name	App Mag[B]	ToS[A]	ToO[A]	Dist (pc)[B]	Spectral Type[B]	$M_\odot$[B]	$R_\odot$[B]	Temp (K)[B]	Metallicity[B]	Age (Gyr)[B]
91 Aquarii A	4.21	"1-2"	S	45.9	K0III	1.4	11	4665	-0.03	3.56
Alpha Centauri A[A]	0.01	"2-1"	S	4.37	G2V	1.1	1.227	5790	0.2	
Formalhaut	1.16	"2-1"	SB	7.704	A3V	1.92	1.184	8590		0.44
HAT-P-8 A	10.17	"1-2"	S	230	F	1.28	1.58	6200	0.01	3.4
HD 178911Aa[A]		"2-1"	S		G	1.1				
Psi1 Draconis Aa[A]	4.56	"2-1"	SB	22.93	FV	1.43	1.2	6546	-0.1	2.3
WASP-12 A	11.69	"1-2"	S	427	G0	1.35	1.599	6300	0.3	1.7
Gliese 667 A		"2-1"	S							
16 Cygni A	5.96	"2-1"	S		G2V	1.11	1.243	5825	0.1	6.8
Kelt - 4A		"1-2"	S	211	F	1.204	1.61	6207	-0.116	4.38
51 Eri A	5.223	"1-2"	S	29.4	F0 V	1.75			-0.027	0.02
HAT-P-57 A	10.47	"1-2"	S	303	A	1.47	1.5	7500	-0.25	1
HD 126614 A	8.81	"2-1"	SB	72.4	K0	1.145	1.09	5585	0.56	7.2
HD 132563 Aa[A]	8.966	"2-1"	S		F8V	1.081		6168		
HD 196050 A	7.5	"1-2"	S	46.9	G3 V	1.17	1.29	5874	0.23	3.17
HD 2567[A]	7.76	"1-2"	SB		G0					
HD 40979 A	6.74	"1-2"	S	33.3	F8V	1.1	1.21	6205	0.194	1.48
HW Virgins A[A]	4.22	"2-1"	P	181	sdB+M	0.485	0.183			
Kepler 444 A	9	"1-2"	S		K0V	0.758	0.752	5046	-0.55	11.23
HD 4113 A	7.88	"2-1"	SB	44	G5V	0.99		5688	0.2	4.8
Kepler - 13 A	10	"1-2"	S		A	2.05	2.55	8500	-0.14	
KOI-2939 A[A]		"1-2"	P		F	1.221	1.79	6210	-0.14	4.4
HD 185269 A	6.68	"1-2"	S	47	G0IV	1.28	1.88	5980	0.11	4.2
HD 41004 A	8.65	"1-2"	S	42.5	K1V	0.7		5035	-0.09	1.64

TSEC DATA – STELLAR COMPONENT B

Star Name	App Mag[A]	ToS[A]	ToO[A]	Dist (pc)[A]	Spectral Type[A]	$M_\odot$[A]	$R_\odot$[A]	Temp (K)[A]	Metallicity[A]	Age (Gyr)[A]
91 Aquarii B	9.9	"1-2"	S		K3 V	0.78				
Alpha Centauri B[B]	1.33	"2-1"	S		K1V	0.907	0.865	5260	0.23	
TW Piscis Austrini	6.48	"2-1"	SB		K4Ve	0.73		4594		
HAT-P-8 B		"1-2"	S		M5V	0.17		3216		
HD 178911 Ab		"2-1"	S		K	0.79				
Psi1 Draconis B	5.7	"2-1"	SB		G0V	1.19		6213		2.5
WASP - 12 B		"1-2"	S		M3V	0.56		3786		
Gliese 667 B		"2-1"	S							
16 Cygni B	6.2	"2-1"	S	21.41	G2.5Vb	1.01	0.98	5766	0.08	8
KELT - 4B		"1-2"	S							
GJ 3305 A	7.7	"1-2"	S		M0	0.67				
HAT-P-57 B		"1-2"	S			0.61				
HD 126614 B		"2-1"	SB		MV	0.324				
HD 132563 Ab		"2-1"	S			0.5				
HD 196050 Ba		"1-2"	S		M3	0.29				3.55
HD 2638 B[B]	9.44	"1-2"	SB	53.71	G5	0.93		5192	0.16	3
HD 40979 B		"1-2"	S		K5	0.833				1
HW Virgins B	15.59	"2-1"	P		sdB+M	0.142	0.175			
Kepler 444 B		"1-2"	S		M	0.29		3464		
HD 4113 B	12.7	"2-1"	SB		M0	0.55		3833		5
Kepler - 13 B	10.2	"1-2"	S		A	1.68	1.68	7530	0.2	0.5
KOI-2939 B		"1-2"	P		G	0.968	0.966	5770		4.4
HD 185269 Ba		"1-2"	S			0.17				
HD 41004 Ba	12.33	"1-2"	S		M2	0.4				

TSEC DATA – STELLAR COMPONENT C

Star Name	App Mag[A]	ToS[A]	ToO[A]	Dist (pc)[A]	Spectral Type[A]	$M_\odot$[A]	$R_\odot$[A]	Temp (K)[A]	Metallicity[A]	Age (Gyr)[A]
91 Aquarii C	10.1	"1-2"	S		K	0.73				
Alpha Centauri C[B]	11.3	"2-1"	S	1.295	M5.5	0.12	0.141	3050		
LP 876-10		"2-1"	SB		M4V	0.18		3132		
HAT-P-8C		"1-2"	S		M6V	0.131		3058		
HD 178911 B[B]	7.98	"2-1"	S	46.73	G	1.07	1.14	5650	0.28	5.2
Psi1 Draconis Ab		"2-1"	SB		K/M	0.526				
WASP - 12 C		"1-2"	S		M3V	0.54		3748		
Gliese 667 C	10.22	"2-1"	S	6.84	M1.5	0.33		3600	-0.55	2
16 Cygni C	13	"2-1"	S		M	0.17				
KELT - 4 C		"1-2"	S							
GJ 3305 B	10.9	"1-2"	S		M0	0.44				
HAT-P-57 C		"1-2"	S			0.53				
NLTT 37349		"2-1"	SB		M4	0.16				
HD 132563 B[B]	9.47	"2-1"	S	96	G	1.01		5985		5
HD 196050 Bb		"1-2"	S		M3.5	0.19				3.55
HD 2638 C		"1-2"	SB		M1V	0.46				
HD 40979 C		"1-2"	S			0.38				1
HW Virgins C		"2-1"	P			0.0186				
Kepler 444 C		"1-2"	S		M	0.25				
HD 4113 C		"2-1"	SB		T9	0.063	0.144	500		
Kepler - 13 C		"1-2"	S			0.57		4700		
KOI-2939 C		"1-2"	P							
HD 185269 Bb		"1-2"	S			0.154				
HD 41004 Bb		"1-2"	S			0.0181				

APPENDIX B

TSEC DATA: EXOPLANETS

Exoplanet Name	System	ToS[A]	ToO[A]	Dp (AU)[B]	M	R	Temp (K)[B]	Type[A]
91 Aquarii Ab	91 Aquarii	"1-2"	S	0.7	1017			---
Prox Cent b	Alpha Centauri	"2-1"	S	0.0485	1.27			Terrestrial
Dagon Ab	Fomalhaut	"2-1"	SB	115	953.7			---
HAT-P-8 Ab	HAT-P-8	"1-2"	S		425.98	16.45		Hot Jupiter
HD 178911Bb	HD 178911	"2-1"	S	0.32	2000			---
Psi1 Draconis Bb	Psi1 Draconis	"2-1"	SB	4.43[A]	486.4[A]			---
WASP - 12 Ab	WASP-12	"1-2"	S	0.02293	446.32	19.04		Gas Giant
Gliese 667 Cb	Gliese 667	"2-1"	S	0.0505	5.595			---
Gliese 667 Cc	Gliese 667	"2-1"	S	0.125	3.8147			Terrestrial
Gliese 667 Cd	Gliese 667	"2-1"	S	0.276	5.1			---
Gliese 667 Ce	Gliese 667	"2-1"	S	0.213	2.702			---
Gliese 667 Cf	Gliese 667	"2-1"	S	0.156	2.702			---
Gliese 667 Cg	Gliese 667	"2-1"	S	0.549	0.461			---
16 Cygni Bb	16 Cygni	"2-1"	S	1.68	534.07			---
Kelt - 4Ab	KELT - 4	"1-2"	S	0.04321	281.02	18.71		Hot Jupiter
51 Eridani b	51 Eri	"1-2"	S	14	2892.88	12.17		Jupiter-like
HAT-P-57 Ab	HAT-P-57	"1-2"	S	0.406	588.11	15.49		---
HD 126614 Ab	HD 126614	"2-1"	SB	2.35	120.8			---
HD 132563 Bb	HD 132563	"2-1"	S	2.62	473.67			---
HD 196050 Ab	HD 196050	"1-2"	S	2.47	899.65			---
HD 2638 Bb	HD 2638	"1-2"	SB	0.044	152.59	11.4		Hot Jupiter
HD 40979 Ab	HD 40979	"1-2"	S	0.846	1274.77			Gas Giant
HW Vir (AB)b	HW Virgins	"2-1"	P	4.69[A]	4545.95[A]			---
Kepler 444 Ab	Kepler 444	"1-2"	S	0.04178		3.73		Terrestrial
Kepler 444 Ac	Kepler 444	"1-2"	S	0.04881		0.48		Terrestrial
Kepler 444 Ad	Kepler 444	"1-2"	S	0.06		0.48		Terrestrial
Kepler 444 Ae	Kepler 444	"1-2"	S	0.0696		0.052		Terrestrial
Kepler 444 Af	Kepler 444	"1-2"	S	0.0811		0.66		Terrestrial
HD 4113 Ab	HD 4113	"2-1"	SB	1.28	495.92			Gas Giant
Kepler - 13 Ab	Kepler - 13	"1-2"	S		1926.46	15.42	2750	Hot Jupiter
KOI-2939 (AB)b	KOI-2939	"1-2"	P	2.72	483	17.54		---
HD 185269 Ab	HD 185269	"1-2"	S	0.077	298.82			---
HD 41004 Ab	HD 41004	"1-2"	S	1.64	807.46			---

APPENDIX C

EQUATIONS

$$\text{AMD} = \frac{\sum_{j=1}^{N}\left[m_j\sqrt{a_j}\left(1-\cos i_j\sqrt{1-e_j^2}\right)\right]}{\sum_{j=1}^{N} m_j\sqrt{a_j}} \quad \text{RMC} = \left(\frac{\sum_{j=1}^{N}[m_j]}{\sum_{j=1}^{N} m_j\left[\left[log_{10}\left(\frac{a}{a_j}\right)\right]^2\right]}\right)$$

Where m_j and a_j are the mass of the semi-major axis of each planet j, N is the number of planets in the system, and e_j and i_j are the orbital eccentricity and inclination of each planet j (references given in text, pg.8).

$$\left.\frac{a_{out}}{a_{in}}\right|_{crit} = \frac{2.8}{1-e_{out}}\left(1-\frac{0.3i}{\pi}\right)\times\left(\frac{(1.0+q_{out})\times(1+e_{out})}{\sqrt{1-e_{out}}}\right)^{\frac{2}{5}},$$

where instability is defined as $\left.\frac{a_{out}}{a_{in}}\right| < \left.\frac{a_{out}}{a_{in}}\right|_{crit}$ and $q_{out} \equiv \frac{m_3}{m_1+m_2}$

References given in text, pg.4

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BIOGRAPHICAL INFORMATION

Greg has not always enjoyed Physics, but when he found the beauty behind the mathematics he was instantly hooked. He likes tutoring, helping others, Astronomy and other space physics subjects, and admiring the simplicity of things around him. He graduated *Cum Laude* with an Honors Bachelor of Physics in May 2018, and plans to obtain a Ph.D. in Astronomy in the future.