Exploring Factors That Influence Exoplanet Habitability

Ian Kozloski

North Penn High School

ABSTRACT

The objective of this research is to determine which conditions influence the habitability of exoplanets. A better understanding of these attributes can help determine if life exists beyond our solar system. It also helps answer the question of whether or not exoplanets could be habitable if it becomes necessary for our survival. The significance of mass, flux, and period were evaluated to determine which factors have the largest influence on habitability. Simulations of temperature and radiation fluctuation on certain exoplanets were run on some of the most earth-like exoplanets to determine the likelihood of habitability on each. This novel approach of analyzing these data sets produced an overview of which parameters are necessary for exoplanet habitability with the ultimate goal of understanding life beyond our solar system. The results show that mass and period have a moderate influence on habitability while flux has a larger impact on the habitability of an exoplanet. The simulations illustrate that the likelihood of habitability on the majority of known exoplanets is low. These findings indicate that the conditions for exoplanets to be habitable are very specific and there are currently no exoplanets that would definitively be able to support life. As exoplanet detection technologies and methods improve, future research could show that habitable exoplanets are more prevalent than what is known today.

Background

Astronomy is becoming more mainstream in the scientific community. The field of exoplanet discovery is a popular and emerging area within astronomy. The first exoplanets were detected in the 1990s, and thousands more have been discovered since then. Recently scientists have been searching for exoplanets that have signs of life as well as exoplanets that can support life. The number of discovered exoplanets has doubled in just a few years, however only a small number of them have similar conditions to Earth. The goal of this research is to clarify the requirements an exoplanet has to meet to be habitable since these attributes are relatively unknown at this time. This research also addresses some of the methods by which exoplanets are detected. By exploring these areas, a more comprehensive understanding is developed (Madhusudhan et al. 2016).

Introduction

For this investigation, several metrics that help determine if an exoplanet is habitable were surveyed. These include determining if the exoplanet is suitable for humans to colonize and assessing if the exoplanet is more or less habitable. The research also attempts to find an exoplanet that can be a good candidate for sustaining life. The paper aims to investigate the correlation between specific factors of an exoplanet and its ESI (Earth Similarity Index) to see if certain factors make an exoplanet more Earth-like than others. Additional details regarding what molecules are required for life and the methods of detecting exoplanets will be explored. It is assumed that the more similar an exoplanet is to Earth, the more likely it will be able to harbor life. This includes a similar mass, flux, and period around their host star.

Conditions of Determining Habitability

Chemistry

The molecules that are necessary for life include CO_2, CO, H_2O CH_4, N_2, O_2, and H_2. These compounds are needed for an Earth-like exoplanet because they are comprised of the building blocks that make up every organism. For an exoplanet to be habitable or have life on it, it needs to be terrestrial with an ocean composed of liquid water. Liquid water is necessary because it is one of the only molecules who's solid form is less dense than its liquid form. Therefore, when temperatures fall below zero Celsius, ice will float instead of sinking and crushing all of the organisms beneath it. Water is also important for the production of sugar and other monosaccharides that provide energy to organisms. Volcanoes may be necessary for the production of CO_2 and CH_2. The water in the ocean then consumes the CO_2 in the atmosphere, and from there, simple life has a chance of forming (Schaefer et al. 2012).

Distance from Host Star

Another factor that limits the chances of habitability is an exoplanet's distance from its host star. An exoplanet that is close to its host star and still in the habitable zone (the zone where the temperature allows for liquid water 273K-373K) will orbit the star extremely fast (often faster than Mercury orbits the Sun). This can cause a variety of issues, such as large temperature changes, vulnerability to solar flares, and vulnerability to high levels of radiation emitted by the host star. It is very unlikely that gas giants will be able to support life due to their lack of a solid surface, but their moons have a chance of harboring life. Exoplanet moons cannot be explored as they are very small and are difficult to detect. The closer a planet is to its host star, the more likely it is to become tidally locked. The planet being tidally locked reduces the likelihood of life because of the differences in temperature when one side is always facing its star.

Mass

The exoplanet will need a substantial mass to support life as well. A high amount of gravity helps form a large atmosphere. This justifies how Earth is the only planet we know to harbor life. It is still possible that other planets have life on them in our galaxy, as we have only discovered less than 0.001% of the total number of estimated exoplanets. Mass is important because a mass too high or too low will make it hard for humans to move properly. Mass also influences the likelihood of an exoplanet being a gas giant which cannot sustain life.

Pressure

For any exoplanet to be habitable, it has to have an atmosphere; life on Earth requires a strong atmosphere that is protected from outside conditions. We have lots of ways to look at indicators for the pressure of an exoplanet. The first is the gravitational pull of the exoplanet; the higher the gravity, the higher the atmospheric pressure. Another way to determine the pressure of the exoplanet is through the thickness of the atmosphere. If the planet has a very large atmosphere or has many heavy elements in it, that could indicate that the pressure is high. Since Earth's atmosphere has an atmospheric pressure of about 101 kPa, a potentially habitable exoplanet will have an atmospheric pressure near that amount.

Methods

Before analyzing the factors that influence exoplanets' habitability, the two primary methods for detecting exoplanets will be explored. The first is radial velocity method and the second is the transit method. The radial velocity method detects exoplanets through a change in the Doppler measurements of a star caused by the exoplanet's gravity. The transit method is used when an exoplanet passes in front of its star, blocking some its light that reaches Earth thereby causing a dip in the star's luminosity (Wright et al. 2012).

The Radial Velocity Method

Hypothesized by Christian Doppler in 1842, when an object passes in front of another object emitting light, the wavelength that is emitted from the light changes thus altering the color and luminosity perceived. This can be applied to detecting exoplanets. If a star's wavelength changed for a period of time, and then returns back to normal, it may indicate that an exoplanet that passed by the star blocking the light (Seager et al. 2010).

The Transit Method

The transit method has proven to be the most effective way to discover exoplanets. It has been used to discover over half of the exoplanets known today. Similar to the radial velocity method, instead of measuring the change in wavelength of the star, it measures the dip in luminosity or flux of the star. The transit method can also calculate the radius of an exoplanet, which is important for knowing if the exoplanet is rocky or gaseous (Haswell et al. 2010).

Determining Habitability

Method 1: Utilization of data from the Habitual Worlds Catalog

In this paper a novel methodology that utilizes data from the Habitable Worlds Catalog (HWC) is used. Through applying a simple log scale on the x-axis, relationships between the Earth Similarity Index amongst other factors, including mass, period, and flux have been determined.

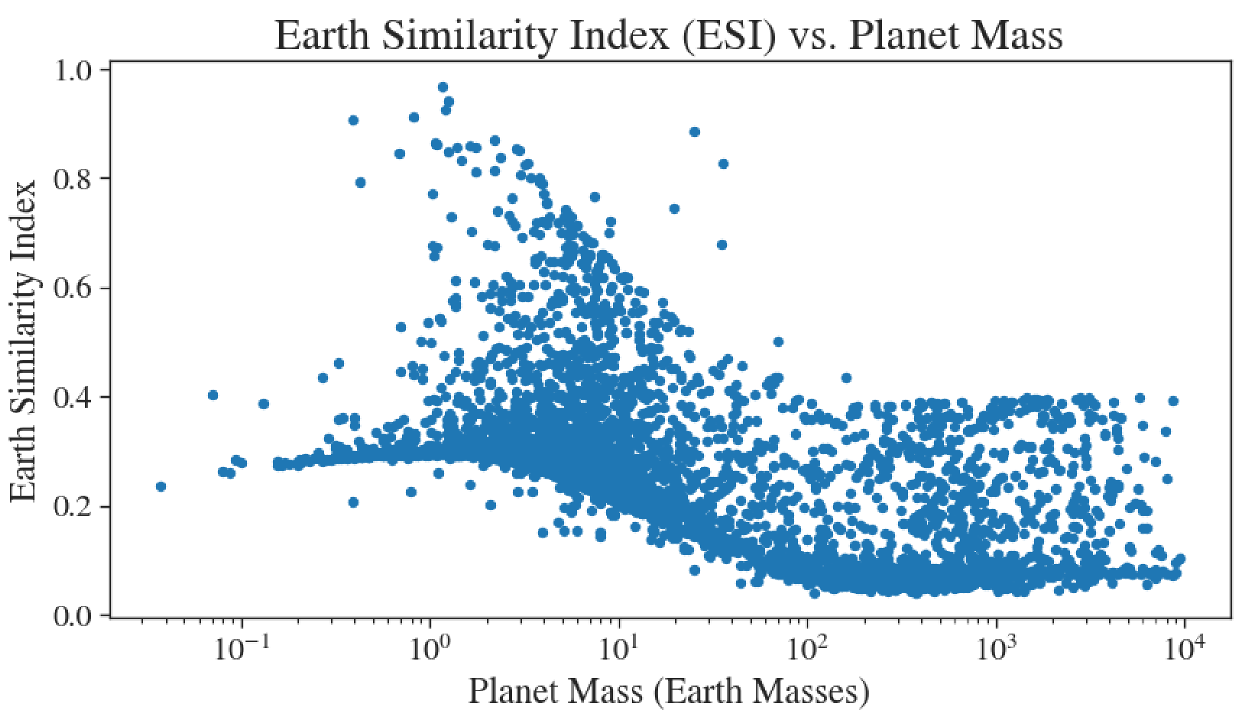

Figure 1. The PHL catalog of exoplanets plots the mass (in Earth masses) of an exoplanet in comparison to its ESI.

It can be concluded that the closer an exoplanet's mass is to Earth's mass, the more likely it is to be habitable. An exoplanet with a very high mass is likely to be a gas giant and, therefore, cannot sustain life. There are a few exoplanets with a much higher mass that have a high ESI. These exceptions prove that mass is not a main contributor to habitability. The closer an exoplanet's mass is to Earth's, the more likely the planet will have a gravitational pull that is similar to Earth's, and therefore more likely to be habitable (PHL @ UPR Arecibo, 2024).

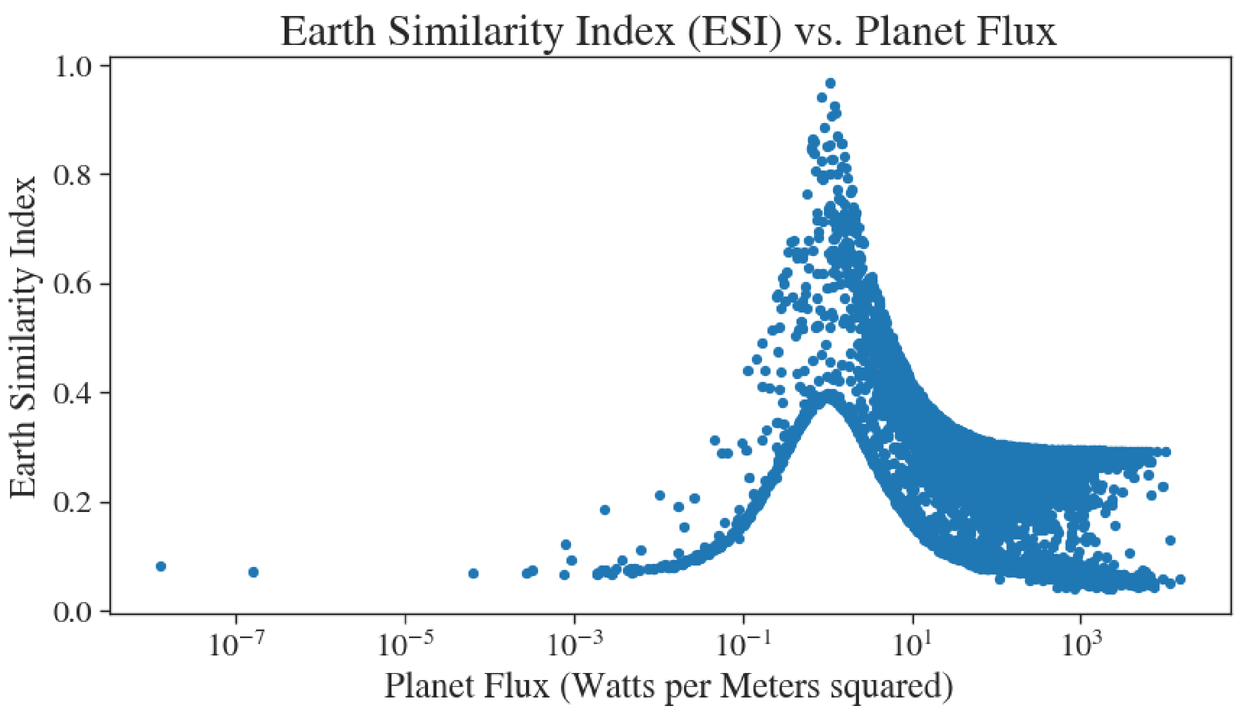

Figure 2. Figure 2 displays the exoplanet's received flux (in Earth's flux of 1400 W/m^2) and ESI.

The influence of flux on habitability was analyzed. One noticeable trend is that the closer the flux is to Earth's flux, the more likely it is to be habitable. This is because most of the exoplanets that are in the habitable zone have a similar flux to Earth. There is a large limitation when addressing the temperature and flux of exoplanets. It is very difficult to discover exoplanets orbiting Sun-like stars because it requires the planet to be very far from the Sun-like star to be in its habitable zone. Therefore, it is much harder to see the changes in the host star's orbit or wavelength. There are exceptions to this, though. There are a couple of exoplanets with a flux like that of Earth's, however they are not habitable. Flux is not the only factor that plays into habitability but it has a large impact on it.

Equation 1

$$F = L/4d^2$$

Where F is the flux of the star, L is the luminosity of the host star, and d is the distance between the two bodies.

This equation shows that higher luminosity (The amount of radiation/light emitted from a star) increases flux, and a larger distance decreases flux. For an exoplanet to be habitable, it must receive a certain amount of light and be a certain distance from its host star so that the exoplanet's temperature allows for liquid water. It proves that many exoplanets with a low luminosity host star must be close in proximity to the star in order to be in the habitable zone.

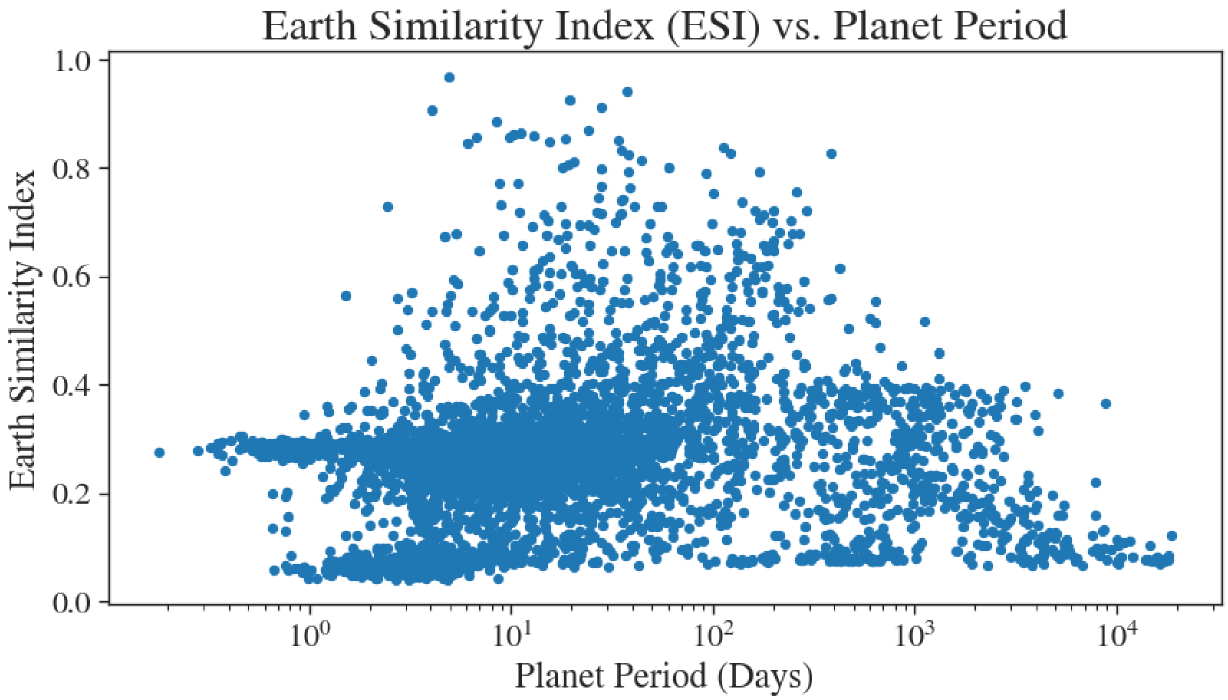

Figure 3. Figure 3 shows the relationship between an exoplanet's period (days) and its habitability (ESI).

An exoplanet's period is the amount of time it takes for the planet to make one revolution around its host star. Typically, the longer the period, the further away an exoplanet is from its host star. The conclusion that can be made from this data is that period has a relatively small amount of influence on the habitability of an exoplanet. There is not an impactful relationship between an exoplanet's period and its habitability. However, the quantity of high period exoplanets I can evaluate is limited due to restrictions of current exoplanet detection technology. Period and distance from host stars are directly correlated, and that is consistent with results. (PHL @ UPR Arecibo, 2024).

Method 2: Determining Habitability from Simulations

Conditions of specific Earth-like exoplanets based on data from the Habitable Worlds Catalog were simulated using information such as mass, radius, period, etc. The Global Climate Model (GCM) was used to simulate the likelihood of habitability of these exoplanets. (PHL @ UPR Arecibo, 2024).

Proxima Centauri b

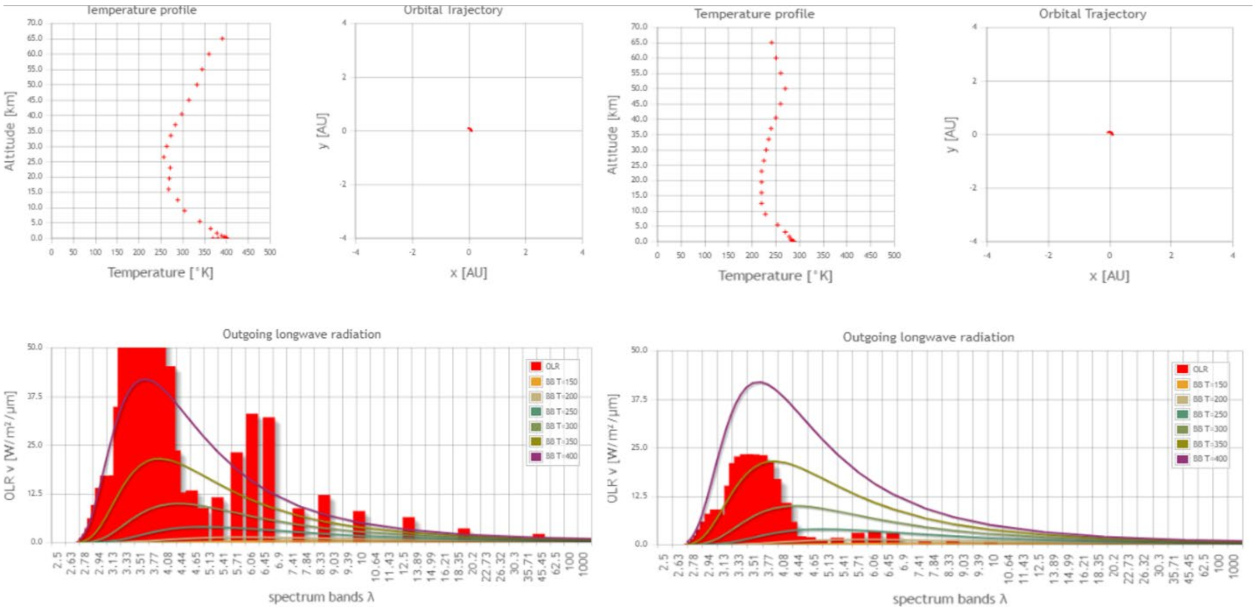

Figure 4a Figure 4b

Figure 4. Figure 4a and 4b illustrate simulated temperature and radiation levels at different points of Proxima Centauri b's orbit around its host star (Turbet et al. 2016).

Proxima Centauri b is the first exoplanet I analyzed since it has the closest proximity to Earth. Its approximate temperature is about 261K (-13C), so if any oceans exist, they are likely comprised of ice or cold water. Proxima Centauri b is similar to Earth in both radius (1.03 Earth radii) and mass (1.07 Earth masses) so the gravitational pull on Proxima Centauri b would be comparable to what we experience here on Earth. Based on the GCM simulation, I observed a large change in temperature and radiation in just a few days because of the planet's very close proximity to its host star, and the short revolution around it. This planet would likely not be able to harbor life because of its temperature and radiation fluctuations, but it might be able to support humans with improvements in technology in the future (PHL @ UPR Arecibo, 2024).

Equation 2:

$$F_{gravity} = Gm_1m_2/r^2$$

Where F is the gravitational force acting between two objects, G is the gravitational constant, m_1 and m_2 are the masses of the objects, and r is the distance between each of their centers of mass.

Newton's Universal Law of Gravitation shows that the amount of force that is acted upon an object on an exoplanet depends on the object's mass, the mass of the exoplanet, and the distance between the centers of mass of each. Since mass and distance are the only two factors that influence gravity, an exoplanet with a similar mass and radius to Earth will feel very similar to being on Earth.

GJ 1002 b

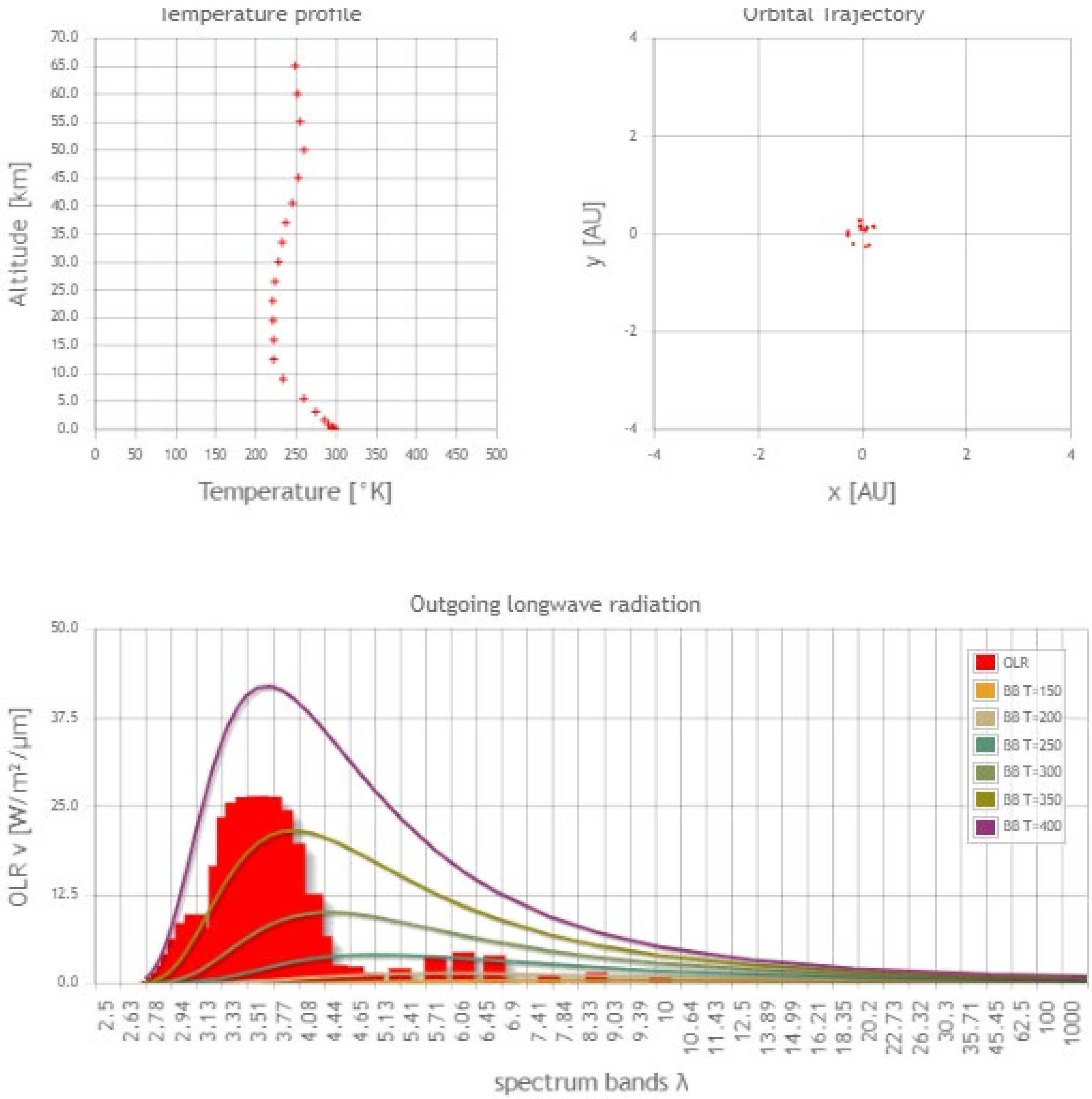

Figure 5. Figure 5 shows GJ 1002 b's temperature and longwave radiation (Turbet et al. 2016).

GJ 1002 b is an exoplanet that is also similar to Earth. It is 15.8 light years away, which is a lot further from Earth than Proxima Centauri b. GJ 1002 b is very close to its host star, but the host star has a very low luminosity. Based on the simulation, the planet's temperature also fluctuates greatly in a short amount of time due to its short orbital period. It most likely doesn't support life because of this, but may be another option for humans to live on because it may have an atmosphere (PHL @ UPR Arecibo, 2024).

TOI-700 d

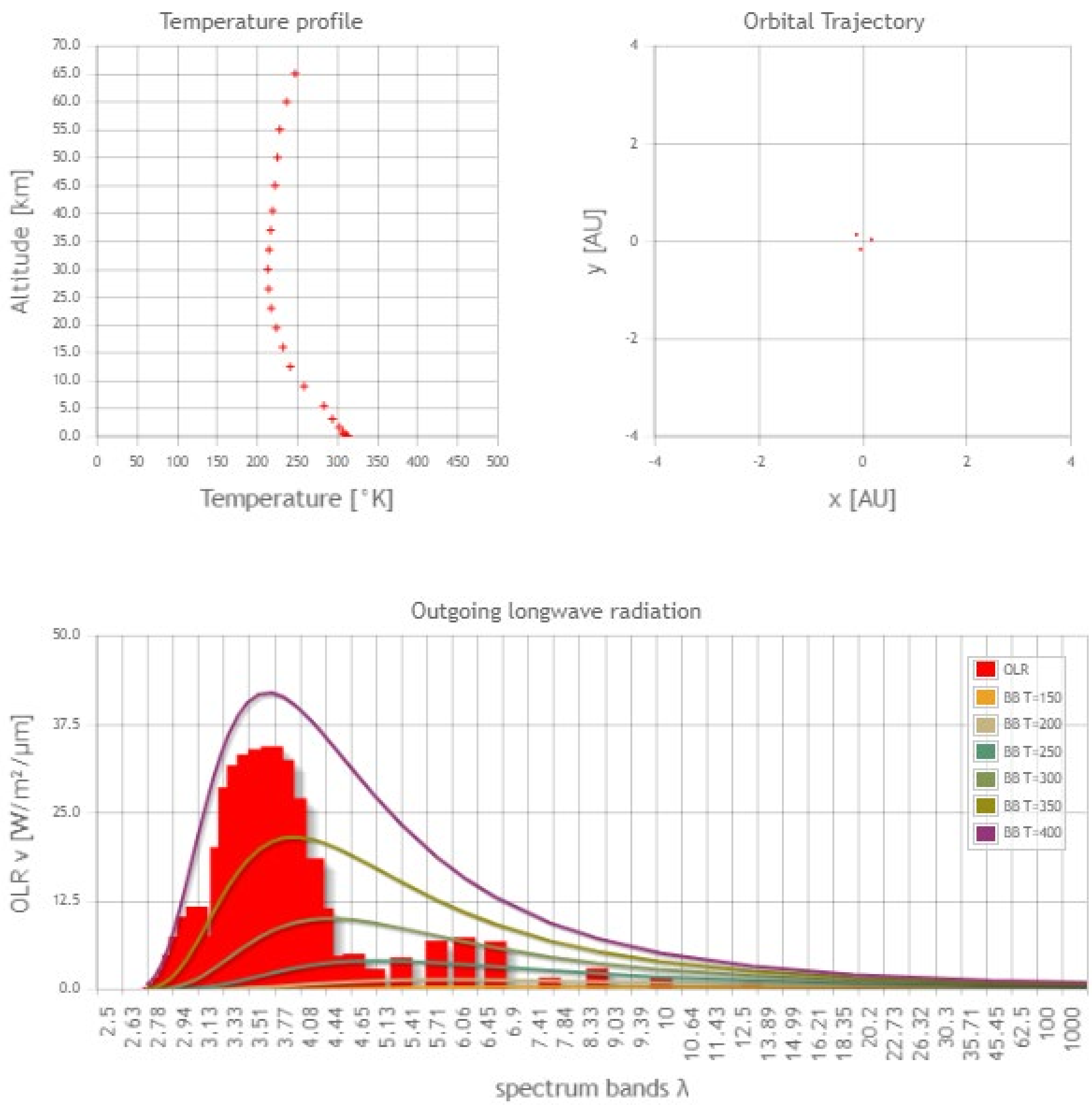

Figure 6. Figure 6 shows the simulated temperature and longwave radiation of TOI-700 d (Turbet et al. 2016). TOI-700 d is an exoplanet with an estimated temperature of 276K, which is just above water's melting point. Its mass is 25% higher than Earth's. Unlike the other two exoplanets above, TOI-700 d has a longer orbital period of 37.4 days. Based on the simulation, its radiation and temperature remained relatively unchanged. The longer orbital period and distance from its host star likely makes the its temperature more consistent. TOI-700 d has a chance of containing or harboring life since it likely has an atmosphere due to its high mass and its relatively constant conditions. TOI-700 d is 101 light years away from Earth, so we won't be able to get there for a very long time, but technology advancements could make it possible in the future (PHL @ UPR Arecibo, 2024).

Kepler 1649 c

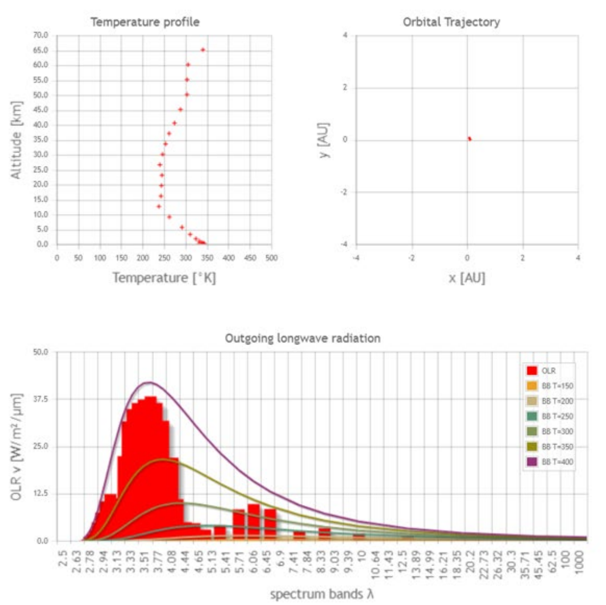

Figure 7a

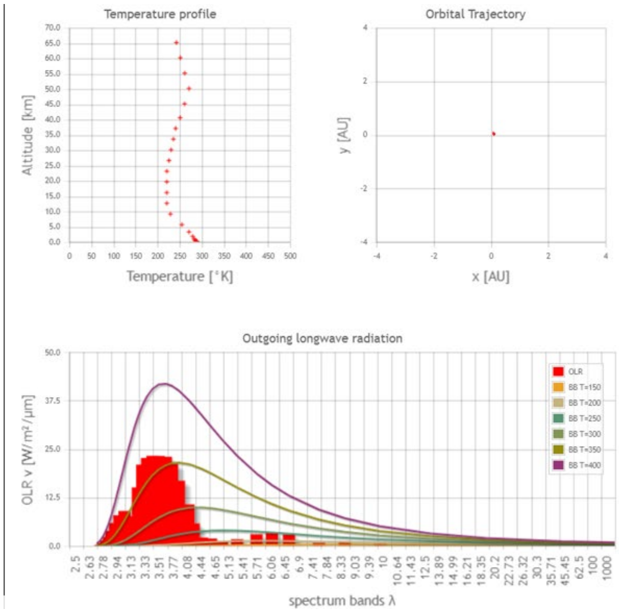

Figure 7b

Figure 7: Figure 7a and 7b display the temperature and longwave radiation that Kepler 1649 c receives during its orbit (Turbet et al. 2016).

Kepler 1649 c is one of the most similar exoplanets to Earth based on its ESI of 0.93 (Earth is 1.00). Even with its very close proximity to its host star, its higher mass and likely thicker atmosphere allowed the radiation and temperature to stay relatively constant throughout the simulation. Still, it does vary moderately enough for it to pose a threat to humans. Kepler-1649 c has a slight chance of harboring life but it is very far away from Earth at 300 light years away.

Limitations

The first limitation of this experiment is the small sample size of Earth-like exoplanets that have been discovered. Although over 6000 total exoplanets have been discovered, the number of Earth-like exoplanets is under 50. Still, the sample size of exoplanets is currently large enough for many logical conclusions to be drawn. However, it is noteworthy that a larger sample size will make conclusions more accepted within the scientific community. Another limitation is that our current methods of detection mostly find very large exoplanets or exoplanets that are close to their host star. These attributes can make Earth-like exoplanets' properties much different than the properties of Earth. For example, exoplanets that orbit close to their host star are very vulnerable to the host star's mega-flares. (Schulze-Makuch et al. 2011).

Due to the lack of advanced technology and telescopes, acquiring exact measurements for an exoplanet's atmosphere is not possible at this time. The absence of atmospheric measurements limits the accuracy of certain factors that influence habitability, such as temperature and pressure. Atmospheric composition is likely the most influential factor when determining habitability, but it cannot be researched in depth with our current limitations. Detection of exoplanets that orbit main-sequence stars like our sun are limited and could not be analyzed in this experiment. However, only a few Earth-like exoplanets have been discovered that orbit a G-type main-sequence star (a white star like Earth's Sun). It is possible that exoplanets that don't orbit a star like our sun aren't habitable. Hopefully, in the future, new detection methods or better equipment can be used to detect exoplanets that are further from their host star but still in the habitable zone. As the scientific community is able to overcome these limitations over time, this type of research will be more impactful.

Conclusion

After conducting a series of tests, a variety of results have been obtained. It can be concluded that an exoplanet's mass is not a deciding factor when determining habitability, although most of the Earth-like exoplanets have a mass similar to Earth. It can also be concluded that period does not affect ESI. However, periods that are too short make habitability less likely, due to large temperature and radiation fluctuations. Flux is one of the most important factors for determining habitability because exoplanets need to sustain liquid water on their surface to support life. After conducting research, it can be determined that an exoplanet that is further away from its host star is more likely to have a stable temperature and atmosphere. Based on the results regarding Proxima Centauri b's risks, humans have not yet detected exoplanets close to Earth that we would be able to colonize in the near future. Even though interest in exoplanets is increasing, the human race should try their best to minimize climate change here on Earth and focus on protecting Earth from dangers in outer space.

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