Exploring Exoplanets

Nora Olson

Abstract

An exoplanet is a planet that exists outside of our solar system. In the future, it is likely that humans will choose to live beyond the Earth, or will have to, and understanding the habitability of exoplanets can guide the process of inhabiting other solar systems. Exoplanets may be very similar to celestial bodies such as the Moon and Mars, but they are more difficult to study and travel to due to their distance from Earth. Public interest in exoplanets often takes the form of fictional planets in pop culture, such as Tatooine in *Star Wars* or Arrakis in *Dune*. The search for habitable exoplanets is connected to the search for extraterrestrial intelligence because these planets could be home to life. Each of these aspects helps to form our understanding of what exoplanets are, why they matter, and how we might continue our research and exploration of them. This paper explores several stages of exoplanet research in order to discuss the future of exoplanet research and space exploration.

Introduction

Have you ever wondered what it would be like to live on a planet like Tatooine from *Star Wars*, which orbits two stars? How about a barren, sandy planet like Arrakis from *Dune*? Today, astronomers are doing the research that they hope will put humans on planets beyond our solar system. Since the discovery of the first exoplanets in 1992, astronomers around the world have been developing technology to learn more about these extrasolar planets. Thousands more exoplanets have been discovered since then, and scientists have studied them in detail, even determining whether they could host human life in the future (Kershner, 2024). Studies are hopeful, but we still have a long way to go before we end up on one. Through the use of modern technology, astronomers can detect and gather information on the planets outside of our solar system. This paper explores these exoplanets, from their discovery to the potential of putting humans on them, while also considering how this information is shared through both research and pop culture.

Exoplanet Detection Methods

The first step to determining whether an exoplanet is habitable is confirming its existence. There are thousands of potential or candidate exoplanets, but not all of them have been confirmed (NASA). A candidate exoplanet must be verified by multiple telescopes or methods discussed below before it is confirmed, but is considered a candidate as soon as there is evidence that it could exist. There are five ways to identify and verify exoplanets, each using different technology and laws of physics. These detection methods are the transit method, the radial velocity method, gravitational microlensing, direct imaging, and astrometry (NASA).

Although there are rogue exoplanets that drift through space without orbiting a star, many exoplanets are part of systems similar to our solar system (NASA). Exoplanets that orbit stars can be detected through a process called transit. A star emits light at a constant luminosity, or brightness. This light can be picked up by astronomers and tells them about the size and temperature of stars. If a star is not being orbited, this light is an uninterrupted stream. However, if an exoplanet is orbiting a star, it will pass in front of the star, causing the light to be dimmer at consistent intervals (Las Cumbres Observatory). If an astronomer can detect a pattern in the brightness of the star, it can be used as proof of an exoplanet. Transit is the most common detection method, having led to 4,216 exoplanets being found (NASA). The more planets orbiting a star, the more difficult it is to discern which drops in brightness are due to which planet, but it is almost always possible to determine the pattern with enough time. Despite the large volume of exoplanets that have been discovered via the transit method, it does have its constraints. Because all observations are from or near Earth, we are limited only to systems whose planes align such that exoplanets will pass between the star and Earth. This only accounts for ~10% of hot Jupiters – gas giant exoplanets that are more similar to Jupiter or Saturn than Earth (Las Cumbres Observatory). Additionally, even though smaller exoplanets and exoplanets with larger orbits can be detected, transit is much more likely to detect large, close-orbiting exoplanets as they create more noticeable dips in luminosity (Las Cumbres Observatory).

The second most common method is radial velocity, which has been the source of an additional 1,089 confirmed exoplanets (NASA). To understand radial velocity, there are two fundamental laws that must be understood: all objects have gravity, and lightwaves can change color when they move. The equation for gravity due to an object is $\frac{GMm}{r^2}$, where G is the gravitational constant, M and m are the masses of the objects, and r is the distance between the objects. A star has significantly more mass than a planet, which is why planets orbit stars and not the other way around, but planets do still have mass. Although this creates a less significant force, stars are drawn in slightly toward the planets orbiting them, creating a “wobble”. This wobble can be detected because the color of starlight will be slightly changed. When an object emitting light is getting closer to an observer, the wavelength of light is getting smaller, causing the light to be bluer. When the object is retreating, the light gets redder. This phenomenon is known as the Doppler effect. An observer on Earth may measure a star’s light and notice a slight fluctuation in color due to a wobble, suggesting that an exoplanet is orbiting the star (NASA).

There is another method, astrometry, that is very closely related to radial velocity. Although a mere three planets have been found by astrometry, it uses similar observations to determine whether an exoplanet may be orbiting a star. Instead of looking at the color of light, astronomers may observe a larger area of space around a star and measure the distance between it and other objects of known distance, usually nearby stars. If the star is being orbited by an exoplanet, the wobble will be detectable because it will move relative to nearby stars. So few exoplanets have been discovered this way because the movement is minute compared to the large section of sky that must be observed – it is usually easier to just look at the star itself. One must therefore know the distances between the reference objects to very high precision (NASA).

When a star passes in front of another star, its gravity bends the starlight and creates a bright flash. This effect is even stronger when the star passing in front has an exoplanet, as it has more gravity and therefore more distortion in spacetime. Astronomers may observe these flares in a detection method called gravitational microlensing. Although the scope of both transit and radial velocity detection can be hundreds of light years, gravitational microlensing can detect exoplanets at greater distances (The Planetary Society). It has picked up on 223 exoplanets so far (NASA). Gravitational microlensing can also detect rogue exoplanets that are not orbiting a star.

The final detection method is the most simple: direct imaging. While only 82 planets have been discovered due to photography (NASA), this method has the potential to be much more successful as technology improves. Currently, the overwhelming brightness of starlight drowns out exoplanets in photographs if blockers are not used. Starshades and coronographs can both act as blockers for telescopes; starshades externally prevent excessive starlight from entering telescopes, while coronographs are installed internally to block light from telescopes' detectors. Exoplanets can also be difficult to detect at a distance, but improvement to telescopes will allow further observations and more detailed images of closer exoplanets.

Habitability Requirements

After confirming that an exoplanet exists, determining whether it is habitable is the next step. There are certain conditions that scientists believe are necessary for all life forms to survive on a planet. Astronomers have not yet been able to clarify all aspects of exoplanets to date, but as technology advances we may be able to gather more and more information from afar. Maybe one day, technology will help us replicate Earth-like conditions on other planets, or we might find an exoplanet that is almost identical to Earth. But for now, the focus is on the criteria that we can determine from Earth.

SEPHI (Statistical-likelihood Exoplanetary Habitability Index) proposes four criteria, based on seven physical attributes that are calculable from Earth, to determine an exoplanet's habitability (Rodrígues-Mozos, Moya, 2017). These criteria are posed as questions: Is the planet telluric (rocky)? Does it have an atmosphere dense enough to support and a gravity compatible with life? Does it have liquid water on its surface? Does it have a magnetic field shielding its surface from harmful radiation and stellar winds? (Rodrígues-Mozos, Moya, 2017). All of these questions can be answered if the planetary mass, stellar mass, planetary radius, stellar radius, planetary orbital period, effective temperature of the star, and planetary system age are known.

One of the most important things to know about a planet is its temperature, since there is a range of temperature that allows liquid water to exist, and determining whether an exoplanet falls in this range can help to determine whether it may be habitable. This range is referred to as the Goldilocks Zone or habitable zone (NASA). Outside of the Goldilocks Zone, water may evaporate or freeze, but being the right distance from a star does not confirm the presence of liquid water, just that if there is water, it would be liquid. The Goldilocks Zone is different for each star; it can be calculated by measuring a star's luminosity and using this to determine the inner and outer boundaries in which exoplanets must orbit to allow for liquid water (Morris, 2023). Many of the nearest exoplanets to Earth orbit red dwarf stars, which are cooler than our sun. This means that the habitable zone is closer to the star, increasing the likelihood that potentially habitable exoplanets are exposed to intense radiation which threatens their habitability status.

Knowing whether a planet has a breathable atmosphere is also essential. The layers of gas that surround a planet and form an atmosphere have many purposes: they provide the air that allows living things to breathe, but they can also be protective against UV rays and can regulate the temperature of the planet (Loiacono, 2024). Earth's atmosphere is roughly 78% nitrogen, 21% oxygen, and 1% other gasses. Astronomers can figure out which elements make up an exoplanet's atmosphere by looking at the color of light it emits. Each element has a unique color spectrum – when its atoms absorb photons they create dark bands throughout the spectrum. By studying emitted light, astronomers can match the missing bands in the color spectrum to the elements that cause those bands and determine which elements are in the atmosphere.

Exoplanet Case Studies

Currently, there are 5,741 confirmed exoplanets. Of course, only some of these fall within the Goldilocks Zone, and even fewer have a high chance of actually being habitable for humans. Right now, the number of potentially habitable exoplanets sits around 66, just over 1% of the total. However, astronomers predict that there could be 60 billion habitable exoplanets in our galaxy, and 50 sextillion total in the universe (Kershner, 2024).

Of the 66 potentially habitable exoplanets, some are more interesting or studied than others. The most researched system apart from our own is TRAPPIST-1, a red dwarf star 41 light years (LY) away from Earth that is orbited by seven Earth-like, rocky exoplanets. TRAPPIST-1's exoplanets all fall within the Goldilocks Zone (NASA). When they were discovered in 2017, public interest was piqued due to TRAPPIST-1's record-breaking number of rocky exoplanets that could host liquid water and the accompanying publicity, including NASA artwork depicting the planets, playing on classic sci-fi imagery. Its potential for sustaining life has made it an incredibly interesting system for astronomers to study.

The exoplanets orbiting TRAPPIST-1 are similar to Earth in that they are telluric and in the habitable zone, but have notable differences as well – and it is likely that more will be revealed as further research is conducted. For example, though they are rocky planets, they are less dense than Earth (NASA). This may have implications for habiting the planet, but it is unclear exactly what the composition is yet. Additionally, their orbits are much shorter than Earth's. The four most likely habitable exoplanets, TRAPPIST-1d, e, f, and g, range from four to 12 days per orbit.

The distance between Earth and TRAPPIST-1 presents a challenge. Not only does it keep astronomers from collecting data, but it is also going to be incredibly difficult to travel to the exoplanets in the future. While science fiction can provide plenty of explanations for light speed travel, we are still only able to travel at relatively slow speeds, confining us to our solar system. Although 41 LY would be an impossible distance to cover right now, it is actually not very far in the big picture. Some of the other exoplanets that have been considered for habitability are thousands of LY away, like Kepler-1606b, which is over 2,700 LY from Earth (NASA).

Kepler was NASA's first "planet hunting" telescope whose primary goal was discovering deep space exoplanets. It revealed to astronomers that there are more planets than there are stars in our solar system. Kepler-1606 is just one of the many stars with orbiting exoplanets that the telescope discovered. Other discoveries included Kepler-452b, the first Earth-sized exoplanet to orbit a star like our sun (although in this case, "Earth-sized" is actually 60 percent larger than Earth, according to NASA); Kepler-22b, a greener and closer to Earth exoplanet than Kepler-452b, though it is even larger; and Kepler-186f, an Earth-like planet in the habitable zone. Kepler was surveying a section of the sky in the constellation Cygnus, so all of its discovered exoplanets are relatively close in the sky.

The information that is being collected on confirmed exoplanets will be foundational for future generations. The data gathered on specific planets will teach us more about the nature of exoplanets as a whole, as well as determine the potential candidates for exploration further into the future.

Habitability of Other Bodies

Before humans travel to exoplanets, we are likely going to establish permanent residency on other celestial bodies within our solar system. The Moon is the only other body humans have set foot on, and it will almost definitely be the next. Plans to visit Mars have also been put in place, and it is likely that we will continue to visit the solar system in the near future. These expeditions will be a foundational part of the process in exploring exoplanets.

Mars may not be the closest planet to Earth, but it is one of the most well-researched. It is also one of the next destinations for astronauts. While Mars is known for being red, barren, and cold, it was not always that way. Studies conducted by NASA have suggested that Mars used to have a thicker atmosphere and an Earth-like climate (Steigerwald, 2022). A thicker atmosphere would have been able to trap more heat and greenhouse gasses, heating Mars and allowing water to be liquid. In fact, there is evidence that Mars used to have an ocean. The presence of liquid water is one of the most significant criteria in determining the habitability of a planet, so even though Mars is currently too cold, it used to be more habitable. There is still the presence of frozen water, too, which can be utilized and melted down by technology. Knowing that the planet is very cold, humans must be prepared to withstand these extreme temperatures.

Mars is also a strong candidate for exploration due to its telluric nature. The name for Martian soil is regolith, and it has the ability to help humans survive in multiple ways (Mars Society). For one, nutrients are a necessity in soil for agriculture, and regolith is filled with them. The ability to grow plants on the surface of Mars makes it a promising place for civilization to survive. Regolith can also be used for construction, allowing settlers to build the necessary structures for survival without having to bring the materials from Earth. Survival on Mars would not be easy, but it would not be impossible either. The challenges it presents are easier to deal with than almost any other celestial body that could be habited. It is close to us, similar to Earth, and has the potential for civilization. While it has its own challenges, the Moon is another celestial body that may be occupied in the near future.

The Moon has no atmosphere, but, like Mars, it could have once held liquid water in the form of lunar pools or oceans (Schulze-Makuch, 2018). While its physical state is even more barren than Mars, it does have the advantage of being significantly closer to Earth, and humans have already visited its surface. The Moon's proximity to Earth boosts its status from a dead rock to an interesting stop on the way to habiting exoplanets.

The Moon has become the finish line in a space race for the second time, as national and non-state organizations rush to put people back on the lunar surface . NASA's Artemis missions aim to put humans on the moon as a stepping stone before putting humans on Mars. Artemis III, which will likely launch in late 2026, will be the first manned mission to the moon since the 70s. In the Artemis Accords (2020), it was agreed upon that the Moon, along with Mars, comets, and asteroids, would be studied for peaceful purposes by NASA and the seven other countries who signed. The Artemis missions are also a step in diversifying the population of astronauts who have been to the Moon and is the first instance of international partnership with NASA regarding lunar landings. Despite some international cooperation, the race is still on between the United States and China, who also plans on landing humans on the Moon by 2030 (BBC). Due to the promise of resources on the Moon, as well as the potential industry of space travel, private companies are also trying to land on the Moon. A lunar economy is likely to emerge in the future, with the increased amount of private companies who intend on profiting off the public interest in the Moon adding fuel to the fire started by the governments' proposed missions (BBC).

The Moon and Mars are just two celestial bodies within our solar system that will likely be occupied before humans step foot on an exoplanet. Some of Jupiter's moons and Venus are also potentially habitable bodies. Wherever we end up within the solar system is just another opportunity to practice the process of occupying another world.

The Search for Extraterrestrial Intelligence

The search for exoplanets goes beyond the search for a place to which humans may relocate in the future. It is closely related to the search for extraterrestrial intelligence. Although aliens have existed in human mythology and pop culture for centuries, there is no evidence that they truly exist. That does not deter scientists who research exoplanets and other celestial phenomena in search of extraterrestrial life.

Even if life were discovered outside of Earth or our solar system, little is known about what it might look like. There are certain commonalities that life forms share on Earth, but that does not guarantee that they would also be requirements for extraterrestrial life. There is also a huge difference between life and intelligence: a tree and a human are both alive, but only one has the ability to learn and understand information, let alone communicate. Discovering non-communicative life beyond our planet would be more difficult. An intelligent species would leave traces that are more detectable, like evidence of society on the surface of the planet or wavelengths including radio and light. Choosing where to send our technology, which can only travel at relatively slow speeds, would require a lot more information than we currently have.

When exoplanets are discovered, there is the possibility that life is present on them. Because all life as we know it has basic requirements (being carbon-based, uses water, uses energy, grows/reproduces), the search for extraterrestrial intelligence often starts where similar conditions can be found; exoplanets that have more similarities to Earth are likely candidates for where we might make contact with alien life. However, there may be life as we do not know it out there, too: life that does not fit into our current definition. What this could look like is purely theoretical. Even if it is not "intelligent" to the degree of possible communication, a planet with liquid water (in the Goldilocks Zone) may be home to extraterrestrial plants or animals.

The Fermi Paradox (SETI, 2024) was a question posed by scientist Enrico Fermi in 1950, suggesting that, if there really are aliens in space, we would already know. The basis of this claim was that intelligent species would choose to expand and essentially colonize space. So, even if aliens exist at a faraway point in spacetime, they would eventually become advanced enough to spread throughout space, creating civilization that would overcome extinction, and we would have come in contact with them already. Aliens would have had more than enough time to colonize space, even if their technology was only a fraction of the speed of light and even if they were not attempting to colonize space as quickly as possible (SETI, 2024). There are several assumptions made by Fermi, however, that could explain why we have not come in contact with aliens. The first is the sheer amount of energy that space travel requires. How are aliens obtaining the billions of joules necessary to travel? And how are they affording and dispersing it amongst themselves? Also, how do we know that aliens would choose to colonize? While it is, at least for now, the path that humans are setting themselves on, there is no proof that aliens would have the same desire to leave their home planet, let alone expand across millions of light years. Aliens could also just be much further away than we imagined, or purposefully excluding us from their network of intelligent life.

The Drake equation was created in 1961 by Dr. Frank Drake and uses seven values to calculate the number of intelligent, communicative civilizations in our galaxy. The equation is $R \times Fp \times Ne \times Fl \times Fi \times Fc \times L = N$ where R is the number of sun-like stars that form in our galaxy each year, Fp is the fraction of these stars which have planets, Ne is the number of

Earth-like planets in each of these planetary systems, Fl is the fraction of these planets on which life forms, Fi is the fraction of life that develops into intelligent life, Fc is the fraction of intelligent life which also learns to communicate, and L is the lifetime of a communicative society. Although this equation may yield remarkably high answers (Drake's estimate is 10,000), we are no closer to contacting these civilizations.

Exoplanets in Pop Culture/Media

Science fiction has been a part of pop culture for decades. Iconic franchises like *Star Wars*, contemporary films like *Interstellar*, and classic books like *Dune* have all made their mark on the genre and on the people who love them. Whether they focus on completely fabricated galactic wars or are as grounded in reality as possible, all of these pieces of storytelling have attracted public interest and garnered fanbases. Fiction is one of the many ways that scientific speculation can be shared, and can inspire exploration.

In media, many characters call an exoplanet home. One of the most recognizable exoplanets is Tatooine, a sandy desert planet that orbits two suns and is home to Luke Skywalker in *Star Wars*. Although Tatooine is not a real planet, the creators and fans alike have compiled a significant amount of information for the canon. For example, there is a precise diameter for Tatooine: 10,465 km. This makes Tatooine larger than Earth, though its orbital period is shorter than ours at only 304 days. The surface of Tatooine is silicon and only 1% of its surface holds water. Just because it is fictional does not mean that a planet like Tatooine could not exist. In fact, Kepler-16b, a gas planet that orbits two stars in the constellation Cygnus, is often referred to as the closest thing to a real-life Tatooine.

One of the more Earth-like exoplanets in fiction, Alderaan was a lush *Star Wars* counterpart to Tatooine's desolation. Alderaan was covered in oceans, forests, and mountains, and even had an orbital period of 364 days – almost exactly the same as Earth. Alderaan had no moons and was the only planet orbiting its sun. After its destruction, it left an asteroid field made of its remains.

Similar to Tatooine, Arrakis is another fictitious desert planet from the sci-fi novel *Dune*, written by Frank Herbert in 1965. Unlike the barren, flat deserts of Tatooine, Arrakis's desert is interrupted by mountain ranges which contain water deep within them. It is reasonable to assume that a planet like this could actually exist (Aridi and Flatow). The desert biome does exist on Earth, and there are plenty of exoplanets and planets within our solar system that do not have water on the surface. Like Venus, Arrakis could have had oceans that have since evaporated, leaving only the hot desert behind.

Christopher Nolan's 2014 film *Interstellar* explores a potential future that forces humans off Earth and onto exoplanets. Famously, American astrophysicist Kip Thorne worked closely with Nolan to create situations, and exoplanets, which could feasibly exist. Several exoplanets are explored in the film, each named after the astronaut who explored it. One of these planets, Miller, was covered completely in a shallow ocean and, due to time dilation, every hour that passed on the planet equated to 7 years on Earth. Another planet from the film, Mann, had no discovered surface, only layers upon layers of icy clouds that characters resided on. Its atmosphere contained ammonia, preventing humans from living on it.

There are hundreds of science fiction novels, movies, and other media that depict exoplanets. These fictional works can make scientific concepts more accessible to people, and often explore potential futures for humans. Science fiction is proof of human interest in space exploration and demonstrates just how much is possible in this universe.

Conclusion

Whether it is due to interest or necessity, humans may eventually travel beyond our solar system to other planets. The research that is being done now will guide this exploration for years to come. Finding exoplanet candidates, gauging their habitability likelihood, and studying them in depth will help us choose where to focus further research and eventually where to go. Astronomers and fanatics alike are hopeful that our future includes inhabiting other worlds, and nothing suggests that that won't be our reality with enough time and development. Understanding how to inhabit celestial bodies that are not Earth and determining if there are other forms of life that have done that also prepare us for future exploration. Interest in exoplanets will only grow, shifting from fictional planets to genuine possibilities, and one day, it almost certainly will be our reality.

Sources

Admin. “Discovery of an Earth-Size, Potentially Habitable Planet.” *Science in the News*, 29 Feb. 2024, sitn.hms.harvard.edu/flash/2024/discovery-of-an-earth-size-potentially-habitable-planet/.

Aridi, Rasha, and Flatow, Ira. “Could a Planet like Arrakis from ‘Dune’ Exist?” *Science Friday*, 15 Mar. 2024, www.sciencefriday.com/segments/dune-2-arrakis-exoplanets/#segment-transcript.

Berkeley SETI, seti.berkeley.edu/. Accessed 25 Aug. 2024.

“The Fermi Paradox.” *SETI Institute*, www.seti.org/fermi-paradox-0. Accessed 25 Aug. 2024.

“Funded Study Extends Period When Mars Could Have Supported Life.” *NASA*, NASA, 26 July 2023, www.nasa.gov/solar-system/nasa-funded-study-extends-period-when-mars-could-have-supported-life/.

“The Habitability of Mars.” *The Mars Society of Canada*, 2 June 2024, www.marssociety.ca/the-habitability-of-mars/.

“The Habitable Zone - NASA Science.” *NASA*, NASA, science.nasa.gov/exoplanets/habitable-zone/. Accessed 25 Aug. 2024.

Howell, Elizabeth, and Ailsa Harvey. “The 10 Most Earth-like Exoplanets.” *Space.Com*, Space, 20 Jan. 2022, www.space.com/30172-six-most-earth-like-alien-planets.html.

“In Depth - NASA Science.” *NASA*, NASA, science.nasa.gov/exoplanets/facts/#h-confirmed-vs-candidate. Accessed 25 Aug. 2024.

“Is Mars Habitable? We Asked a NASA Scientist: Episode 2.” *NASA*, NASA, 17 Nov. 2023, www.nasa.gov/solar-system/is-mars-habitable-we-asked-a-nasa-scientist-episode-2/.

Kershner, Kate. “How Many Planets in Our Universe Could Support Life?” *HowStuffWorks Science*, HowStuffWorks, 7 Mar. 2024, science.howstuffworks.com/planets--universe-support-life.htm#:~:text=Considering%20the%20vast%20number%20of,many%20candidates%20for%20hosting%20life.

Kershner, Kate. “What Conditions Are Required for Life?” *HowStuffWorks Science*, HowStuffWorks, 12 Mar. 2024, science.howstuffworks.com/environmental/earth/geophysics/conditions-required-life.htm#:~:text=Common%20requirements%20for%20Earth%2Dbased,sources%20to%20fuel%20metabolic%20reactions.

"Largest Batch of Earth-Size Habitable Zone Planets Found Orbiting TRAPPIST-1 - NASA Science." *NASA*, NASA, science.nasa.gov/exoplanets/trappist1/. Accessed 25 Aug. 2024.

"Life beyond Earth - Drake Equation." *PBS*, Public Broadcasting Service, www.pbs.org/lifebeyondearth/listening/drake.html. Accessed 25 Aug. 2024.

Loiacono, Milan. "What Is... Earth's Atmosphere?" *NASA*, NASA, 14 May 2024, www.nasa.gov/general/what-is-earths-atmosphere/.

Magazine, Smithsonian. "Earth's Moon Could Have Been Habitable 3.5 Billion Years Ago." *Smithsonian.Com*, Smithsonian Institution, 23 July 2018, www.smithsonianmag.com/air-space-magazine/earths-moon-could-have-been-habitable-35-billion-years-ago-180969719/.

Miller, Katrina. "An Ocean Moon Thought to Be Habitable May Be Oxygen-Starved." *The New York Times*, The New York Times, 4 Mar. 2024, www.nytimes.com/2024/03/04/science/europa-moon-oxygen.html#:~:text=Under%20its%20bright%2C%20frosty%20shell,whether%20Europa's%20ocean%20has%20it.

Morris, Tom. "Calculating the Habitable Zone." *Calculating the Habitable Zone*, www.planetarybiology.com/calculating_habitable_zone.html. Accessed 25 Aug. 2024.

"NASA's Kepler Mission Discovers Bigger, Older Cousin to Earth." *NASA*, NASA, 26 July 2023, www.nasa.gov/news-release/nasas-kepler-mission-discovers-bigger-older-cousin-to-earth/.

Nelson, Sue. "Moon Race 2.0: Why so Many Nations and Private Companies Are Aiming for Lunar Landings." *BBC News*, BBC, 16 Feb. 2024, www.bbc.com/future/article/20240216-moon-race-20-why-so-many-nations-are-aiming-for-lunar-landings.

Refining the Transit-Timing and Photometric ... - Iopscience, iopscience.iop.org/article/10.3847/PSJ/abd022/pdf. Accessed 25 Aug. 2024.

Requirements and Limits for Life in the Context of Exoplanets | Proceedings of the National Academy of Sciences, www.pnas.org/doi/10.1073/pnas.1304212111. Accessed 25 Aug. 2024.

"Sellers Exoplanet Environments Collaboration (SEEC)." *NASA*, NASA, seec.gsfc.nasa.gov/Research/atmospheres.html. Accessed 25 Aug. 2024.

"Sellers Exoplanet Environments Collaboration (SEEC)." *NASA*, NASA, seec.gsfc.nasa.gov/what_makes_a_planet_habitable.html#:~:text=The%20standard%20definition%20for%20a,water%2C%20energy%2C%20and%20nutrients. Accessed 25 Aug. 2024.

SETI Institute, www.seti.org/?gad_source=1&gclid=EAIaIQobChMI29LinuGfhwMVD05HAR29uwpYEAAYASAAEgKb5fD_BwE. Accessed 25 Aug. 2024.

“SETI, the Search for Extraterrestrial Intelligence.” *The Planetary Society*, www.planetary.org/sci-tech/seti. Accessed 25 Aug. 2024.

“Seven Rocky Trappist-1 Planets May Be Made of Similar Stuff - NASA Science.” *NASA*, NASA, science.nasa.gov/universe/exoplanets/seven-rocky-trappist-1-planets-may-be-made-of-similar-stuff/. Accessed 25 Aug. 2024.

“Space-Warping Planets: The Microlensing Method.” *The Planetary Society*, www.planetary.org/articles/space-warping-planets-the-microlensing-method. Accessed 25 Aug. 2024.

Staff, Astronomy. “Ask Astro: How Do Scientists Determine the Chemical Compositions of the Planets and Stars?” *Astronomy Magazine*, 18 May 2023, www.astronomy.com/science/how-do-scientists-determine-the-chemical-compositions-of-the-planets-and-stars/.

Statistical-Likelihood Exo-Planetary Habitability Index (SEPHI), arxiv.org/pdf/1707.07986.pdf. Accessed 25 Aug. 2024.

“Tatooine.” *StarWars.Com*, www.starwars.com/databank/tatooine. Accessed 25 Aug. 2024.

“Transit Method.” *Las Cumbres Observatory*, lco.global/spacebook/exoplanets/transit-method/. Accessed 25 Aug. 2024.

The TRAPPIST-1 Habitable Zone | Hubblesite, hubblesite.org/contents/media/images/2017/07/3986-Image.html?news=true. Accessed 25 Aug. 2024.

Trosper, Jaime. “Earth-Similarity Index: Where Could We Live besides Earth?” *Interesting Engineering*, 26 Feb. 2021, interestingengineering.com/science/earth-similarity-index-where-could-we-live-besides-earth.

Wiki, Contributors to Dune. “Arrakis.” *Dune Wiki*, Fandom, Inc., dune.fandom.com/wiki/Arrakis. Accessed 25 Aug. 2024.

Wiki, Contributors to Interstellar. “Mann (Planet).” *Interstellar Wiki*, Fandom, Inc., interstellarfilm.fandom.com/wiki/Mann_(planet). Accessed 25 Aug. 2024.

Wiki, Contributors to Interstellar. “Miller (Planet).” *Interstellar Wiki*, Fandom, Inc., interstellarfilm.fandom.com/wiki/Miller_(planet). Accessed 25 Aug. 2024.

Wookieepedia, Contributors to. “Alderaan.” *Wookieepedia*, Fandom, Inc., starwars.fandom.com/wiki/Alderaan. Accessed 25 Aug. 2024.

Wookieepedia, Contributors to. “Tatooine.” *Wookieepedia*, Fandom, Inc., starwars.fandom.com/wiki/Tatooine. Accessed 25 Aug. 2024.

Wordsworth, Robin. “Can Mars Be Made Habitable in Our Lifetime?” *Scientific American*, Scientific American, 20 Feb. 2024, www.scientificamerican.com/blog/observations/can-mars-be-made-habitable-in-our-lifetime/.