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Sustaining liquid water on Earth-like planets: the importance of star-planet interactions

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Abstract

Many factors relating to the star, planet, or both can contribute to its ability to maintain surface liquid water. Important stellar characteristics include spectral type and luminosity while key planetary features include distance away from the star and mass. Given the right combinations, a planet could potentially support prolonged surface water. In order to find these optimal conditions, I created a set of hypothetical star-planet systems with varying stellar masses, planetary masses, and semi-major axes. For this study, each system was given four Terrestrial Oceans, TO, of water to start. To deduce habitability, I observed planets only when they were located within their star's habitable zone at one billion years. I deemed a planet habitable if it had at least one TO at this period in time. Given these parameters, I found smaller semi-major axes require low-mass stars for the planets in that system to be considered habitable. This proportional relationship also applies to larger semi-major axes. However, there are

some exceptions when it comes to middle-range planet masses since they cannot maintain enough water to be considered habitable. After determining the most habitable hypothetical systems, I compared them to NASA's archive of exoplanets to see how likely it is for these systems to exist within the database. Based on what is currently known, there are only a few systems that match the ones modeled in this study.

Introduction

As scientists continue to explore space, thousands of new planetary systems are still being discovered. It was first assumed that our Solar System was alone, but current research indicates that nearly every star in the Milky Way is thought to have at least one planet orbiting it (Cassan 2012). Given the vast variety of star types, each planetary system develops a little differently. Some are similar to our solar system– with relatively smaller terrestrial planets orbiting close to the star– while others are unique, deviating from any previous observations or assumptions. Terrestrial planets are described as planets that are mostly composed of rocks, iron, and water usually in the form of ice and often have iron cores and silicate mantles (Cuartas-Restrepo 2018 and Do Amaral 2022). This non-uniform internal composition allows for convection throughout the interior layers which help stabilize surface temperatures (Cuartas-Restrepo 2018). Planets below 1.6 Earth masses, $M_\oplus$, are usually considered to have a rocky composition (Wordsworth & Kreidberg 2022). Being that Earth is the only known habitable planet, scientists tend to place a special emphasis on Earth-like or terrestrial planets when searching for habitability, a focus that will also be reflected in this research. As of now, the key habitability indicator is water vapor. The presence of water vapor within a star-planet system can be located through the habitable zone, HZ. The HZ is the region around a star where a planet can support a surface temperature consistent with liquid-water survival (Seager 2013). The distance and size of the HZ varies for each star type. Even if a planet is within the HZ, that does not mean it has liquid water on the surface. For example, both Venus and Mars are within the Sun's HZ yet neither possesses water. The HZ can be described with two parts. The inner edge is indicated by water loss as a result of the runaway greenhouse effect, and the outer edge is marked by carbon dioxide condensation. The existence of water vapor also relies on a planet's surface temperature which is contingent on the concentration of atmospheric greenhouse gasses (Seager 2013). One gas, carbon dioxide, plays a major role in providing a livable temperature on the surface of a planet (Wordsworth & Kreidberg 2022).

Both stellar and planetary properties contribute to the potential habitability on a planet. Some of these key stellar features include luminosity, mass, spectral type, rate and intensity of magnetic activity, and orbital dynamic properties (Cuartas-Restrepo 2018). Luminosity and mass relate to the lifetime of a star, and the spectral type influences magnetic activity. If a star has a high rate of magnetic activity, it will also have many solar flares and coronal mass ejections, both of which release great amounts of high energy particles. This abundance of solar activity can weaken a nearby planet's atmosphere because of the intense amount of incoming radiation. M type stars are usually associated with greater coronal mass ejections and extreme UV, EUV, and X-ray radiation, or UEX (Garraffo 2016). UEX radiation drives atmospheric stripping through stellar winds and photoevaporation which occurs when a gas is ionized and scattered away by harsh radiation (Garraffo 2016 and NASA). Low mass, dwarf stars, or M-type stars tend to have more frequent and severe energy flares (Linsky 2019 and Do Amaral 2022). This greatly affects close-in planets orbiting M stars since they are more susceptible to both thermal and nonthermal atmospheric stripping. Thermal erosion relates to how radiation can change a planet's temperature and trigger mass loss (Cuartas-Restrepo 2018). Thermal and nonthermal processes work together to deteriorate the atmosphere (Linsky 2019). The two main atmospheric stripping methods are ion pickup and exposure to X-ray and EUV radiation (Cuartas-Restrepo 2018). Ion pickup occurs when atmospheric molecules become charged by stellar wind. Once these molecules are ionized, their acceleration increases which allows them to reach escape velocities and get carried away by stellar wind. X-ray and EUV radiation works in a similar way, but instead of gaining acceleration from charged stellar winds, molecules become energized through the thermal heat of radiation. This heat allows the atmosphere to expand which causes molecules to be pushed into the upper regions where they can be transported away by stellar winds. Atmospheric stripping can still occur in the HZ making some planets desolate despite having all the proper planetary characteristics (Cuartas-Restrepo 2018).

Aside from the location of the planet, other vital planetary features include a planetary magnetic field (PMF) and magnetosphere, atmospheric composition and thickness, interior structure, and tectonic plate movement (Cuartas-Restrepo 2018). The magnetic properties of a planet are controlled by the convective flows within the planet. Magnetic fields are created by the internal dynamos driven by the thermal and compositional convection inside the core and mantle (Linsky 2019). In order to have a PMF, there must be electrically conductive fluid in motion. Qualities of the PMF are regulated by the structure, composition, and thermal history of a planet (Cuartas-Restrepo 2018). Core convection occurs due to non-uniform composition which is common in terrestrial planets, and this convection can cause tectonic plates to move. The movement of these plates ensures a stable surface temperature which is crucial for sustaining life. With sudden fluxes of temperature, many life forms have little chance of survival. Along with surface temperature, the PMF also impacts the magnetosphere of a planet. A magnetosphere is formed by the interaction of the PMF and stellar winds (Cuartas-Restrepo 2018). The magnetosphere is a planet's main defense against harsh radiation, stellar winds, and coronal mass ejections. Without a strong magnetosphere, the rate of atmospheric stripping severely increases.

Considering the effects of greenhouse gasses, the presence of an atmosphere is crucial for a planet's habitability. Greenhouse gasses regulate surface temperature, and without them, a planet would be inhospitable. Depending on how the planet and its atmosphere were formed, the concentrations of greenhouse gasses will vary. Terrestrial planets can obtain their atmosphere in three ways: capturing gas from the original nebula, the process of accretion, or incorporating emissions from the tectonic process (Cuartas-Restrepo 2018). There are two different types of atmospheres, thick and thin. Thick atmospheres are classified as being able to retain thermochemical equilibrium at high pressures, yet thin atmospheres kinetically prohibit the attainment of thermochemical equilibrium at the surface. When it comes to the productivity of life, thin atmospheres are preferred (Hu 2015). Moreover, the ability for any atmosphere to support life is reliant on the energy balance between the planet and the star. This means that the incoming solar energy received by a planet must be balanced with the outgoing energy (Cuartas-Restrepo 2018).

Each layer of the atmosphere reveals a specific physicochemical process that can serve as a host to different chemical species only visible by certain sectors of the electromagnetic spectrum. Depending on which type of observational method is employed, information obtained from exoplanetary atmospheres may vary. For example, UV instrumentation is useful for upper regions of the atmosphere since it is mostly composed of atomic particles while IR instrumentation is better suited for lower portions of the atmosphere where the composition is predominantly molecular compounds. Although past efforts were made to observe exoplanetary atmospheres, only recently has technology been able to accurately depict atmospheric spectra. Currently, there are three dominant methods of detection: transit spectroscopy, direct imaging, and Doppler spectroscopy. With these methods, it is now possible to observe low-mass planet spectral signatures which would've been unthinkable merely a decade ago (Madhusudhan 2019).

Along with the advancements in observational data, great progress has been made with atmospheric modeling and theoretical studies. There are three major models: the self-consistent, inverse, and disequilibrium model. Over the years, self-consistent models have been updated to span from 1D to 3D and assess the atmospheric spectra for exoplanets given macroscopic parameters such as gravity, radiation, and elemental abundances. Inverse modeling combined with atmospheric retrieval techniques calculates planetary properties such as chemical composition, temperature profiles, and deviations from chemical or radiative equilibrium. Lastly, disequilibrium models are used to investigate various processes that drive atmospheres out of equilibrium. These include kinetic processes, photochemistry, and atmospheric escape. Together, these modern observational methods and modeling techniques illustrate a comprehensive picture of an exoplanet's atmosphere given certain conditions (Madhusudhan 2019).

In order to fully examine all of these stellar and planetary properties, I simulated five test planets with varying semi-major axes and masses that served as habitable planet candidates. I then paired these planets with different stars with masses ranging from K dwarfs to early F stars. I modeled the test systems to account for stellar flaring, atmospheric escape, and stellar evolution. I also compared them with the NASA Exoplanet Archive to evaluate how common they are in reference to the known population of exoplanets.

Methods

To create and compare the test planets, I used the software package VPLanet which is a virtual planet simulator used to model a planet system's evolution. VPLanet works by reading in all the parameters needed to derive primary variables such as a star's luminosity or a planet's obliquity. If needed, it will adjust the time set which is dictated by the fastest-changing variable which ensures accuracy within the model (Barnes 2020). In total, there are 12 different modules within VPLanet. For this research, I used the modules STELLAR, ATMESC, and FLARE. These specific modules simulate stellar evolution, atmospheric escape, and stellar flaring respectively. The STELLAR module for VPLanet runs by creating a time evolution of stellar parameters such as luminosity and effective temperature. For the ATMESC module, atmospheric loss caused by high energy radiation considers both the loss of a primordial hydrogen envelope and water photolysis followed by hydrogen and oxygen escape. Finally, the FLARE module was developed to approximate the time-averaged XUV luminosity produced by stellar flares (Do Amaral 2022).

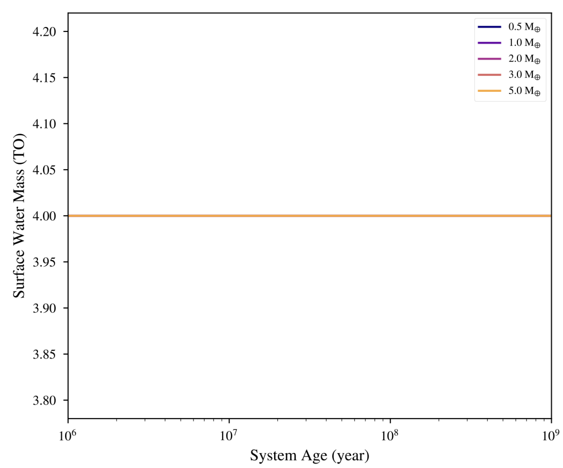
With these modules, I decided the optimal star-planet properties for sustained surface liquid water. It is assumed that the runaway greenhouse gas effect is insignificant within the HZ and that all hypothetical systems have flares and start with four TO in water. With these assumptions, I made five test planets with masses ranging from 0.5-5 $M_{\oplus}$. I then paired these planets with stars ranging from 0.6-1.3 Stellar masses, $M_{\odot}$. Stellar masses were calculated using a step size of 0.025 $M_{\odot}$ which produced 44 different star masses. For each of these star-planet systems, I combined them with four different semi-major axes ranging from 0.07-2.70 AU. After combining all planetary masses, stellar masses, and semi-major axes, there were a total of 880 models produced. All of these constraints are quantified in Table 1. Each parameter is assigned an initial value or range of values denoted by the model. Most of these variables are predetermined by VPLanet to represent general planetary evolution, but some, such as planet mass, stellar mass, surface water mass, and simulation time, were customized to fit this particular research.

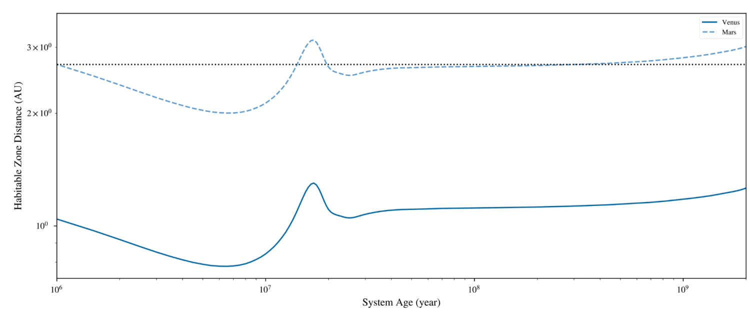
Parameter	Value
Planet Mass (M⊕)	[0.5-5]
Planet Density (g cm^{-3})	5.5
Envelope Mass (M⊕)	1.e-3
Surface Water Mass (TO)	[1-4]
XUV water escape efficiency	0.3
XUV hydrogen escape efficiency	0.15
Semi-axis major (AU)	[0.3-2.7]
Stellar mass (M☉)	[0.3-1.6]
Saturated XUV luminosity fraction	1.0E-3
XUV saturation time (units)	0.1
Initial stellar age (Myr)	1.0
Flare energy (ergs)	[1.0E33-1.0E36]
Simulation time (yr)	[1.0E6-1.0E9]
Time step (yr)	[1.0E-2, 1.0E7]
VPLanet modules	STELLAR, ATMESC, FLARE

Table 1. Parameters used to model test planets. Note, the time step value varies due to simulation software.

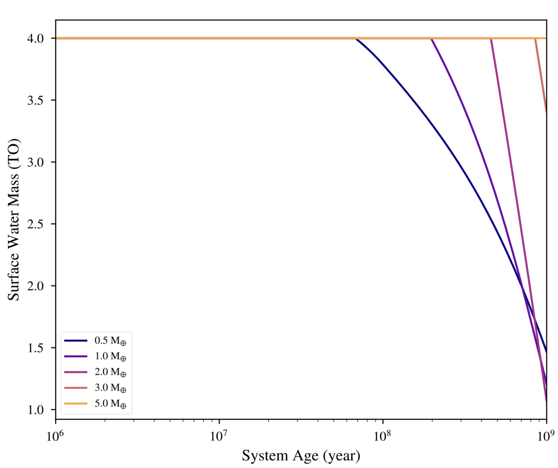
To conclude whether or not a planet is habitable, I only observed water loss while the planet was in its respective HZ by the end of a billion years. For this model, I use the optimistic habitable zone. The optimistic HZ is confined by current Venus and early Mars, and due to these bounds, the HZ includes a much broader range of potential planets. Thus, a planet falling in between the characteristics of either current Venus or early Mars would be situated within the range of the HZ. If a planet is in the HZ at a billion years and still has at least one TO, I concluded that it is habitable. Knowing that Earth is the only planet that can produce life, I set the minimum value to one TO. These restraints divide the test planets into 3 groups: planets with no water loss, planets with some water loss but at least one TO, and planets with no water left. Figures 1, 3, and 5 respectively reflect examples of these star-planet systems and illustrate water loss in

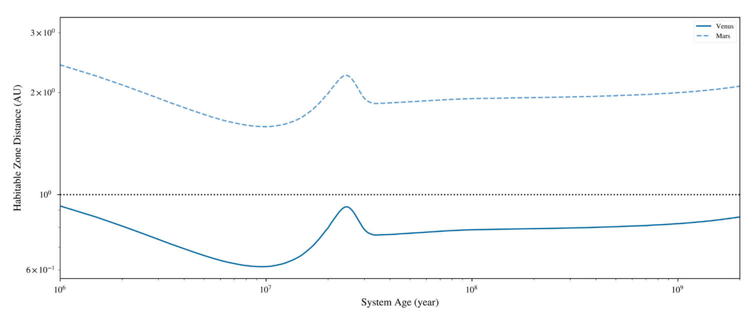
TO for each planet starting with the given four TO. Each of these figures only represent one stellar mass and semi-major axis, but all varying planetary masses are shown and distinguished by the different colors. Figures 2, 4, and 6 show the HZ for each of these systems indicated by both of the blue lines. The black dotted line shows the planetary orbit for a given semi-major axis. Over time, the planetary orbit remains constant, but the HZ changes as the luminosity of the star flunctuates. Despite each system having varying habitable zones, all of their orbits are within their particular HZ at the billion-year mark, but only Figures 1 and 3 are considered habitable since each planet has at least one TO. For Figure 5, all planets have less than one TO by a billion years rendering them inhospitable despite being in the HZ.



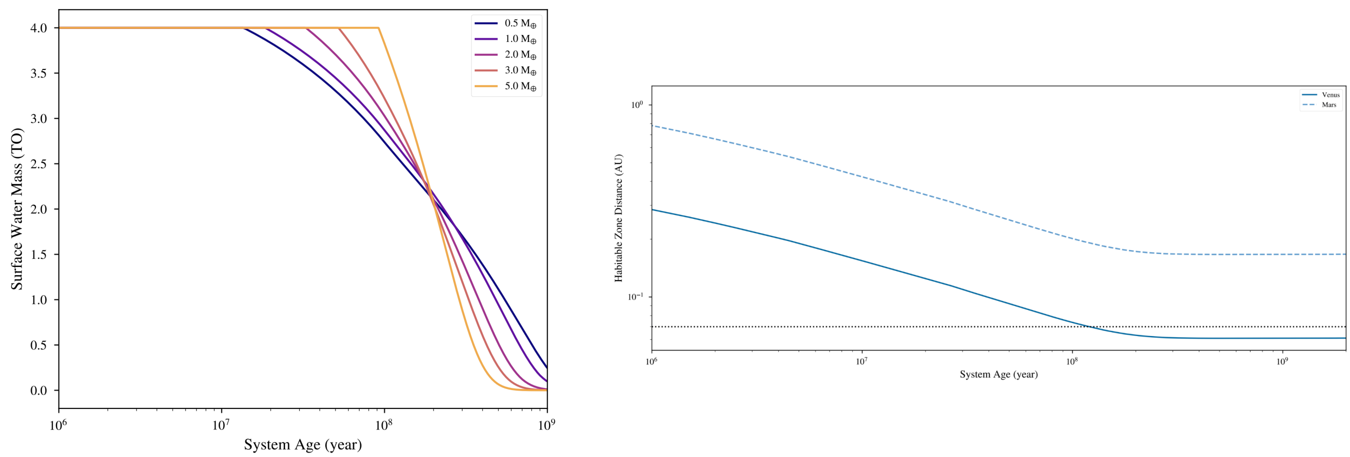


Figures 1 and 2. These plots illustrate the loss of surface water mass (left) and the HZ (right), represented by the black dotted line, for a system with a semi-major axis of 2.70 AU, a stellar mass of 1.275 M⊙ from one million years to one billion years.





Figures 3 and 4. These graphs show the loss of surface water mass (left) and the HZ (right) for a system with a semi-major axis of 1.0 AU and a stellar mass of 1.10 M☉ from one million years to one billion years.



Figures 5 and 6. These plots represent the loss of surface water mass (left) and the HZ (right) for a system with a semi-major axis of 0.07 AU and a stellar mass of 0.225 M☉ from one million years to one billion years.

After sorting through the most habitable test planets, I compared them to the confirmed exoplanets from NASA's Exoplanet Archive[1]. I specifically used the list of all known planets and hosts. The data in this online astronomical catalog includes both stellar and exoplanet parameters along with the method of discovery and any images. I focused my search on star-planet systems where the star is less than 1.3 M☉, and the planet is less than five M⊕. I chose these restraints in order to ensure the most habitable planets given their stellar and planetary traits.

Results

Overall, these graphs reflect similar trends that link planetary and stellar properties to sustained surface water. For smaller semi-major axes, less than 1 AU, planets only retain water if the stellar mass is also small, between 0.2-1 M☉. This outcome alludes to the crucial connection between stellar mass and the semi-major axis. When a planet is close to its star, it is more susceptible to atmospheric stripping, and this vulnerability requires a less massive star to help prevent desiccation. For a semi-major axis of 1 AU, planets retain water when the stellar mass is within the range of 0.825-1.15 M☉. This result is easily verified since Earth falls within this range with its stellar mass of 1 M☉. For a larger semi-major axis, 2.70 AU, larger mass stars are preferred for sustained water, 1.225-1.275 M☉, but there is no preference for planetary

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

mass. Generally, when the semi-major axis is less than or equal to 1 AU, it appears that as stellar mass increases planetary mass must also increase to optimize the amount of surface water leftover. This mass dependence can be attributed to the fact that high-mass planets can more easily keep their atmospheres due to the stronger force of gravity. Although, there is a trend regarding the upper stellar limit of these habitable systems where only the lowest and highest mass planets, 0.5 M☉ and 5 M☉, can sustain water. This outcome implies that middle-range masses are not always ideal for certain stellar masses exceeding a specific maximum. An example of this phenomenon is highlighted in Figure 7 where the only planets above the threshold of one TO have masses of 0.5 M☉and 5 M☉. For most cases, there seems to be a strong correlation between the semi-major axis and the stellar mass with a secondary dependence of planetary mass near the upper stellar mass limit for that particular semi-major axis.

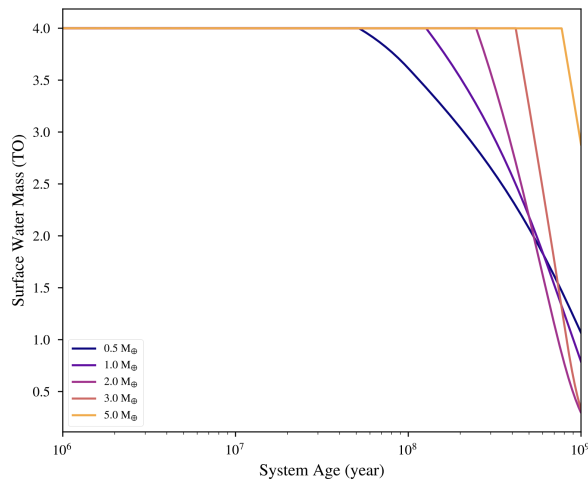


Figure 7. This plot displays the loss of surface water mass (TO) for a system with a semi-major axis of 1 AU and a stellar mass of 1.15 M☉ from one million years to one billion years.

I then compared my findings with the NASA Exoplanet Archive to see the likelihood of these hypothetical systems existing within the database. Given the current record of exoplanets, the probability of such habitable systems appears to be minimal. For a semi-major axis of 0.07 AU, there is a 1 in 113 chance of a planet having the proper conditions to sustain liquid water. However, the host star for this planet has an unknown mass, so it is hard to know for sure if it could really support life. Although, there is another star-planet system that has a similar stellar mass, but a slightly larger planetary mass. Meaning, it could be habitable as long as that system follows similar trends to what is modeled. As the semi-major axis increases to 0.10 AU, the probability for habitability also improves. There are 852 planets within this semi-major axis range and about 10 of them have planetary masses that match up with the ones in this research. Furthermore, the stellar masses for most of these planets are significantly higher than the ones used in this study. For stars within the desired range, the associated planets typically have masses that are either very large or unknown, but there is one planetary system that meets both the stellar and planetary mass requirements provided in the model. With a semi-major axis of 1 AU, the likelihood of life decreases in comparison to 0.10 AU. Out of the 98 planets in this section, only one planet has a mass within the range outlined by the model, but this planet's host star has a mass significantly lower than what was found to be habitable. For the habitable stellar masses within this semi-major axis, most of the planets have masses significantly higher than the ones modeled except for one planet with an unknown mass. When it comes to larger systems with a semi-major axis of 2.70 AU, none of the 36 planets have a mass within the range of the model. Only one star had a stellar mass within the ideal range, but the planet associated with this star has a mass of over 1000 $M_{\oplus}$. Overall, there seems to be a low likelihood of the modeled habitable systems existing given the constraints of the current available data.

Discussion and Future Research

After running all of the simulations with the given restraints in Table 1, the relationship between stellar and planetary parameters became evident. Once a planet is within the HZ, its ability to retain water depends primarily on the mass of the host star. For low-mass stars, HZs are located closer to the star which means the potential for atmospheric stripping is high. This form of desiccation can be prevented in three ways: the stellar mass is low enough so that stellar winds are weaker, the planetary mass is large enough so that the force of gravity holds the atmosphere in place, or the planetary mass is small enough so that the area exposed to stellar winds is too small to play a major role in atmospheric stripping. For star-planet systems with a semi-major axis of less than 0.1 AU, both small stellar masses and large planetary masses allow for some liquid water to be preserved. As the semi-major axis approaches 1 AU, the stellar mass can slightly increase but still remain relatively small to account for the severe incoming radiation, but planetary masses can either be large or small. The smaller surface area for these low-mass planets prevents the stellar winds from stripping away the atmosphere (Chin 2024). For the large planets in this range, their gravitational force allows them to keep their atmosphere despite the harsh incoming stellar wind. By contrast, none of this can be applied to the planets with middle-range masses. These planets have enough area exposed to stellar winds where atmospheric stripping can occur, and their masses are too small to conserve their atmosphere through gravity (Chin 2024). For larger semi-major axes, 2.70 AU, stellar mass becomes more significant to water survival than planetary mass. These systems require stars with masses greater than the Sun, at least 1.225 $M_{\odot}$, to maintain liquid water for any planetary mass.

After defining the best systems for surface liquid water survival, I cross-referenced them with the planets documented in NASA Exoplanet Archive. When considering only the length of the semi-major axis and the planetary mass, I found that the most likely system to garner life has a semi-major axis of 0.10 AU. Based on NASA's data, this semi-major axis group has a 10 in 852 chance of sustaining a habitable planet. When examining the semi-major axis length, planetary mass, and stellar mass, the chances of habitability decrease significantly. I was only able to find one star-planet system that had all of the ideal parameters set by the model. When examining the other systems, either the stellar or planetary masses were unsuitable for habitability, or the database did not have a value for them. The existing exoplanet population documented by NASA contains very few, if any, planets capable of sustaining liquid water, as outlined by this research, but it is hard to know for certain due to the many gaps in the database when it comes to stellar and planetary masses.

This research is restricted to systems with stellar masses less than 1.3 $M_\odot$, so these conclusions may not be applicable to planetary systems with more massive stars. Furthermore, this model does not consider the presence of clouds or a planetary magnetosphere, both of which can greatly impact a planet's temperature and ability to maintain liquid water. Improvements can also be made on the FLARE module used to simulate stellar flares since it only accounts for flares similar to the Sun and not low mass stars (Barnes). Time is also an important factor for habitability, and because this only modeled the first billion years, more work would have to be done to assess long-term liquid water survival. Future research should include simulations with a wider range of both semi-major axes and planetary masses to better understand the observed dip in habitability for middle-range planets. Additionally, there needs to be more technological advancements in order to get a clearer understanding of the statistical probability of habitable star-planet systems. Currently, there is an observational bias for larger planetary systems being they are easier to detect, so when it comes to studying Earth-like systems finer resolution is required. With a greater variety of planets sampled, scientists will be able to develop a clearer representation of the potential biospheres of these confirmed planets.

Conclusion

Through the simulations of my test planets, I established the optimal stellar and planetary characteristics that will yield sustained surface liquid water. My research found that the main factors of habitability are stellar mass, planetary mass, and semi-major axis distance. Stellar mass controls the amount of radiation a planet receives, the strength of the stellar winds, and the distance of the HZ. Planetary mass determines if the planet will be able to retain its atmosphere through gravity or if it can protect itself from incoming stellar winds. The semi-major axis describes how far away the planet is from its host star which impacts the amount of radiation a planet is receiving. With the right combination of these conditions, it is possible for a planet to maintain surface water. I found that these combinations are mainly based on the semi-major axis and stellar mass. Conversely, there is a secondary dependence involving planetary mass with a bias against middle-range planet masses since they are unable to retain their atmosphere or protect themselves against stellar winds. After considering the data found in the NASA Exoplanet Archive, the likelihood of these habitable systems producing life looks to be very low with only a few systems matching the ideal conditions, but future technology could alter these results by providing a more inclusive set of planetary systems.

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