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ATMOSPHERIC COMPOSITION AND SUSTAINABILITY OF LIFE ON EXOPLANETS

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ABSTRACT

One of the most impactful discoveries within the fields of astronomy and astrophysics over the last few decades was the discovery of planets, outside our solar system, orbiting stars other than our own. These planets are referred to as *exoplanets* or as *extrasolar planets*. Since the discovery of exoplanets, scientists have searched the cosmos for signs of life on these alien worlds. A great portion of exoplanetary discoveries and data comes through the analysis of light spectra, with the help from advancing space telescope technology. By analyzing the spectra of numerous exoplanets, it has been determined that the combined presence of several biochemical gases (most notably CO_2, H_2O, and O_3) within an atmosphere greatly increases the probability of there being life on that planet. It has also been concluded that the presence of liquid water on an exoplanet may have a profound, positive impact on the planet's ability to sustain life. These conclusions allow scientists to narrow their search for exoplanets to regions around a star which physically promote the presence of liquid water. Numerous computer simulations have resulted in there being an estimated one solar system out of every twenty containing a planet with the necessary physical conditions to sustain liquid water.

INTRODUCTION

This paper concerns the use and analysis of spectroscopic data from telescopes to determine the chemical compositions of various exoplanets in order to ascertain whether or not a planet is capable of sustaining life. Methods for analyzing spectroscopic data of a planet's atmosphere will be examined in helping further understand whether or not a planet is habitable. The technology used to determine such data will be briefly touched upon. Favorable chemical compositions of exoplanetary atmospheres will also be discussed along with a brief look at the variables encountered within a solar system which have ability to alter the desired atmospheric chemical compositions. To properly discuss exoplanets, one must first delve into the principal discovery of a planet outside of our solar system.

51 PEGASI B

In October of 1995, during a conference in Florence, Italy, Michel Mayor of the University of Geneva and Didier Queloz, a doctoral student, presented their findings of a large, gaseous planet (a gas giant) orbiting around a main sequence star—the first such planet to ever be discovered (Mayor and Frei, 2003). The star, designated 51 Pegasi (51 Peg), is relatively unremarkable. It is a sun-like star—middle-aged and average-sized—which can be found within the northern constellation, Pegasus. The planet in question, 51 Pegasi b, is said to be around the size and mass of Jupiter, except it lives at a much closer distance away from 51 Peg than Jupiter does from our Sun (Mayor and Queloz, 1995). This raised questions about the then accepted processes of planetary formation.

51 Peg b was discovered through a technique which measures variations in a star's radial velocity. These variations are resulted from one or more high-mass planetary objects (i.e. a gas giant)

orbiting around the star. At the time, only large, gaseous planets were able to be detected. Nowadays, due to advancements in technology and technique, more terrestrial planets are able to be detected.

THE QUEST FOR LIFE

Before Mayor and Queloz made their discovery in 1995, some people considered the opinion that our solar system, and by extension our planet, was unique. Many were growing doubtful that life throughout the universe was common. Following the confirmation of the existence of an extrasolar planet orbiting around 51 Pegasi (Marcy and Butler, 1995) scientists began to wonder whether the apparent prevalence of planetary systems in the universe meant that life on other planets was more common than we thought.

In the present day, current reports show the discovery of over 3400 extrasolar planets since 1995.[1] During the course of each discovery there are two questions scientists ask themselves. (1) Does this exoplanet exist with the necessary conditions to sustain life? If the first question is answered with 'yes', (2) does this exoplanet harbor life or signs of life's existence? During the course of this paper, both questions will be discussed in order to better understand the search for extraterrestrial life.

DISCUSSION: METHODS OF ANALYSIS

Over the past two decades, significant advancements in technology and methodology have allowed researchers to believe in the possibility of someday finding life in the universe and confirming that we are not alone. To begin our search for life, we must first understand what the mechanisms are which create life. The search for life involves thousands of people from different backgrounds and fields of study to form an interdisciplinary team of researchers who all share the same goal. Astrophysicists work with biologists, who work with chemists, and so on. Finding life does not necessarily mean finding sentient beings with complex brain functions. Primarily, scientists are focusing on finding primitive life—that which consists of the most basic life forms. As is evident on Earth, life can exist in many forms and survive in many conditions, but a lot of research is being done to isolate worlds that share some of the same characteristics as the Earth. One characteristic that is unique to our planet's ability to sustain life is its atmosphere. Other planets in our solar system have atmospheres, like Venus and Jupiter, but only the Earth's atmosphere is capable of harboring life in our solar system (to our knowledge).

SPECTROSCOPY

Before we discuss the necessary chemical and physical conditions a planet needs to sustain life, we must first detail the methods and techniques for determining an exoplanet's atmospheric properties. One such technique analyzes the light spectrum of transiting extrasolar planets in order to determine the chemical composition of the atmosphere (see Figure 1). Because of the nature of detecting exoplanets, spectroscopy was primarily done on large, Jupiter-like gas giants, even as recently as 2013 (Deming *et al.*, 2013). The first detection of an exoplanet's atmosphere occurred in 2002 (the optical sodium absorption lines of the transiting planet.

Traditionally speaking, analyzing the spectrum of an object in space by a telescope was primarily done on stars. In an ideal situation, the light spectrum of a star will appear unblemished. It will contain every color of the rainbow with smooth transitions from one color to the next. In a more realistic spectrum of a star, there appear to be black bands in random locations, where colors do not necessarily transition smoothly to the next. This is due to some wavelengths of light being disrupted by molecules in the stellar atmosphere, hence, a particular color on the spectrum may seem 'missing'. What is actually happening is that each element or molecule present in the atmosphere absorbs a specific wavelength of light. Therefore, the imperfections in a light spectrum of a star actually tell us about that star's chemical composition in its atmosphere. The same process is used to determine the chemical composition of exoplanetary atmospheres, except with much more difficulty (especially for a terrestrial planet). We detect the majority of exoplanets through the transiting method, i.e. as the planet is moving *in front* of the host star. Therefore, the vast majority of light intake by our telescopes comes from the star itself, not the planet. Techniques for distinguishing the exoplanet's light spectrum from that of the star are used in order to get a better sense of an exoplanet's atmospheric composition.

According to a mission called *Darwin* (Cockell *et al.*, 2009), to differentiate the signal of a small, Earth-like, terrestrial planet from that of the much more massive host star, the planet must be *spatially resolved*. This simply is a process which differentiates between light at different distances, which improves the quality of the image. The degree of resolution is determined by the quality of the imaging device aboard the telescope, as well as the quality of the imaging software on the ground (Deming *et al.*, 2009).

Taking observational data from a space telescope as opposed to a ground telescope is preferable in this case due to the interference by spectral data obtained from the Earth's atmosphere when using a und-based telescope.

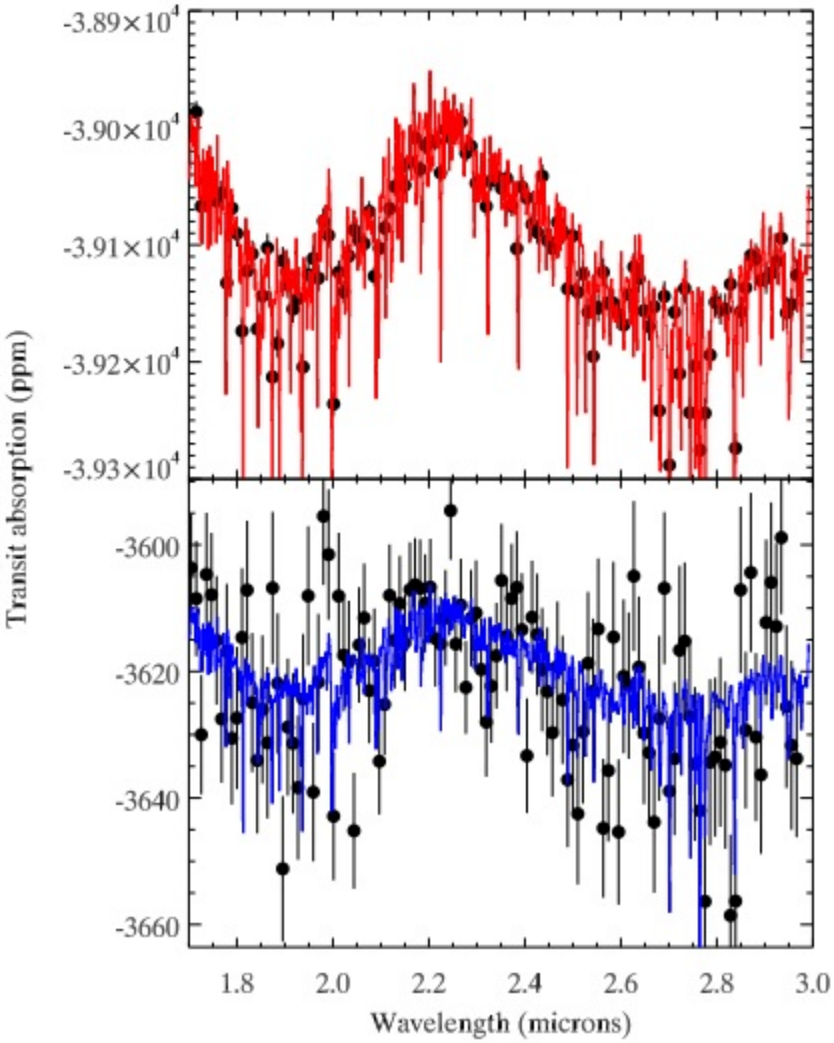


Figure 1: Spectral observations of water absorption for two different transiting, terrestrial exoplanets. *Upper panel:* For a planet with T = 506 K and R = 2.1 Earth-radii at a distance of 32 pc. *Lower panel:* For a planet with T = 302 K and R = 1.8 Earth-radii at a distance of 20 pc. © Deming *et al.*, 2009.

Charbonneau *et al.*) and was done using the Hubble Space Telescope (HST) to analyze

TECHNOLOGICAL ADVANCEMENTS

Since the first discoveries of exoplanets in the mid to late 1990's, technological advancements have enabled scientists to see clearer images at larger distances than ever before. The closest exoplanets found to date can be located around our nearest stellar neighbor, Alpha Centauri, at a distance of 1.3 parsecs away (Demory *et al.*, 2015). Conversely, the farthest known exoplanet has been found in the galactic bulge, at around 8500 parsecs away (Sahu *et al.*, 2007). This is akin to being able to see—from a New York City apartment—a person living across the street in a different apartment building, as well as being able to see a person living in their apartment in Albuquerque, New Mexico. This may begin to illustrate the current minimum and maximum relative distances at which we are able to detect extrasolar planets.

HUBBLE SPACE TELESCOPE

Used during the first exoplanetary discovery by Mayor and Queloz (1995), the Hubble Space Telescope remains one of the most widely used space telescopes in the 21st century. HST was deployed in 1990 with the ability to see in the range of 100 nm to 2500 nm, which includes ultraviolet, visible, and infrared radiation. Hubble's optical resolution is 0.05 arcseconds which is more than one order of magnitude better than many ground-based telescopes, due to interference with Earth's atmosphere. On board HST there are a total of six scientific instruments, including cameras, spectrographs, and fine guidance sensors which all allow for amazing images at near or far distances (HubbleSite, 2016).

KEPLER SPACE YELESCOPE

The mission of the Kepler Space Telescope (KST) is to find extrasolar planets, specifically Earth-like terrestrial planets within the Milky Way Galaxy. KST was launched in 2009 with the ability to see in the range of 400 nm to 850 nm, which mostly consists of visible light. Kepler's optical resolution is approximately 10 arcseconds which makes it 200 times less focused than the HST, but this is to ensure the precision of the optical systems on board. The KST primarily focuses on one patch in the sky, monitoring around 150,000 stars for planets. This ensures the stability of the telescope while taking images (NASA, 2016).

JAMES WEBB SPACE TELESCOPE

Set to launch in October of 2018, the mission of the James Webb Space Telescope (JWST) is wide-ranging. It will image everything from remnants of the Big Bang to solar system formation with the hope of furthering our understanding of the universe. JWST will have the ability to see in the range of 600 nm to 28500 nm, which consists of some visible light, but mostly infrared radiation. The key aspect of the telescope's future success will depend largely on its IR capabilities. A new technology, called a *microshutter array* was created by a team of scientists and allows 100 objects to be observed simultaneously. Webb's optical resolution is approximately 0.1 arcseconds, which is smaller than that of Hubble, but its ability to capture light from 100 sources at the same time greatly make up for its slightly diminished resolution. The microshutter arrays paired with advanced coronagraphs will allow JWST to gather more data on exoplanets and solar systems than ever before. It will also contain a number of other innovations in space telescope technology, including a folding, segmented mirror which will allow controllers on the ground to better focus the optics while the system is in orbit. JWST will make good use of the largest optical mirror to ever be launched into space as it ushers in a new era in space telescope technology (NASA, 2016).

DISCUSSION: ATMOSDPHERIC PROPERTIES

In order to begin talking about the search for life on other worlds, one must first understand the basic definition of life itself, and the conditions necessary for it to exist. In discussing the biological concept of life, Cockell *et al.* (2009) use Brack's definition of life (2007) by stating, "A living being is a system that contains information and is able to replicate and evolve through random mutation and natural (Darwinian) selection".

As was mentioned previously, some life on Earth has the ability to survive in the harshest conditions, at least according to human standards. There is no evidence to suggest that this does not hold true throughout the grand scope of the universe. Many scientists, however, have made the decision to conduct their research with the assumption that life exists throughout the universe in much the same way it exists on Earth. That is, life on other worlds mostly requires liquid water and is primarily carbon-based, but this is not to say that it cannot exist under other conditions (Léger *et al.*, 1996). It is worth noting, however, that any gas which is not in equilibrium within the constraints of the chemistry of an exoplanet's atmosphere may suggest the presence of life (Cockell *et al.*, 2009).

CHEMICAL CONDITIONS

There is only one true example researchers have when discussing planetary habitability, and that is the Earth (Beckwith, 2008). Earth is the only planet we know for certain able to foster and sustain life. Therefore, we look to the Earth as a generic model from which to possibly confirm or deny an extrasolar planet's ability to produce life (see Figure 2). With this in mind, astrobiologists, chemists, physicists, etc. look for the atmospheric signatures of life on other worlds which are similar to those found on Earth.

TRIPLE SIGNATURE

There are three gases found in the Earth's atmosphere which can appear most commonly during biological processes—oxygen (O_2), carbon dioxide (CO_2), and water vapor (H_2O).[2] If these gases are found to be present in the atmosphere of an exoplanet, then there may be a possibility that these are signs of life, however primitive it may be. Nevertheless, this statement is not entirely true. It is true that Earth-like life on another planet will produce relatively the same chemicals in the atmosphere. It is false, however, that the individual presence of O_2, CO_2, H_2O, or others in a planetary atmosphere corresponds with the

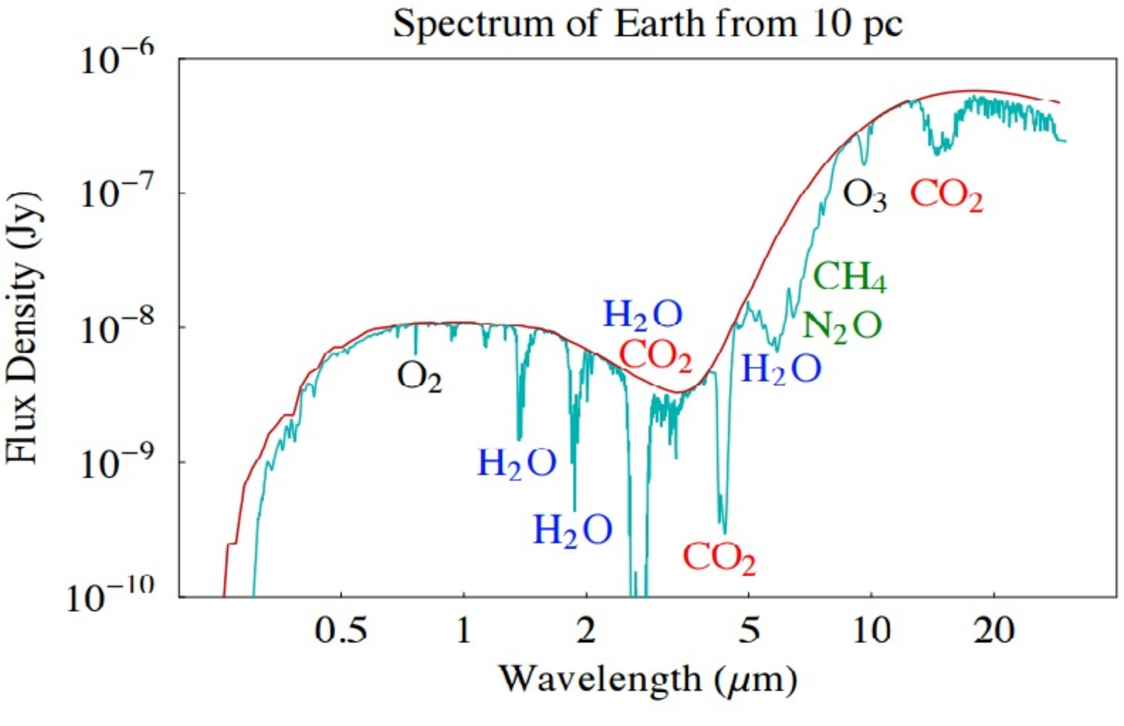


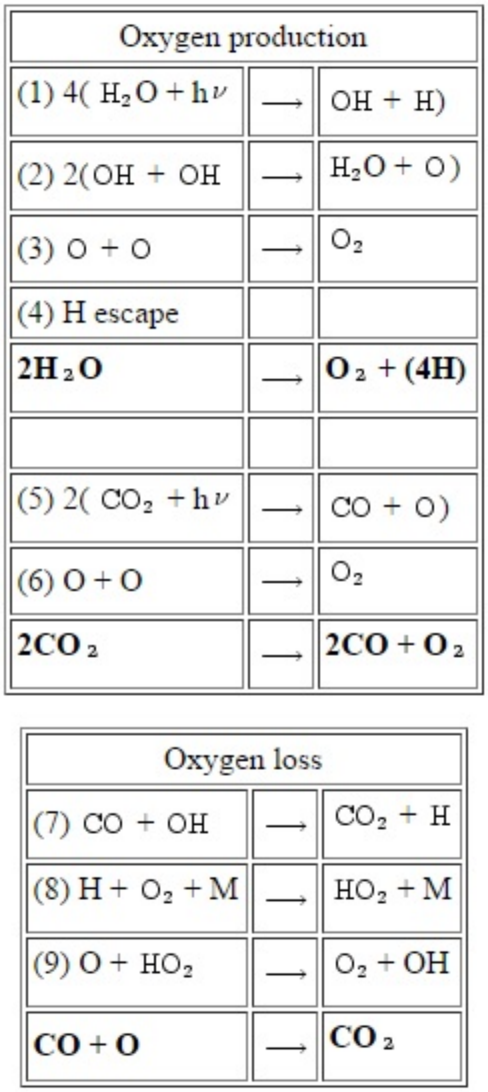
Figure 2: The lower line is a synthetic representation of what the Earth's spectrum would look like in the present day, from a distance of 10 pc. The upper line is a combination of the solar irradiance and a Planck function at 286 K. © Beckwith, 2008.

presence of life. It has been shown that through some abiotic, photochemical processes, life-signature gases—such as O_2 (Selsis *et al.*, 2002) and CH_4 (Swain *et al.*, 2008)—can be produced in both terrestrial and gaseous exoplanetary atmospheres (see Figure 3). One way to tell, with minimal uncertainty due to false positive results, that there has been photosynthetic life on an exoplanet is to find the presence of all three of the above gases in the atmosphere (Selsis *et al.*, 2002). The presence of these three gases is known as the *triple signature* and is often represented as $CO_2—H_2O—O_3$ IR.[3] Ozone (O_3) is used due to it being a signature of an O_2-rich environment.

In atmospheres created by primitive lifeforms, CO_2 is the most prevalent gas. Therefore, an indication of life could be shown if the level of CO_2 was reduced by photosynthesis, and O_2 levels were correspondingly increased (Léger *et al.*, 1996). It is stated by Léger *et al.* that a presence of up to 1000 mbar of O_2 in an exoplanetary atmosphere would be a strong indication of primitive life. It should be noted that experimentally, a relatively high O_2 content (~50 mbar) can be produced abiotically through geochemical means (Selsis *et al.*, 2002).

LIQUID WATER

Although there is no absolute certainty that the individual presence of any one molecule in an exoplanet corresponds to the presence of life (Selsis *et al.*, 2002), it is still not wrong to believe that the presence of liquid H_2O may provide a higher possibility of life's existence. Again, the only true reference scientists have is the Earth and the planetary neighborhood in which it resides (Beckwith, 2008). With this in mind, scientists take the relationship between life on Earth and the presence of liquid water on the surface very seriously when considering the sustainability of life on other planets. Going back to Léger *et al.* (1996), it can be assumed that the majority of life is carbon-based and requires liquid water to survive. Therefore, the ability of a planet to sustain liquid water may be an important first step toward the goal of producing life.



Oxygen production		
(1) 4($H_2O + h\nu$	$\longrightarrow$	$OH + H$)
(2) 2($OH + OH$	$\longrightarrow$	$H_2O + O$)
(3) $O + O$	$\longrightarrow$	O_2
(4) H escape		
$2H_2O$	$\longrightarrow$	**$O_2 + (4H)$**
(5) 2($CO_2 + h\nu$	$\longrightarrow$	$CO + O$)
(6) $O + O$	$\longrightarrow$	O_2
$2CO_2$	$\longrightarrow$	**$2CO + O_2$**

Oxygen loss		
(7) $CO + OH$	$\longrightarrow$	$CO_2 + H$
(8) $H + O_2 + M$	$\longrightarrow$	$HO_2 + M$
(9) $O + HO_2$	$\longrightarrow$	$O_2 + OH$
$CO + O$	$\longrightarrow$	**CO_2**

Figure 3: The most important reactions for abiotic production of O_2. © Selsis *et al.*, 2002.

Through simulations involving data from GJ581d and others (Wordsworth *et al.*, 2011), it was concluded that an atmosphere with over 1×10^4 mbar of CO_2 (along with varying amounts of other gases) produced a global mean temperature above 0 ˚C, resulting in the sustainability of liquid H_2O.[4] It was also concluded that the presence of other greenhouse gases and/or clouds of H_2O in the atmosphere can have an effect on the overall surface temperature of the planet, but as long as the atmosphere is in geochemical equilibrium the temperature should be above the freezing point of H_2O.

PHYSICAL CONDITIONS

It has been demonstrated that a number of possible chemical conditions can lead to signatures of extraterrestrial life, but there are a number of physical factors involved which determine if those conditions can exist. Without the relatively precise physical conditions, a planet may not have any chance to produce or sustain Earth-like life. Three of the most commonly analyzed conditions, which have the ability to alter the desired chemical composition of an exoplanetary atmosphere, include the energy output of the star, the size of the planet, and the planet's distance away from the star. Once again, we look at the Earth in relation to the solar system for inspiration.

As is evident in our solar system, these three factors can vary depending on the planet's atmospheric composition as well as on the values of the others. Venus, for example, is approximately the same size of the earth, closer to the sun, yet its atmosphere is denser than Earth's due to the amount of greenhouse gases present. Mars, on the other hand, is farther away from the sun, yet contains a much thinner atmosphere compared to the Earth due to its smaller size and lack of a strong magnetic field. Conversely, the size of gas giants, Jupiter and Saturn, and their distances away from the sun allow for the retention of gases and the buildup of substantial atmospheres.

These are all examples of dependency the factors have on one another, but a closer look at the latter two will help to further understand what scientists are looking for in the search for habitable exoplanets.

Habitable Zone

Any planet which supports Earth-like life must satisfy two broad criteria: (1) it must have surface temperatures (T) capable of sustaining liquid water ($0 < T < 100$ ˚C), and (2) it must contain an atmosphere. The first item is satisfied if the planet is located within the *habitable zone* (HZ) (Beckwith, 2008). The habitable zone can be defined as the region around a star in which life-supporting planets can exist (Kasting *et al.*, 1993). Popularly, the HZ is often referred to as the *Goldilocks zone*, due to it being the region where the temperature is neither 'too hot' nor 'too cold', rather 'just right' for liquid water to exist on the surface (see Figure 4). For our own solar system, Kasting *et al.* estimate the HZ to be between 0.95 and 1.37 AU, although the realistic width's value may be greater. Through the use of computer models, the lower limit to the HZ is determined by the loss of water through photolysis and hydrogen escape—with the latter being dependent on the mass of the planet. The upper limit of the HZ is determined by CO_2 cloud formation, which increases the albedo and cools the planetary surface. Over time, the HZ migrates away from the star because solar luminosity increases with age.

EARTH-SIZED PLANETS

The second of Beckwith's criteria (2008) is satisfied if the planet is rocky in nature and has enough mass to retain its atmosphere. It is estimated that a planet has the ability to retain its atmosphere when it has mass (M) in the range $0.5 < M < 10$ Earth-masses. Planets smaller than 0.5 Earth-masses will not have

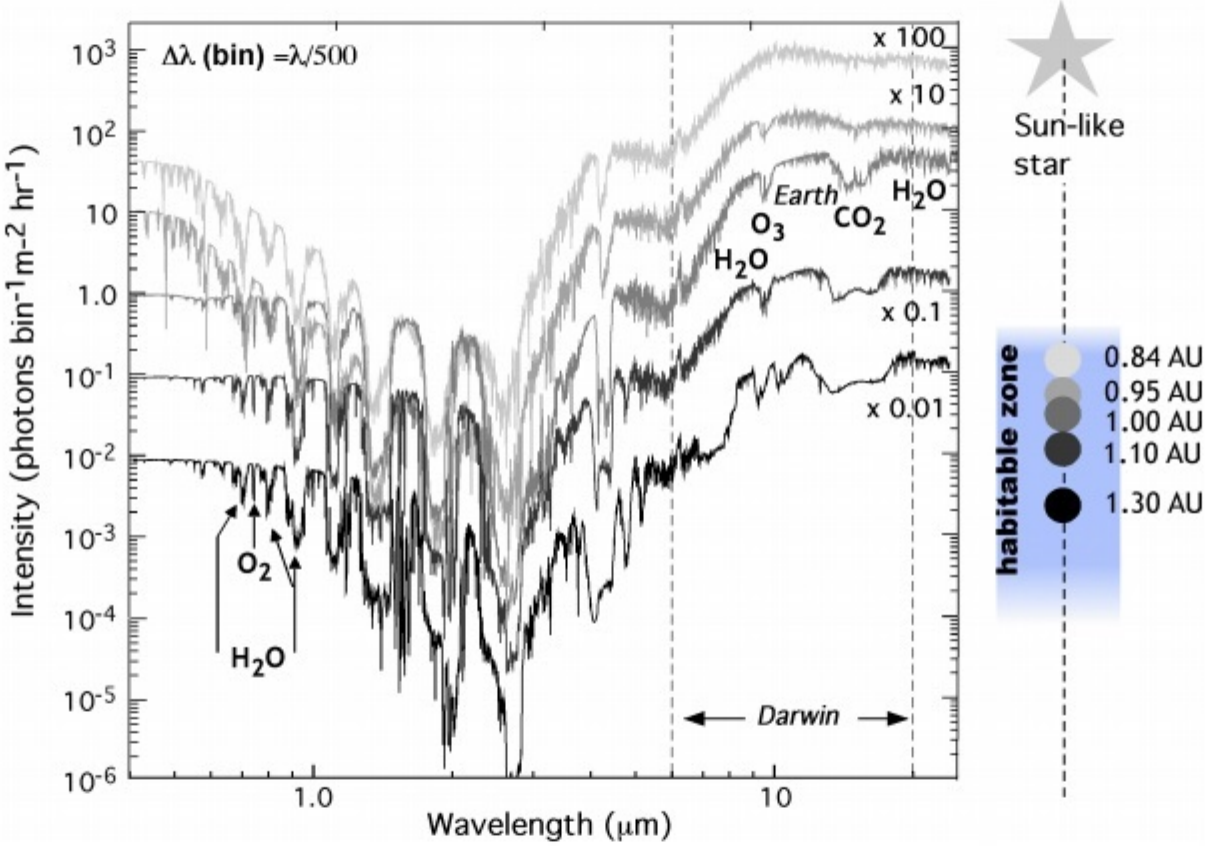


Figure 4: The estimated evolution of the H_2O, O_3, and CO_2 features in the spectra of an Earth-like planet as a function of its location in the HZ. Shown are the wavelengths in which the Darwin project is interested. © Cockell *et al.*, 2009.

enough gravitational attraction to capture their atmospheres. Planets larger than 10 Earth-masses will accrete gas to become gas giants.

Many of the terrestrial planets that have been discovered are more massive than the Earth, therefore closer to the upper mass limit discussed above. These planets are classified as *super-Earths* and have an approximate mass range $2 < M < 10$ Earth-masses (Wordsworth *et al.*, 2011). After conducting numerous simulations, Deming *et al.* (2009) came to the conclusion that the number of Earth-size exoplanets exceeds the amount of Jupiter-size exoplanets. The simulations concluded that approximately 30% of stars have at least one Earth-like or super-Earth-like planet orbiting around them. There was also found to be a ~5% likelihood that an Earth-like or super-Earth-like planet exists in the HZ of any given star. With the number density of stars in the Milky Way Galaxy alone, 5% could result in a substantial number of candidates for habitable exoplanets.

CONCLUSION

One of the most important scientific discoveries over the last two decades was the discovery of a planet, orbiting a member star of the Pegasus constellation, around 50 light-years away (Mayor and Queloz, 1995). Since 1995, the search for extraterrestrial life has become a central theme in the scientific community, and will continue to drive scientific advancement during the 21st century (Léger *et al.*, 1996). Before the 1990's, it was beginning to look more and more as if the Earth was unique, that is, life was an exceedingly rare phenomenon which humans were lucky to be a part of. Significant advancements in technology and refinement of technique have renewed our hope of finding extraterrestrial life.

By studying stars closely with various telescopes, we have currently located and classified more than 3400 extrasolar planets. From the first exoplanetary discovery (Mayor and Queloz, 1995) to some of the most recent, the Hubble Space Telescope continues to play a major role in detecting exoplanets. With the perennial help of HST, along with KST, and eventually JWST, and others, more and more exoplanets will be discovered in the quest for finding extraterrestrial life.

Through the use of spectroscopy, we are able to analyze exoplanets for signatures of life. Biochemical processes on Earth produce a number of different gases, including CO_2, H_2O, and O_3, among others. Although the presence of any individual gas mentioned does not necessarily correspond with the presence of life, the presence of all three gases—known as the *triple signature* ($CO_2 — H_2O — O_3$ IR)—can significantly increase the likelihood of life existing on that planet. Also, in a more primitive atmosphere, the decrease of CO_2 and the increase of O_2 can also indicate the presence of life due to photosynthesis (Selsis *et al.*, 2002).

Another sign of life's existence is the ability of an exoplanet to sustain liquid water. Through various simulations, it was concluded that H_2O can remain in a liquid state if the atmosphere contained over 1×10^4 mbar of CO_2, along with varying levels of other gases (Wordsworth *et al.*, 2011). In order to keep the surface temperature of a planet above the freezing point and below the boiling point of liquid H_2O, it must be located within the habitable zone of a solar system. In order to contain an atmosphere—which is also needed for planetary habitability—a planet needs to be terrestrial in nature, and have a mass in the range $0.5 < M < 10$ Earth-masses. This ensures that the planet's gravitational pull is great enough to hold on to the gases which make up the atmosphere, yet not so great as to accrete too much gas (Beckwith, 2008).

Simulations performed by Deming *et al.* (2009) have concluded that there are more Earth-like planets than Jupiter-like planets in the galaxy. There was also found to be a ~5% chance that any given star will have at least one Earth-like planet within the HZ. When compared to the sheer number of stars located within the Milky Way Galaxy, this percentage, albeit small, shows that there exists the possibility for a massive number of habitable exoplanets. This means that in just over two decades, the scientific community went from thinking of the possibility that the Earth is unique (or at least rare), to there being a realistic probability of the existence of habitable extrasolar planets. Extending this line of thought, in just twenty years, the question of finding evidence of extraterrestrial life went from 'if' to 'when.'

REFERENCES

[1] Beckwith, S.V, 2008. Detecting life-bearing extrasolar planets with space telescopes. *The Astrophysical Journal, 684*(2), p.1404.

[2] Brack, A., 2007. From interstellar amino acids to prebiotic catalytic peptides: a review. *Chemistry & biodiversity, 4*(4), pp.665-679.

[3] Charbonneau, D., Brown, T.M., Noyes, R.W. and Gilliland, R.L., 2002. Detection of an Extrasolar Planet Atmosphere Based on observations with the NASA/ESA Hubble Space Telescope (HST), obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555. *The Astrophysical Journal, 568*(1), p.377.

[4] Cockell, C.S., Léger, A., Fridlund, M., Herbst, T.M., Kaltenegger, L., Absil, O., Beichman, C., Benz, W., Blanc, M., Backs, A. and Chelli, A., 2009. Darwin-a mission to detect and search for life on extrasolar plantes. *Astrobiology, 9*(1), pp.1-22.

[5] Deming, D., Seager, S., Winn, J., Miller-Ricci, E., Clampin, M., Lindler, D., Greene, T., Charbonneau, D., Laughlin, G., Ricker, G. and Latham, D., 2009. Discovery and characterization of transiting super Earths using an all-sky transit survey and follow-up by the James Webb Space Telescope. *Publications of the Astronomical Society of the Pacific, 121*(883), p.952.

[6] Deming, D., Wilkins, A., McCullough, P., Burrows, A., Fortney, J.J., Agol, E., Dobbs-Dixon, I., Madhusudhan, N., Crouzet, N., Desert, J.M. and Gilliland, R.L., 2013. Infrared transmission spectroscopy of the exoplanets HD 209458b and XO-1b using the Wide Field Camera-3 on the Hubble Space Telescope. *The Astrophysical Journal, 774*(2), p.95.

[7] Demory, B.O., Ehrenreich, D., Queloz, D., Seager, S., Gilliland, R., Chaplin, W.J., Proffitt, C., Gillon, M., Günther, M.N., Benneke, B. and Dumusque, X., 2015. Hubble Space Telescope search for the transit of the Earth-mass exoplanet α Centauri B b. *Monthly Notices of the Royal Astronomical Society, 450*(2), pp.2043-2051.

[8] HubbleSite, 2016. *HubbleSite – The Telescope*. [online] Available at: <http://hubblesite.org/the_telescope> [Accessed 23 Feb. 2016].

[9] Kasting, J.F., Whitmire, D.P. and Reynolds, R.T., 1993. Habitable zones around main sequence stars. *Icarus, 101*(1), pp.108-128.

[10] Léger, A., Mariotti, J.M., Mennesson, B., Ollivier, M., Puget, J.L., Rouan, D. and Schneider, J., 1996. Could we search for primitive life on extrasolar planets in the near future?. *Icarus, 123*(2), pp.249-255.

[11] Marcy, G.W. and Butler, R.P., 1995, December. The planet around 51 Pegasi. In *Bulletin of the American Astronomical Society* (Vol. 27, p. 1379).

[12] Mayor, M. and Frei, P.Y., 2003. *New worlds in the cosmos: the discovery of exoplanets*. Cambridge University Press.

[13] Mayor, M. and Queloz, D., 1995. A Jupiter-mass companion to a solar-type star.

[14] NASA, 2016. *Spacecraft and Instrument*. [online] Available at: <http://www.nasa.gov/mission_pages/kepler/spacecraft/index.html> [Accessed 23 Feb. 2016].

[15] NASA, 2016. *JWST Vital Statistics*. [online] Available at: <http://jwst.nasa.gov/facts.html> [Accessed 23 Feb. 2016].

[16] Sahu, K.C., Casertano, S., Valenti, J., Bond, H.E., Brown, T.M., Smith, T., Clarkson, W., Minniti, D., Zoccali, M., Livio, M. and Renzini, A., 2007. Planets in the Galactic Bulge: Results from the SWEEPS Project. *arXiv preprint arXiv:0711.4059*.

[17] Selsis, F., Despois, D. and Parisot, J.P., 2002. Signature of life on exoplanets: Can Darwin produce false positive detections?. *Astronomy & Astrophysics, 388*(3), pp.985-1003.

[18] Swain, M.R., Vasisht, G. and Tinetti, G., 2008. The presence of methane in the atmosphere of an extrasolar planet. *Nature, 452*(7185), pp.329-331.

[19] Wordsworth, R.D., Forget, F., Selsis, F., Millour, E., Charnay, B. and Madeleine, J.B., 2011. Gliese 581d is the first discovered terrestrial-mass exoplanet in the habitable zone. *The Astrophysical Journal Letters, 733*(2), p.L48.

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[1] Cataloged by The Extrasolar Planets Encyclopedia.

[2] In a broader look at life on Earth and elsewhere, gases CH_4 and NH_3 may also be found.

[3] The triple signature can be found in the infrared spectrum from $\lambda_{min} \approx 6$ µm to $\lambda_{max} \approx 17$ µm due to the difficulty of detecting O_3 with other wavelengths (Léger *et al.*, 1996; Selsis *et al.*, 2002).

[4] GJ581d orbits a red dwarf Gliese 581 for which M = 0.31 Earth-masses and L = 0.0135 Earth-luminosities.