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What are the Critical Factors that Affect the Habitability of Celestial Bodies in Our Solar System?

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Abstract

The study of habitability on planets and celestial bodies apart from Earth has gathered increased interest over the last few decades due to grand technological advancements. Space agencies like NASA are spending billions of dollars on spacecraft, probes, and satellites for this specific purpose, but as of now, no one knows what different (and possibly quite similar) species reside in our solar system, and where they live (moons, planets). However, a planet/moon being habitable to life is not that easy, and there are hundreds of factors that can make a celestial body habitable. This paper will cover a few of the several factors: existence of liquid water, atmospheric composition, chemical composition of the planet's surface, and biofuel, along with linking these factors to different celestial bodies in our solar system, specifically focusing on Mars, Venus, Europa, and Titan.

Introduction

The presence of liquid water on a celestial body is critical, and increases the chances of any form of life surviving. Since water is essential for the survival of humans, it is also assumed that something like water (if not water itself) might be needed by extra-terrestrial organisms to survive. Linked with water, the next factor is a celestial body's atmosphere and temperature. For water to remain in its liquid state, it's temperature needs to be ideal, where it is not too hot or cold , which can be largely related to the Stellar Characteristics of the celestial body . This also tells us that the celestial body has an atmosphere (of a decent density which can provide ample pressure to retain certain elements, while trapping greenhouse gases). A fairly dense atmosphere can shield the surface of the celestial body from solar flares which can harm the surface and tear through a weak atmosphere over time. Along with an atmosphere protecting us from solar flares (which could be deathly for life on a celestial body), the atmosphere can also trap certain elements in it. For example, the Earth's atmosphere has trapped nitrogen, carbon dioxide, and oxygen , allowing for organisms to evolve.

The different elements present on a celestial body have a grand impact on life thriving. The elemental composition is crucial to life sustainability, because different types of organisms need their own unique set of elements to survive. For example, humans require the elements of oxygen, carbon dioxide, and nitrogen, which are present on our planet. Biofuels are also critical to understanding how life may thrive on a planet or moon, as they are derived from energy sources to facilitate mechanisms to support life. For example, the Sun emits biofuel, because it's light is used in the process of photosynthesis to grow trees, plants, and power many ecosystems. There are still other sources of biofuel on Earth rather than the Sun, such as volcanoes. In order to explain the critical factors that affect habitability, this paper will cover satellites in our own solar system that have or once had the ability to sustain life: Mars, Venus, Europa, and Titan.

Stellar Characteristics

The habitability of a planet is determined by numerous factors, and the characteristics of its star are extremely important. In our solar system, the Sun is classified as a yellow dwarf star, or a G type star. A G type star is a star that is in its main sequence (most stable part, and the longest stage in a star's life) of life, and is often red/yellow/orange in Color. Temperatures for such stars range from 5,300 Kelvin to 6,000 Kelvin.[1]

Throughout all of the stages of life in the Sun, the highest possibility for life to sustain when a star is in its main sequence. The luminosity of the Sun, or the thermal energy and light of the Sun that it is being released is changed throughout the Sun's life.. Red dwarf stars or K type stars (orange dwarfs) are both in the main sequence, and show the most promising conditions to sustain life with celestial bodies in its orbit.[2]

Throughout the universe, the best chance of finding life will be celestial bodies in orbit around a K type star. These stars are in the main sequence, and are usually orange/yellow dwarves. K type stars can live for 15 billion to 45 billion years. Our Sun has a relatively shorter life span of around 10 billion years, and is about half way through it. K type dwarf stars usually have the ideal temperature (around 4000 degree Celsius) , and lifespan to sustain life. Unlike other stars, K type dwarf stars do not have very active magnetic fields, which means that there are not many strong X Ray and UV emissions.[3] Therefore, planets in its habitable zone will not face so much radiation, destroying the planet's atmosphere. For example, through NASA research, it has been found that a K type dwarf star, Kepler-422 is 2124 light years away from our Earth, and has the ideal Goldilocks region for planets to sustain life. Additionally, a planet in its orbit, one with almost twice Earth's mass, has been listed as a potential candidate for life to sustain.

Scientists have identified that for life to sustain on a planet, liquid water must be present, as humans cannot survive without it. For liquid water to remain in its liquid state, it must not be too hot, becoming gas, or too cold, becoming ice. This applies to the surface temperature of the planet, as it shouldn't be too hot or cold. Scientists have applied this to stars and planets, identifying a zone where the temperature is just right for liquid water, calling it the Goldilocks zone. In our solar system, the Goldilocks zone starts from around 107.81 million kilometers away from the Sun, and ends at about 247.53 million kilometers. Planets in this zone of our solar system include Venus, Earth, and Mars. This is one of the main reasons scientists are studying Mars and Venus so thoroughly, because they believe the temperature is right, or could have been right in the past to sustain life. The Goldilocks region depends on the size of the star, and the age of the star. If the star is too young, it would be sending out too many solar winds, and could destroy the atmosphere of the planet, whereas if it is too old, the star could be too hot. If stars are smaller, they are usually cooler, and that means that planets need to be closer to the star to get the perfect temperature. This also means that the distance of the Goldilocks zone is usually a shorter span. When a star is large, and is hotter and denser, the Goldilocks zone is usually farther away from the star, with a larger range.[4] A planet's Goldilocks zone can move in position, because stars can gain or lose mass as they grow. This can burn planets or moons in the star's previous Goldilocks zone. For example, scientists suspect that when the Sun was at an earlier stage of life, Venus might have had life on it. In the Sun's earlier stage of life, the Sun was less luminous, and therefore the Goldilocks zone at the time would have been around the location of Venus. Now the Sun has gained more mass, and become hotter, the previous habitability zone has become too hot. This could be a leading reason as to why Venus is now so hot, because as the Sun grew, it simply got too close, and the Goldilocks zone shifted to where Earth is now. This same event will happen to Earth, because as the Sun grows, it's surface will get closer to Earth, and the planet will become too hot to sustain life. Even though planets are not in the Goldilocks zone, it doesn't mean that they can't sustain life, they just can't sustain liquid water on its surface. For example, if we take Europa, a moon of Jupiter, it isn't in the Goldilocks zone, but scientists still suspect that it has liquid water under its surface (it's too cold on the surface), which could sustain life.

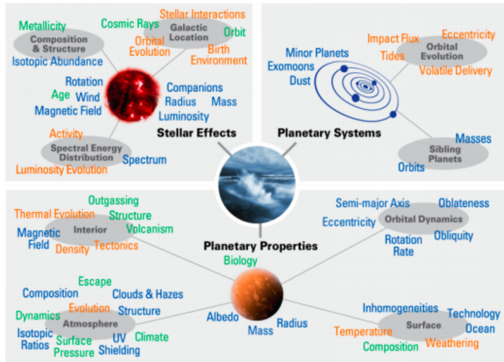

Figure 1: A chart which shows the numerous other factors that affect habitability, especially stellar effects, planetary systems, and planetary properties. The figure breaks down the sub factors that can affect bigger ones such as how the birth environment can affect stellar effects.[4] This figure is taken from reference 4.

Mars

Mars, also known as the red planet, is the 4th star from our Sun (in distance), right after Earth. As Mars rotates around the Sun, it's distance from Earth varies from about 49 million kilometers to 400 million kilometers. The planet has 2 moons, Phobos, and Deimos, both irregularly shaped, and has the highest discovered mountain in the solar system yet (Mount Olympus). As of now, scientists have observed its surface to be dusty, barren, and plain, with no sign of life from satellites. The planet also has 2 ice caps, and scientists believe that the ice present is from liquid water. As mentioned previously, Mars is also in the habitable zone, like Earth. The Earth is in a prime position, or the Goldilocks position in the habitable zone. with Mars on the colder edge of this zone.

Currently, Mars is unable to sustain water, due to its low atmospheric pressure; however, scientists believe that the planet could have had life when the Sun was younger. The reason why Mars's atmosphere is so thin is because at some stage in the Sun's life, it sent out a solar wind, which was too much for Mars's atmosphere to handle. This tore the atmosphere, and hence it dissipated away. As of now, due to the lack of an atmosphere, the red planet has harsh surface conditions, and it is unlikely there is life on the surface today. Additionally, the surface now does not have any protection from solar flares, or solar winds, due to the lack of an atmosphere.[5]

With the focus being shifted from Mars having life on it today, scientists are investigating if it could have in the past. This is due to the fact that minerals were found in the Curiosity NASA rover mission (in 2013), the same minerals that we often find in water (calcium sulfate). Since water is one of the most crucial indicators of life, this could mean that there was water and it evaporated, or there still is water, but deeper under the surface (scientists estimate around 8km subsurface.[6] Many structures on the surface of the planet also look like dried lakes and oceans, further strengthening this theory. Mars also has seasonal changes, which could be compared to Earth's seasonal changes and its water cycle.

Scientists hypothesize that some 3.8 billion years ago, the conditions on Mars were habitable. At this time, Mars could have had a water cycle, active volcano systems, and liquid water present on its surface. A key reason as to why Mars had a thin atmosphere, and lost it goes back to volcanoes. Volcanoes are the foundation of our atmosphere on Earth, and so must be the same for Mars (the gasses they emit). For volcanic eruptions to occur, there needs to be enough heat at the center of a planet, but Mars may have just not had enough heat. Now that the rovers from NASA's missions are roaming the surface, they are finding much fewer volcanoes than here on Earth, so the atmosphere may have been weak to begin with. This also explains a lot about the elemental composition on the planet (one of the factors of habitability). It illustrates how important it is for elemental composition, especially in the core of the planet, to be key for producing biofuel, and many natural phenomena that are crucial for life. Once there is a hole in the atmosphere, the gasses trapped will start to dissipate, and the atmosphere vanishes. Right now, the atmospheric pressure of Mars is less than 1% of Earth's.This is why when the Sun was at a younger, less stable stage in its life, it would have sent out a solar flare too strong for Mars's atmosphere, tearing a hole, and causing the gases to dissipate.

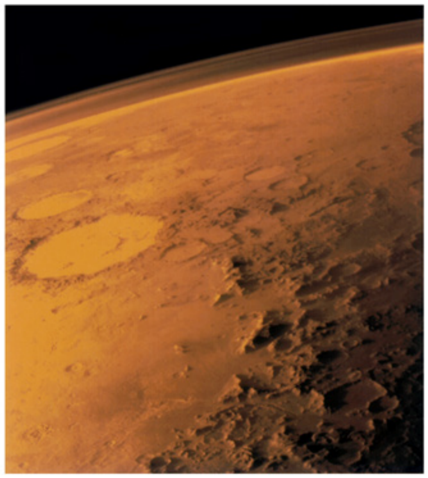

Figure 2: An image of Mars's surface that clearly shows the planets tenuous atmosphere, along with its barren and rough surface with crater impacts.[6] This figure is taken from reference 6.

Venus

Venus is often called Earth's sister planet, because the planets have similar shape, size, and mass (Venus is around 94% of Earth's size). It is known to be one of the 4 terrestrial planets in our solar system, alongside Mars, Earth, and Mercury. Venus's atmosphere, unlike Mars, is far denser than Earth's, in fact it is so dense that just on the surface, you can feel the same pressure you would feel 900 meters under our ocean. Even though it is not the closest planet to the Sun, it's surface temperature is by far the hottest, reaching 464 degree Celsius. The planet is covered by an opaque layer of clouds composed of sulfuric acid, that are highly reflective. This prevents its surface from being seen from any light in space. The planet was one of the first planets to be explored, due to it being so close to Earth, and was the first planet in which a spacecraft successfully landed in 1962 (the Mariner 2). Since then, Venus has been a hot topic for exploration, because it is believed that Venus sustained life, and mainly water, for about a billion years.[7] Like Earth and Mars, Venus is also in the habitable zone, but it is in the inner section, making it the closest to the Sun, and therefore the hottest planet in the habitable zone.

Scientists believe that Venus sustained water, but due to a runaway greenhouse effect, most water evaporated. A runaway greenhouse effect is when too many greenhouse gases, such as water vapor, carbon dioxide, methane, ozone, are released into the atmosphere, making it thicker, and very dense. Due to a very dense atmosphere, almost all thermal energy becomes trapped on Venus's surface, making the surface too hot for water to sustain. A key reason why this could have happened, is because many volcanoes have been spotted on Venus. As explained previously, volcanoes emit the chemicals that are necessary to create an atmosphere, and with so many volcanoes, the atmosphere might have simply become too thick. Volcanoes are also a great biofuel, as they are a source of heat on the surface, so at a time where water was able to remain, life might have been possible. Biofuels are processes which create biological energy, such as a volcano creating natural heat, or through photosynthesis, oxygen being created. On Earth, biofuels are essential to life, and so they should be to other life on other planets. On Venus, the biofuel is noticed as volcanoes, similar to the ones we have here on Earth. Unlike Mars, the volcanoes failed to create a proper atmosphere, whereas on Venus an extremely thick one was created. The fact that there are so many volcanoes on Venus also shows how the core of the planet, or it's interior, must be very hot, and definitely hotter than the one of Mars and Earth. Therefore, the elemental composition, interior of a planet, it's atmosphere, liquid water, are all interconnected.[8]

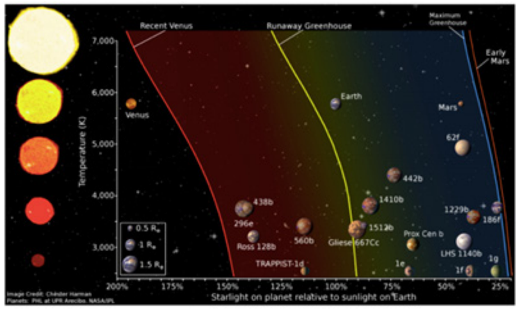

Figure 3: This figure shows the extent of Venus's greenhouse runaway affect, in comparison to Earth and Mars.[7] This figure is taken from reference 7.

In the past, around 3 billion years ago, when scientists believed that it was possible for Venus to sustain life, atmospheric conditions would not have been so harsh, and the surface would be much cooler. There would have been a fewer number of volcanoes, or those volcanoes did not get enough time to erupt, and make the atmosphere as thick as it is today. It is also important to note, that at this time, the Sun would have been much smaller, and it's stellar characteristics compared to today would be much more different. The Sun's luminosity was much cooler, and even though Venus was very close to the star, it wasn't too hot. Assuming, the same way that on Earth, with a perfect temperature, and under pressure, hydrogen bonded with oxygen to create water, it could have done the same when Venus too had the ideal temperature that Earth has today.

Titan

Planets are not the only celestial body in our solar systems that can harbor life, but moons have the potential to do so as well. However, moons are a bit different when considering habitability, because they face other problems as well, such as tidal bulging. This is when the gravity is much stronger on one part of the moon, compared to the others, due to the planet that it is orbiting. Tidal bulging can also cause deformations on the moon's surface if the planets gravitational pull is too strong, just like how when the Earth is closer to the moon, the moon's gravity influences the oceans tide.Titan, the largest moon of Saturn, is known to have a thick atmosphere abundant with elements such as nitrogen (and a bit of oxygen). Titan is 5,149.46 kilometers in diameter, and only receives about 1% as much sunlight as Earth, because 90% of the sunlight is absorbed by the moon's thick atmosphere.[9] The surface of Titan is composed of rocky and icy solids and water, while stable bodies of ammonia-rich water flow on the surface. The surface is also covered in organic molecules that have been drained out of the atmosphere, either in the form of liquid, or sand.[9] It is also the only other celestial body in our solar system other than Earth, to be confirmed to have a stable body of liquid.[9] The elements are liquid, not water, because most of the lakes in Titan are made from methane, ethane, and propane. Titan's surface is similar to the one of Earth's, and has rivers, seas, lakes, and dunes. Titan also has a methane cycle, similar to Earth's water cycle. Scientists have even noticed occasional rain, and wind on the distant moon. [9] Titan's seasons last 7 years, as Saturn takes 29 years for one revolution around the Sun. The most significant mission to Titan was the Cassini Huygens spacecraft which landed a space probe on the moon for a few minutes, and conducted a series of flybys in its atmosphere (1997). This mission gathered data of gravitational and magnetic fields around Titan, as well as capturing many images of the moon.

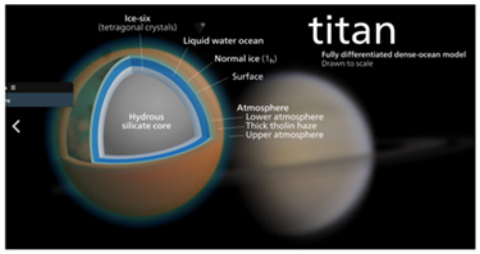

Figure 4: A diagram of the internal structure that illustrates the different layers from Titans surface to its core.[9] This figure is taken from reference 9.

Titan has shown promising conditions on its surface, which could help sustain life. It is able to sustain elements like methane and ethane in their liquid form, meaning the surface could be around -50 degree Celsius in temperature, which is not considered extremely harsh, similar to Antarctic temperatures on cold days. Scientists speculate that there could be life present in various liquid methane lakes of Titan, similar to how organisms on Earth can survive in water. These organisms would have to inhale H_2 in place of O_2, metabolize acetylene instead of glucose and instead of exhaling carbon dioxide, would exhale methane.[10] Experts at NASA have even discovered that Titan looks like what Earth did just before it started harbouring life.[9] The critical factor of habitability at play here is not liquid water, but in fact elemental composition, because elements like methane can also be carefully studied on Earth, as they are not that rare, so it is easier to draw conclusions for scientists. The discussion of habitability amongst scientists, also shifts from finding out whether life is present, to can humans survive on the celestial body, and researchers believe that the conditions and elements in abundance are useful to the humans survival in extraterrestrial planets other than Earth.

The next critical factor that can help decide the habitability of this moon is Titan's atmosphere. It has a thick atmosphere, similar to ours except it has more nitrogen (the atmosphere is about 95% nitrogen, unlike Earth's 78%).[11] However, unlike other planets like Mars, it still has an atmosphere, which is a key factor to habitability. Due to this atmosphere, it is able to maintain a more stable temperature, one similar to Mars, even though its distance is much farther away than the Sun (1.4 million kilometers). The atmosphere is also why the liquid form of most of these elements are able to sustain, just like water would need an atmosphere to remain under. The habitability factor can also be applied on Titan. This is because the different gravitational measurements carried out by the Cassini spacecraft indicate that there could be a subsurface ocean of water (probably rich in ammonia.[12] Having liquid water itself opens new possibilities for life on the moon, because it is more rich in minerals that life needs to survive. This also leans into the internal structure of Titan, which connects to the topic of biofuels. The previous biofuels that were discussed were volcanoes fuelled from the inner heat and core of the planet, however a different type of volcano has been spotted on Titan. This is an ice volcano, which could spew ice, or hydrocarbons. If it spews ice, it could further confirm the presence of water subsurface. Secondly, this is a biofuel, and must have some significance to the moon's natural processes just like normal lava volcanoes can help create atmospheres.

Europa

Another moon that has a high chance of harbouring life is Europa, one of the 16 moons orbiting the gas giant, Jupiter. Europa is slightly smaller than the moon orbiting the Earth, being 3,100 kilometers in diameter, and is the sixth largest moon in the solar system. Europa is also known for having the smoothest surface of any object in our solar system, which strengthens many scientists' theories of the moon having a subsurface ocean. Its young surface is mainly composed of silicate rock, and the crust is made of water-ice. Europa has a thin atmosphere which is mainly composed of oxygen, but the atmosphere is far too tenuous for species like humans to breathe oxygen. There are numerous reasons as to why Europa is already sustaining life, or has the potential to do so. The most significant Europa mission that has happened yet was in 1989 by the Galileo spacecraft, and the next Europa mission, The Europa Clipper is set to take flight in 2024/2025. The Galileo mission took images and some gravitational measurements of Europa through a flyby, while the Europa Clipper mission will conduct a much closer flyby in its atmosphere, reach down to the moon's surface, sample the ice, and even drill a hole in the ice.

Europa has always been a moon of great interest to scientists because of the strong belief that water is present in an ocean under the surface of the moon. The surface is believed to be made of a layer of crust composed of ice, and has some cracks and fissures, similar to the ice patterns in the Arctic on Earth. Many data readings strengthen this theory, especially the Galileo spacecraft that took gravitational measurements of the moon. The layer of water and ice on the moon's surface is around 100 kilometers thick, composed of hard brittle ice, warmer convective ice, and liquid water.[13] Beneath the ocean, there is a rocky and metallic core.[14]

Europa has significant amounts of biofuel present on the surface; the most prominent method of generating heat on the moon comes from tidal heating. Since Europa orbits a planet with such great mass, the parts of the moon that are closest to Jupiter feel more gravity. This makes Europa stretch, from looking like a sphere, to looking more like an oval. As the moon continues on the orbit, and it stops feeling that gravity, it returns to normal shape. This continuous process creates friction in the core, producing heat which fuels underwater volcanoes that Europa might have in its subsurface.[15 16] Without this phenomenon, water would not be able to sustain under the surface, because it would be too cold (too far away from the sun).The surface also possesses an abundance of charged particles that come from Jupiter, along with radioactive waves bombarding the surface of Europa.[17] These radioactive waves also come from Jupiter, as the charged particles are influenced by the strong magnetic field of the planet. The NASA Hubble telescope has also discovered water vapor plumes being ejected from the surface of Europa, further confirming the belief of a subsurface ocean and subsurface water volcanoes.[18]

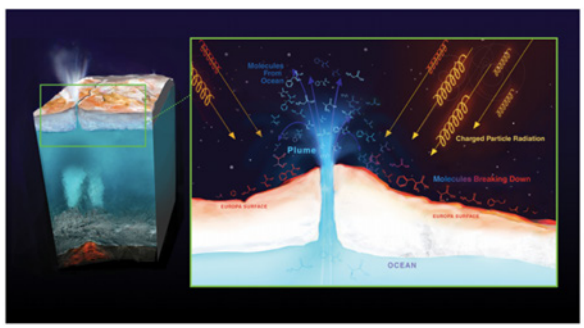

Figure 5: A detailed illustration of water plumes being ejected from Europa's surface, coming from its subsurface ocean. The diagram also shows charged molecules, and radiation coming from Jupiter.[14] This figure is taken from reference 14.

Tidal flexing from the gravitational pull from Jupiter can also open up heat vents . Since there is a lot of biofuel and heat for life to form, scientists believe that bacteria that survives on formaldehyde as its sole source of carbon could be swimming alive in the oceans in Europa (such microbes are present here on Earth as well).[19] This bacteria is one of the most common on Earth, called Hyphomicrobium. Scientists believe that this bacteria exists on Europa, because Jupiter's strong magnetic field sends charged ions that slam on Europa's surface. Furthermore, this could react with frozen water or carbon molecules, turning them into organic compounds that this microbe would feed on, such as formaldehyde.[19]

Conclusion

In conclusion, the habitability of any celestial body has many different factors that could make the planet inhospitable or able to sustain life. If the stellar characteristics are perfect for the celestial body, but its atmosphere is thin or too thick, the planet will have almost no chance of sustaining life . Moons also have the potential to be habitable, with Europa and Titan being the most promising moons to harbour life in our solar system, however moons have different natural phenomena such as tidal heating and tidal bulging that could affect life on the satellite. As scientific technology is advancing, and data measurements are becoming more accurate, the amount of factors to determine the habitability of a celestial body is increasing. Space agencies like NASA have already planned future missions to further explore celestial bodies in our solar system that hold probabilities of harbouring some form of life; it is possible that a celestial body that ticks all the boxes for habitability apart from Earth may be discovered soon. The advanced technology that is being developed will help carry out more atmospheric, magnetic field, elemental, gravitational measurements through flybys, rovers, probes. As the Earth also continues to face more and more environmental issues (greenhouse gases making the atmosphere thick, rising ocean levels), scientists are also searching for planets that could be habitable for humans, Mars being the most promising planet as of now. Therefore, all of the factors discussed in this literature review are crucial to determining the habitability of any celestial body in the solar system.

Figure 6: A flow chart that demonstrates the numerous other factors that affect the habitability of celestial bodies, and how they are inter related (especially connecting stellar properties with planetary properties).[20] This figure is taken from reference 20.

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References

[1] Wikipedia contributors, Wikipedia article, G-type main sequence star

[2] Mohon, NASA article, Assessing The Habitability Of Planets Around Old Red Dwarfs

[3] Wikipedia contributors, Wikipedia article, K-type main sequence stars

[4] Kopparapu et al, 2019, arXiv:1911.04441

[5] Scherf, 2021 arXiv:2102.05976

[6] Wikipedia contributors, Wikipedia article, Life on Mars

[7] Maathewson, Space Article, Venus May Have Supported Life Billions of Years Ago

[8] Kane et al,2008, arXiv:2008.01888

[9] NASA contributors, NASA article, Titan

[10] Wikipedia contributors, Wikipedia article, Life on Titan

[11] NASA contributor, NASA article, NASA solar system exploration

[12] University of Arizona contributor, University of Arizona article, Titan's Atmosphere Comes from Ammonia, Huygens Data Say

[13] Soderlund, 2019, arXiv:1901.04093

[14] NASA contributors, NASA article, Europa

[15] Howell et al, 2006, arXiv:2006.15803

[16] Wikipedia contributors, Wikipedia article, Europa (moon)

[17] Nordheim, IOP article, Galactic Cosmic-Ray Bombardment of Europa’s Surface

[18] ESA and science technology contributor, ESA and science technology article, Photo composite of suspected water plumes on Europa

[19] Shwartz et al, Stanford news article, New findings support prospect of life on Jupiter's moon Europa

[20] Hinkel et al, 2020, arXiv:1904.01089