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Observing Exoplanet Atmospheres for Signs of Extraterrestrial Life

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ABSTRACT

The discovery and characterization of exoplanet atmospheres has been a growing field over the last decade. With the James Webb Space Telescope (JWST) launching this year, we will expect to see a significant increase in the number of habitable exoplanets discovered. The most promising indications of life beyond Earth will rely on the detection of atmospheric biosignature gases, such as oxygen, produced by the presence of life on the extrasolar world. The basic techniques used to study exoplanet atmospheres, transmission spectroscopy and observed secondary eclipses, will be discussed along with our current limitations and future observing facilities, including the JWST. This paper aims to provide an overview of the different types of biosignatures astronomers can detect when observing exoplanets and gives a brief example of thermal emission and transmission spectra data for the hot Jupiter WASP-43b. Overall, the study of exoplanet atmospheres is essential in determining if a planet is habitable or likely inhabited with the ultimate goal of answering the most pressing question, “are we alone?”

1 BACKGROUND

Before the early 1980s, the idea of an extrasolar world orbiting a distant star was something you could only read in science fiction. Within the last few decades, technology has advanced enough for astronomers to be able to detect these planets. The field of exoplanetary science quickly gained attention after the first planetary disk, made up of dust and gas around the star Beta Pictoris, was photographed by a 2.5-meter telescope at the Las Campanas Observatory in Chile in April of 1984 [Brennan, 2017]. During the same time, a NASA research team found six indicators of past life in the famous ALH84001 meteorite from Mars, uncovered in the Allan Hills region of Antarctica [Kaufman, 2021]. Although this paper was not widely accepted by the astrobiology community, the excitement surrounding the idea that microbial life once existed on Mars jump started NASA’s search for life beyond Earth. The NASA Astrobiology Institute was founded two years later with the goal of providing a framework for the field of astrobiology and creating technologies to be used on other worlds while exploring the origins and early development of life on Earth. Astronomers Aleksander Wolszczan and Dale Frail soon discovered two rocky planets orbiting a pulsar, PSR B1 257+12, in the constellation Virgo at the beginning of 1992 [Brennan, 2017]. Due to the immense radiation from the neutron star they orbited, scientists knew the two rocky planets would not be habitable for even microbial life. Shortly afterwards, Didier Queloz and Michael Mayor published their findings of a planet, roughly half the size of Jupiter, orbiting close to a main sequence star [Brennan, 2017]. Transit and radial velocity surveys, two of the most efficient methods of detecting exoplanets, have now confirmed well over 4,000 exoplanets with a shockingly large number of them being located within the habitable zone of their parent stars. The habitable zone is defined as the region encompassing the range of distances from a star for which liquid water can exist on a planetary surface [Anand et al., 2018]. The search for life beyond our solar system is dependent upon the detection and characterization of these exoplanets, especially their atmospheres.

Planets that undergo a transit across their star’s surface are of particular interest because we can analyze their atmospheric conditions through transmission spectroscopy. Similarly, we can observe the direct emission from a planet’s atmosphere through secondary eclipses or sometimes referred to as secondary transits. Planets at sufficient distances away from their host star are also excellent candidates for direct-imaging spectroscopy. These methods will be discussed in further detail in later sections. The first revolutionary mission that aided in the identification and study of exoplanets was the Hubble Space Telescope (HST) which launched in April of 1990 [Brennan, 2017]. The first atmosphere of an exoplanet was detected by David Charbonneau and Timothy Brown in 2001 using the spectrometer on the HST to analyze the atmospheric composition of the planet orbiting the star HD 209458 [Brennan, 2017]. The second influential mission that provided a unique, infrared view of the universe and served as a powerful tool for detecting exoplanets and characterizing their atmospheres was the Spitzer Space Telescope, which launched in August 2003. The spectra from HD 209458 b, the planet Charbonneau and Brown detected, was later analyzed by the Spitzer Space telescope in 2007 and identified a spectral feature of sodium [Crossfield, 2015]. This was the first indication that observing exoplanet atmospheres for signs of alien life was possible. In May 2018, Helium was detected in the gas giant WASP-107b by the HST located roughly 200 light years away [Brennan, 2017]. These discoveries led to the development of the Kepler Space Telescope and the Transiting Exoplanet Survey Satellite (TESS) which have now contributed to the majority of confirmed exoplanets. The Kepler Space Telescope was launched in March 2009 and the mission ended in October 2018. The primary goal of Kepler was to observe a patch of the night sky for Earth-like planets orbiting stars similar to that of our Sun. Kepler observed over 150,000 Sun-like stars in search for habitable worlds and allowed astronomers to draw the conclusion that exoplanets are plentiful and extremely diverse [Johnson, 2015]. Kepler helped identify extreme worlds from styrofoam planets to lava planets to entire ocean worlds. The mission confirmed over 2,662 planets throughout its lifetime [Overbye, 2018]. TESS launched in April of 2018 and is still actively finding transiting exoplanets that could potentially support life. The original mission was to survey 200,000 of the brightest stars near our Sun [Garner, 2016]. As of March 2021, TESS has confirmed 122 exoplanets [Brennan, 2017]. Looking ahead, we will see a huge growth in not only the number of exoplanets discovered, but also our overall knowledge of the formation and characterization of these planets with the help of the James Webb Space Telescope (JWST) and the European Extremely Large Telescope (EST). It is crucial we develop more precise techniques to observe planetary atmospheres since it is the only way to infer whether or not a planet is habitable or likely inhabited.

It is important to note that our definition of life is limited to the biological life we observe on Earth, and our current understanding of the universal laws of physics and chemistry. Most biologists would agree on two key features that indicate life: the capacity for self replication, and the capacity to undergo Darwinian evolution [Anand et al., 2018]. Evolution is a necessary process for organisms to adapt to their ever changing environments and guarantee their survival over long periods of time. According to [Schwieterman et al., 2018], "a consensus has emerged that life requires three essential components: an energy source to drive metabolic reactions, a liquid solvent to mediate these reactions, and a suite of nutrients both to build biomass and to produce enzymes that catalyze metabolic reactions." Based on our understanding of life on Earth, scientists are confident water is most likely a universal solvent essential for extraterrestrial life. Water is extremely abundant in the universe and has been detected on several interstellar objects such as comets, which scientists have theorized delivered the first raw materials for life to form on Earth. Water, under the right temperature and pressure, is able to hold a liquid form for a large range in temperature, about 100°C, unlike other common elements such as ammonia and methane [Voytek, 2021]. This allows the habitable zone of a planet to widen around its host star. Water is also a polar molecule made up of two atoms of hydrogen and one atom of oxygen that allows water to easily break apart or dissolve other molecules [Voytek, 2021]. Water also has the unique characteristic of being denser in its liquid form rather than solid ice due to the spaces created in the crystallized ice structure. If frozen water sank, marine life in the Earth's oceans would most likely cease to exist. Our biochemistry is based on the molecules made of carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur [ope, 2021]. Carbon is favored as a basis for biomass because carbon is highly abundant in the universe, similar to water, and has the ability to form a large variety of bonds and serves as the foundation atom for macromolecules such as proteins and nucleic acids. Looking for alien life in places with lots of water and evidence of carbon based lifeforms is a good place to start when searching for possible extraterrestrial life. However, other biochemistries may exist with a different set of nutrients or liquid solvent, but the plausibility of these alternative chemistries are unlikely and have yet to be convincingly demonstrated in the field of astrobiology [Schwieterman et al., 2018].

2 TECHNIQUES OF DETECTING EXOPLANET ATMOSPHERES

Before introducing the techniques of detecting exoplanet atmospheres, it is important to review the two most common methods of detecting exoplanets. The most successful method utilized by TESS is the transiting method. When an exoplanet crosses in between us and its parent star, we are able to measure the decrease in brightness from the star. For a Jupiter-like world, this dip in brightness is on the order of 1% which is extremely small and already challenging to observe [Crossfield, 2015]. Another successful method is the radial velocity method. Orbiting exoplanets, especially those with masses similar to Jupiter's or more, cause their parent star to exhibit a "wobbling" motion due to its gravitational pull which is also referred to as the star's reflex orbit. The wobbling motion of the star causes the color of the light observed to shift as the star moves away and towards us, which is known as Doppler spectroscopy. Spectroscopy splits up incoming light into all its wavelengths (the electromagnetic spectrum) often to observe the absorption and emission lines of present molecules. Both the transiting and radial velocity methods have inherent biases towards larger planets that orbit closely to their host star. This is not ideal for detecting Earth-like worlds since these planets tend to be inhabitable. However, the Kepler Space Telescope was able to detect the first Earth-sized planet orbiting within its star's habitable zone in April 2014. Kepler-186f is only 10 percent larger than Earth and orbits a red dwarf roughly 500 light years away [Brennan, 2017]. Since red dwarfs size, brightness, and effective temperatures are significantly less than that of our Sun, astronomers were lucky enough to glimpse the planet transiting its star due to its close orbit. If one is able to observe the planet transiting its star, they should be able to study the composition and structure of the planet's outer layers via transmission spectroscopy.

Transmission Spectroscopy

Transmission spectroscopy is the study of light through an exoplanets atmosphere as the planet transits in front of its parent star [Crossfield, 2015]. The key idea behind transmission spectroscopy is that the planet's transit depth is wavelength dependent. We can view the transit in different wavelengths of light and depending on the absorption of molecules, the planet blocks slightly more or less stellar flux from its star. We can measure these variations and create a transit model of the exoplanet's atmosphere and understand the composition of the planet's outer layers. The most successful mission used to study transiting exoplanet atmospheres has been the Hubble Space Telescope since space-based spectroscopy has less interference than ground-based telescopes. However, the one caveat to transmission spectroscopy is the misrepresentation of atmospheric compositions, known as flat transmission spectra, due to clouds and hazes acting as absorbers masking spectral features [Crossfield, 2015]. To date, due to the current limitations of our observing facilities, we have only been able to study the atmospheres of hot Jupiter's and Neptune-like planets. Although, we should be able to study the atmospheres of Earth-like planets with the launch of the James Webb Space Telescope (JWST). The JWST will be able to provide astronomers with a wider spectral range especially in the infrared and three times the sensitivity than the HST [Crossfield, 2015]. The JWST will be most successful observing the atmospheres of Earth-like planets orbiting around M classified red dwarf stars.

Secondary Eclipses

Another successful method of measuring the emission and reflectance spectrum of a planet is through secondary eclipses or sometimes called secondary transits. We can do this by removing the "star" from the "star plus planet" flux obtained during most of the planet's orbit to reveal the planets thermal emission or albedo [Crossfield, 2015]. Albedo is the total fraction of solar radiation that is reflected by a planet [Anand et al., 2018]. The difference between emission and reflectance spectrum is essentially the source of the radiation. With emission spectra, the radiation originates within the source object which could be from internal heating of the planet. Reflectance spectra is the amount of light reflected by a substance from some separate radiation source, which in this context is the light from the planet's star. The dominant source of thermal emission from a planet is not internal heating but rather the re-radiation of incident light from the star which helps astronomers determine the albedo of a planet [Crossfield, 2015]. Consider a situation where we are outside observers who just detected the presence of Venus and Earth orbiting around the Sun. At first glance, these planets are roughly the same size with the same density orbiting close to or within the habitable zone of our star. However, upon further investigation via secondary eclipse and transmission, we know life on these planets are extremely different. Venus has an albedo of 0.77 which means 77% of the incident light from the Sun is reflected back by the planet [Grayzeck, 2020]. This is because Venus has an incredibly dense cloudy atmosphere composed of 96% CO_2 which reflects the light back out into space. Venus is also an extremely hot world with a surface temperature of 464°C due to its thick atmosphere trapping heat causing a runaway greenhouse effect [Grayzeck, 2020]. By observing the thermal emission and reflectance spectrum of Venus and Earth, we can draw further conclusions which planet is likely habitable. Another method worth mentioning, similar to secondary eclipse, is phase curves. Phase curves are continuous time series photometry or spectroscopy of a planet over its entire orbital period [Brennan, 2019]. The total systems light throughout an orbit constraints atmospheric circulation and/or composition [Crossfield, 2015]. Although phase curves provide more information than secondary eclipses due to observing the day and night side of the planet, phase curves take a substantial amount of observing time which is not always the most efficient.

Direct-Imaging

Direct-imaging is a rather straightforward method of taking an image of an exoplanet using a coronagraph to block the glare from its star. A coronagraph is a telescopic attachment designed to block out the glare from a star so otherwise hidden objects can be observed. Direct-imaging holds a lot of potential in detecting Earth-like planets orbiting far away from their host star. As the precision of our observing facilities increase over the next decade, we will be able to remove the residual starlight more effectively and increase the spectral resolution of the image [Crossfield, 2015]. Since the images are taken in infrared wavelengths, the JWST will be able to detect more exoplanets using this method. Some astronomers believe in the near future we can identify atmospheric patterns, oceans, and landmasses from these images [Brennan, 2019].

3 BIOSIGNATURES AND INDICATIONS OF LIFE

As previously demonstrated with the example of observing Venus and Earth, we know the detection and characterization of exoplanetary atmospheres is essential in determining if the world is habitable or likely inhabited. Astronomers are currently searching for potential biosignatures to draw conclusions about the habitability of a planet. A biosignature is an object, substance, and/or pattern whose origin specifically requires a biological agent [Schwieterman et al., 2018]. Although there is no universally known classification system for biosignatures, the paper is split up similar to [Schwieterman et al., 2018] for convenience. It is also important to note the potential biosignatures the paper refers to are those with a global planetary impact that would be detectable with our current technology. We will also adopt the definitions of gaseous, surface, and temporal biosignatures from [Schwieterman et al., 2018]. Gaseous biosignatures are direct or indirect products of metabolism, surface biosignatures are spectral features imparted on radiation reflected or scattered by organisms, and temporal biosignatures are modulations in measurable quantities that can be linked to the actions and time-dependent patterns of a biosphere. The most efficient way astronomers can practice their modulations and methods of detecting potential biosignatures is to make observations of Earth. The paper [Schwieterman et al., 2018] analyzes Earth's biosignatures through measurements of Earthshine reflected from the Moon and photometric and spectrophotometric observations of Earth by interplanetary spacecraft.

Gaseous Biosignatures

The most indicative biosignature in Earth's atmosphere is the presence of oxygen, especially our signature ozone layer made up of O_3. Oxygen is produced through photosynthesis by UV radiation breaking up water molecules that serve as an "electron donor" to produce organic matter from carbon dioxide (CO_2) and the waste product O_2 [Schwieterman et al., 2018]. Oxygen can also be produced from non-biological origins such as photodissociation, or photolysis, of water. However, the amount of oxygen we have in the atmosphere is more than what would be produced in this manner, and the atmosphere has a constant concentration of 21% O_2. This is due to three biological processes that happen simultaneously on Earth: respiration, combustion, and photosynthesis.

Almost all living cells on earth obtain energy from their food through respiration which takes oxygen out of the atmosphere and releases carbon dioxide. Combustion is the burning of organic materials such as wood. Oxygen reacts with the carbon and hydrogen molecules within the organic materials, releasing heat and light in the form of fire. This takes oxygen out of the atmosphere and releases carbon dioxide. Plants use direct sunlight to synthesize food from carbon dioxide and water, photosynthesis, which generates oxygen as a bioproduct. Due to the emission and reflectance spectrum of Earth being in the infrared wavelengths, astronomers are only able to detect a strong spectral feature for the ozone layer (O_3). Trioxygen is created through UV radiation breaking up O_2 molecules and these reactive atoms will recombine to form ozone molecules (O_3). Since O_2 is a homonuclear diatomic molecule, it absorbs infrared light very weakly [Schwieterman et al., 2018]. Another biosignature gas detected in Earth's atmosphere is methane. Methanogenesis is an ancient form of anaerobic microbial metabolism that produces CH_4 as a waste product, and the single-celled organisms responsible for methanogenesis are called methanogens are considered to be Archaea [Schwieterman et al., 2018]. Methane is often considered to be a companion biosignature when observed together with O_2/O_3 or other oxidizing gases such as CO_2. In an atmosphere with a significant amount of oxidizing gas, methane would have to originate from biology or abiotic water since methane is the not the most stable form of carbon present [Schwieterman et al., 2018]. However, with intelligent life on Earth, methane is also created from landfills, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and more. Depending on the levels of methane and other gases in a planet's atmosphere, we will have a good indication if life possibly exists. Earth's modern atmosphere is exceedingly different from the Earth's atmosphere 2.5 billion years ago. During the Archean period of the Earth's formation, only methane was detectable in the Earth's atmosphere [Schwieterman et al., 2018]. This introduces a significant problem with observing exoplanets during their early stages of development. Thus, we may miss certain gaseous biosignatures due to observing time limitations.

Surface Biosignatures

Earth also has distinct surface biosignatures due to the presence of plant life. Surface biosignatures are created due to the existence of life on the planet that alters the spectrum of its surface through a variety of mechanisms. One method is the absorption and reflection of light by pigments in living organisms such as Chlorophyll in green plants. Another common method is the scattering of light by physical structures of organisms which can also be caused by reflective man made structures [Schwieterman et al., 2018]. The degradation products of biological molecules and fluorescence of pigments and bioluminescence are also present surface biosignatures on Earth, but may not be necessarily detectable on a global scale in a distant exoplanet [Schwieterman et al., 2018]. Halophiles are a great example of non-photosynthetic pigments that absorb light in the red wavelength part of the spectrum due to their pinkish color. The most notable surface biosignature shown in Earth's reflectance spectrum is a phenomenon known as the Vegetation Red Edge. Chlorophyll in green plants absorb photons from solar radiation which enables the organism to capture solar energy and fix carbon to perform its necessary life functions [Anand et al., 2018]. However, Chlorophyll only absorbs photons at specific wavelengths, notably red and blue, which is why plants develop their greenish color. If we graphed the Earth's measured reflectance of light we would see a sharp increase around the 0.7 microns mark. This is because the plant is admitting near infrared radiation to protect itself from overheating due to absorbing solar radiation. We are able to detect this sharp increase of reflective light in all different types of plant life from algae to moss to different types of trees. The sharp edge is a clear indication that light is being scattered by a physical structure within a present organism.

Temporal Biosignatures

Temporal biosignatures do not hold as much importance in comparison to the detection of gaseous and surface biosignatures of exoplanets. This is mainly due to the complexity of modeling temporal biosignatures of exoplanets and the fact that measuring temporal biosignatures requires a significant amount of observation time without a guarantee they will even be detectable at such a far distance. In order to model temporal biosignatures of an exoplanet, the axial tilt, orbital eccentricity, and surface diversity must be known for the planet [Schwieterman et al., 2018]. Due to limitations with our current technology, most of this information will remain unknown to the observer. However, temporal biosignatures are still worth mentioning since we are able to detect them on Earth. One of the most significant temporal biosignatures is the seasonal change of the concentration of CO_2 in the Earth's atmosphere. As the spring/summer comes, we can see a decrease in the amount of CO_2 in the atmosphere due to CO_2 being fixed into organic matter by vegetative growth [Schwieterman et al., 2018]. Similarly, in fall/winter we see an increase in the amount of CO_2 in the atmosphere due to the decay of plant matter. This oscillatory motion can be graphed over time. Methane also oscillates since in summer water vapor is more prevalent in the atmosphere. Hydroxide (OH) is produced from tropospheric water and destructively interacts with methane, which leads to a decrease in methane concentrations during the warmer season [Schwieterman et al., 2018]. Another example of a temporal biosignature is changes in the Earth's surface albedo. This is again due to the growth and decay of plant life and can be measured with the normalized difference vegetation index (NDVI). NDVI is a graphical indicator measured from an orbiting satellite that determines if a target object contains green vegetation or not [Schwieterman et al., 2018]. The albedo of the Earth's surface changes due to the freezing and thawing of the planet's surface.

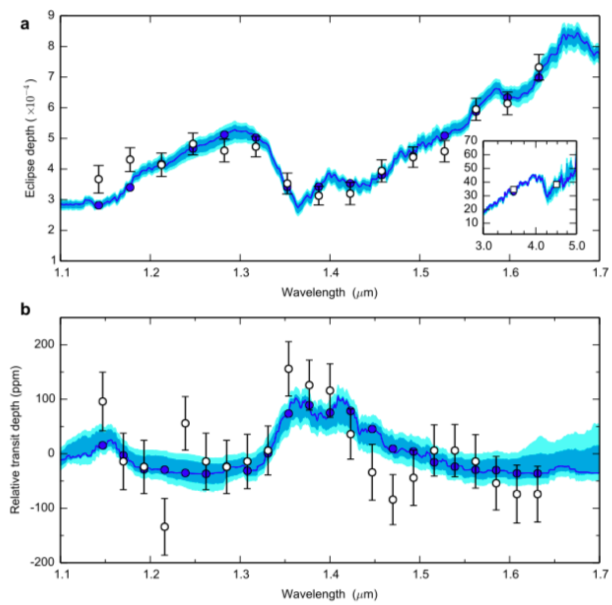

Fig. 1. The top graph represents the thermal emission spectrum for the hot Jupiter WASP-43b. The data is from the Hubble Space Telescope. The bottom graph is the transmission spectrum for the planet. The blue line corresponds to the best fit model, and the dark and light blue shading corresponds to the 1 and 2σ confidence intervals from an atmospheric retrieval [Kreidberg, 2018].

Biosignatures of Exoplanets

Detecting these biosignatures on exoplanets is a considerable feat that depends on a variety of factors. The observing telescope architecture needs to be precise and sensitive enough to observe these signatures. The targeted system needs to be within observing distance, within our observing spectral range, and have the right type of star. Planetary parameters must also be sufficient enough including the size, albedo, and composition of the planet to be able to produce these biosignatures. Of the hot Jupiters and Neptune-like planetary atmospheres we have observed, water vapor has been the most common atmospheric gas observed [Kreidberg, 2018]. This is mainly due to the significant spectral features found within our accessible wavelength range, unlike carbon-bearing molecules. The paper [Kreidberg, 2018] provides an excellent example of thermal emission and transmission data from the hot Jupiter WASP-43b shown in Figure 1. The top graph shows the thermal emission spectrum of WASP-43b taken by the Hubble Space Telescope during its secondary eclipse around its host star. The dip that occurs around 1.37 microns is a spectral feature due to the presence of water vapor in the planet's atmosphere [Kreidberg, 2018]. The water vapor is absorbing the planet's emitted near infrared radiation at that wavelength. Due to the large size and close orbit of WASP-43b to its host star, the HST was also able to obtain transmission data of the planet. In the bottom graph, there is again a spectral feature due to the presence of water vapor at 1.37 microns. Although we have yet to detect spectral features in Earth-like planets, astronomers are continually developing these techniques by practicing on hot Jupiter's and Neptune-like planets.

4 DISCUSSION/CONCLUSION

The characterization and detection of exoplanetary atmospheres is a growing field and essential for determining the habitability of Earth-like planets. The James Webb Space Telescope will allow astronomers to peer into the night sky with more sensitivity and a broader spectral range in the infrared. The JWST is said to launch in October 2021, but due to complications with testing over the last couple years, the launch date has been continuously pushed back. Another exciting observing facility under development is the European Extremely Large Telescope which will be located in the Chilean Atacama Desert. The telescope will contain a mirror 39 meters in diameter that will gather 100,000,000 times more light than the human eye [Information@eso.org, 2020]. The ELT will help us peer into the far reaches of space with the goal of being the first telescope to detect life outside of our solar system. The construction of the ELT is scheduled to be completed in 2025. Until the implementation of these new technologies, astronomers are stuck with our current observing facilities. The methods of detecting and characterizing exoplanets remain biased towards planets that orbit close to their parent star and have a mass similar or greater than Jupiter's. Astronomers are also limited by the precision of our technologies and techniques of observing exoplanet atmospheres. Transmission spectroscopy sufferers due to the interference from clouds and/or hazes, which mask biosignatures in the planet's atmosphere. Secondary eclipses are biased towards larger planets close to their parent stars outside of the habitable-zone. However, as technology continues to improve, researchers will be able to see deeper into exoplanet atmospheres, observe more Earth-like planets, and obtain better data. Overall, the detection of extraterrestrial life is reliant on the ability to identify biosignatures on these extrasolar worlds.

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