How can we determine the Chemical Composition of Exoplanets using Spectroscopy and Exoplanet Detection Methods?

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Abstract

Exoplanetary sciences are progressing constantly with the launch of new telescopes and development of many ground-based telescopes. This progress has led to an increased rate of exoplanet discovery in the last 25 years. Moreover, more intricate spectroscopic methods, along with other types of techniques described herein, have allowed for more efficient characterization of exoplanets that allow us to describe their atmosphere, temperature, and size, just to name a few. It is expected that in the future these characterization methods will lead to the discovery of the first biosignature along with progressing technologies such as the James Webb Space Telescope (JWST). This paper explores these various methods of spectroscopy and exoplanet detection. Graphs such as transit curves, spectrograms and spectra are shown to support the argument on determining the chemical composition and other features of exoplanets. Based on the effect of understanding composition, this paper discusses atmospheric and exoplanet characterization, as well as several aspects of life detection using biosignatures and markers.

1. Introduction

The study of exoplanets has been constantly increasing in intricacy, but also allowing us to collect several new details about discoveries. Determining the composition and characteristics of the atmosphere of an exoplanet are essential in understanding all physical processes taking place, the possible presence of life, characterization of planets, understanding what unique planets are present. There are over 4000 confirmed exoplanets (Brennan, n.d.), which have allowed for the creation of categories such as Hot Jupiters, Sub-Earths, Neptunian, and several others. Each of these exoplanets have had their composition identified, using precise methods of spectroscopy, which will also be implemented by the JWST using the assistance of transits to observe closer details as well on an exoplanet's surface itself.

In the 16th Century Giordano Bruno suggested that there are many stars similar to the sun, which means there could be hundreds and thousands of planets like the ones we know of (The History of Exoplanets, n.d.). A myriad of theoretical models of exoplanets were produced and ideas about detecting exoplanets using doppler spectroscopy and the transit method was suggested in 1952. Eventually, the first exoplanet, PSR B1257+12 was discovered in 1992 (The History of Exoplanets, n.d.). Since then, the field of exoplanetary sciences has exploded with new discoveries and a plethora of unique methods to understand the way other worlds function in the universe. Understanding chemical compositions are the Rosetta stones for understanding the functioning of an exoplanet and determining whether there could be life on another world.

In the past 25 years, there have been new methods of discovering exoplanets using mathematical applications and graph interpretational skills to determine planetary properties like mass, radius, density, orbital period, orbital radius and composition. The technology and our knowledge have grown so immensely, we are able to capture actual images of exoplanets. Different telescopes and missions have contributed heavily to the field. Discoveries made by the Kepler mission led to the observations of hundreds and thousands of planets.

Eventually, we may detect the first lifeform and find out several more discoveries about exoplanets. The launch of telescopes such as Hubble, Spitzer, CoRoT and Tess each contributed to different aspects of exoplanetary components. The future holds promising results about exoplanetary sciences, with the upcoming launch of the JWST in November, 2021 and the WFIRST telescope in 2025 (Quanz et al. 2019).

This paper is divided into 4 sections. The first section discusses the different exoplanet detection methods what do they tell us about an exoplanet such as chemical composition, orbital radius and mass. Part 2 discusses the different spectroscopic methods, how they work and what do they tell us about an exoplanet's chemical composition and atmospheres. The third section elaborates upon the classification of exoplanets and the characterization of exoplanetary atmospheres. The final section is about habitability and biosignatures. In section 5, the concluding remarks state an overall analysis of the paper and future prospects for exoplanetary sciences.

2. Exoplanet Detection Methods

Determining the chemical composition and habitability of exoplanets can only be done once exoplanets are detected. Detection methods reveal planetary features such as orbital radius, mass and density. These details are in turn used to understands composition and habitability. The primary, indirect methods of detection include radial velocity and transit photometry. The only direct method is direct imaging. Before establishing an exoplanet's features, it is important to know the distance and mass of the parent star. Distance is determined using the parallax method, and the mass is determined using mass-luminosity relations from the Hertzsprung-Russel diagram. Once this has been determined, uncovering the orbital radius of the exoplanet is key in understanding factors such as habitability. This can be measured using Kepler's third law; $p^2 \propto a^3$, where p is orbital period and a is the semi-major axis. Using orbital radius, the determination of the mass can be done using the RV method, which is spoken about in subsection one of section 2. Various conclusions can be drawn about the exoplanet's characteristics. Other methods such as transit and direct imaging are elaborated upon below.

2.1. Radial Velocity Method

The Radial Velocity (RV) method relies on the observations of stellar "wobbles" which is a gravitational tugging effect from a planet on its host. The detection of this doppler shift and gravitational wobble proposes the existence of an exoplanet in that stellar system. In the presence of a large Jupiter-mass planet, with a close orbit, has a minor, yet measurable gravitational tug, upon the parent star. This tug causes both celestial bodies to orbit a common centre of mass. This effect causes light from a star to be red-shifted or blue-shifted. If the star moves closer to us it is blue-shifted and red-shifted if the opposite.

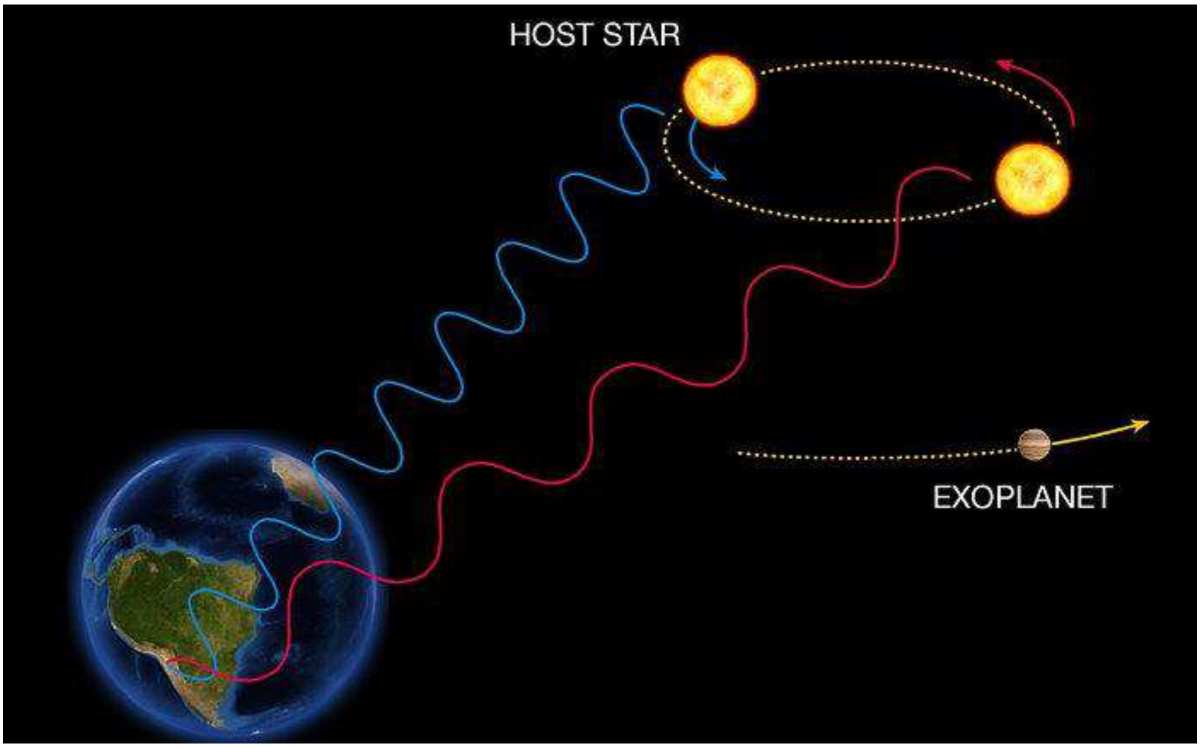

Figure 1: Shows the light from a star being red or blue-shifted due to the influence of an exoplanet. As observed, an exoplanet (Jupiter-like) orbits a star, and causes it to wobble as well. As a result, they each orbit a common centre of mass, causing the difference in wavelengths of light when it reaches Earth. *Figure courtesy European Southern Observatory.*

The RV method is best at finding Hot Jupiters which are exoplanets having between 100 and 10000 $M_\oplus$ and with an orbital period of approximately 10 days. This is because they are close enough and large enough to create a measurable gravitational impact. 51 Pegasi b was the first exoplanet discovered in 1995 using the radial velocity (Mayor and Queloz, 1995).

Today, the HARPS and ESPRESSO spectrographs are used to detect the radial velocities from stars caused by orbiting planets. Spectrographs use telescopes which obtain the light from a star, reflecting it from a mirror onto a diffraction grating, which in turn reflects the diffused light onto a photodetector to convert the photons into an electric current. These currents are displayed onto a computer screen as a line graph, depicting the radial velocity of a star.

RV in turn allows the mass to be derived (Wright and Gaudi, 2012). Once the radial velocity is found, using the Doppler shift, the force of gravity between the two bodies can be found based on the gravitational tugs. This force of gravity is equivalent to the gravitational constant times mass 1 (mass of body 1 – the parent star) multiplied by mass 2 (mass of orbiting exoplanet), the whole divided by the orbital radius, squared: $F_g = G\frac{m_1 m_2}{r^2}$. From this equation, the mass of the planet can be easily found. This value is an estimate.

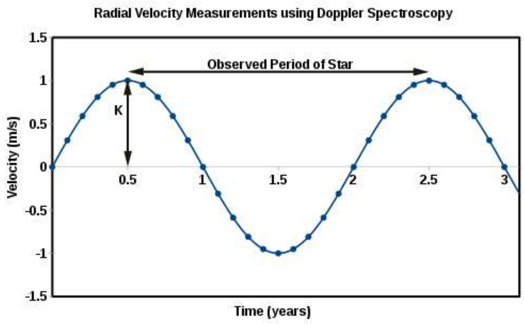

Figure 2: Radial Velocity curve using of a hypothetical star. As the star orbits the common centre of mass, the wave with positive velocity indicates redshift, and negative represents blueshift. *Figure from Howard, S. 2011*

Planet-to-star mass ratios are extremely dissimilar, hence causing an estimate of mass to be derived. Once one knows the mass and orbital radius, one is able to make predictions beforehand based on habitability. Mass plays an important role in the force of gravity. If mass is too low on a planet, gravity is weak, declaring the planet unable to maintain a stable atmosphere, but if mass is too high, say tenfold Earth's, an iron-nickel core increases in size, increasing the strength of gravity, finally increasing surface pressure, making it uninhabitable for humans. Simultaneously, orbital radius helps decide whether an exoplanet is within the habitable zone (See section 5.1).

The RV method is mainly capable of measuring only these properties of the exoplanet. Radius, density, surface temperature and chemical composition can be found using other methods; Transit and Direct Imaging.

2.2. Transit Photometry

By number of exoplanets detected, the major contributor is the transit method. It is responsible for 3363 exoplanet discoveries. The method is extremely reliable and robust given its commonality in the terms of the constraints and necessities applied by different planets' positions relative to our observations. The transit method involves measuring the light from a star constantly along with the period where an exoplanet passes between the stellar light, which is called a transit. Transits cause the brightness levels of a star to drop. This produces a transit curve. The relative flux is directly affected, making it possible to detect exoplanets orbiting a star. (Example: Kepler-7b dims a star's brightness by 0.5%).

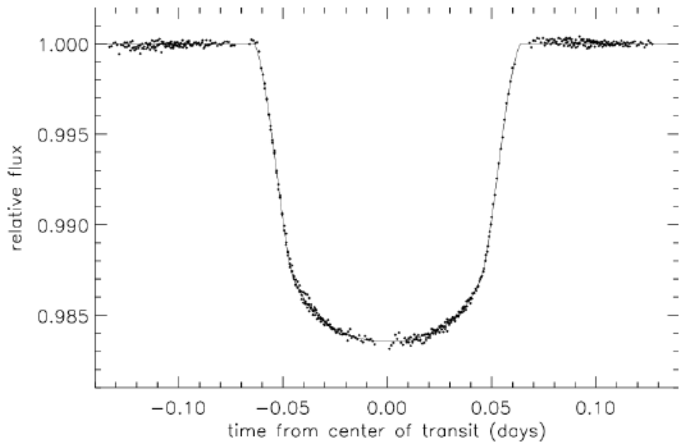

Figure 3: The transit curve of HD 209458b. Time is measured on the x-axis and brightness on the y-axis. As observed, the change in relative flux is with low intervals, and only describes a change every 0.5% of the star's brightness. Additionally, on the x-axis, the time for the transit is very low. *Figure from Mayor, M. (et al.) 2005*

This method does not work on red giants and supergiant due to their constant brightness pulsations, creating an uncontrolled variable. The transit method is splendid in identifying exoplanets which are in close orbits and large to block as much light as possible to provide a far greater measurable effect. When it comes to negatives, transits only block about 0.5-2.0% of the stellar light (Howard, 2011), which does not make it easy to observe. It also requires the planet and star to be aligned with the observer. Additionally, post, transit observations of planets, several other methods must be used to confirm the presence of an exoplanet, as from the Kepler mission, transits were often identified as non-planetary objects such as a second star in a binary star system or possibly even an asteroid. Luckily, using current ground-based telescopes, its often planets that are detected instead of a binary eclipse. Another major roadblock in the method corresponds to the time taken to observe transits. While a planet could take days or even years to orbit its star, the time gap to observe the transit is only a few hours or days. This decreases the likeliness to detect transits. Another major disadvantage is the fact that transits must be aligned relative to our view. There is a 10%

chance that planets in a small orbit are aligned. The larger the orbit, the less likely it is to be aligned (Howard, 2011). For Hot Jupiters, typically orbiting at 0.05 AU, the geometric probability for observing it is 10%. For Earth-like planets orbiting at 1 AU this probability is lowered dramatically to 0.5% (Howard, 2011).

Given that transits have several disadvantages, in order to overcome these problems, certain observational solutions have been used. Different telescopes make sure to observe stellar light for hours or even months in order to prevent missing of a transit. Second, making one telescope survey approximately 100,000 stars is quite efficient to increase the chances of detecting a transit. It is also less costly than setting up many telescopes to observe only a few stars in one survey. Furthermore, different telescopes such as TRAPPIST and HAPnet utilize automated techniques to constantly observe stars for long periods of time, given they are robotic.

Transit curves when analysed, offer key insights about exoplanet properties. The curve's depth can be measured, defining the radius, further determining the density. The transit depth in the curve is measure in order to determine the radius of an exoplanet. Transit curves are measured on the basis of how much of the relative flux of the star is affected. The radius of an exoplanet, ('r') is equal to the root of the transit depth (T_d) of the curve multiplied by the star's radius ('R') squared: $r = \sqrt{R^2 \times T_d}$ (Stellar radii are found using Stefan-Boltzmann Laws). The radius, can usually determine whether an exoplanet might be rock or not. Additionally, the radius of an exoplanet helps determine the density. We calculate the approximate volume of the planet, assuming it as a sphere with the following equation: $v = \frac{4}{3}\pi r^3$. Using the mass found via RV and volume, the density is determined: $D = \frac{M}{V}$. Density plays a vital role in differentiating between rocky and gaseous planets and therefore gives information on chemical composition. Apart from density, using the transit method we are able to identify the actual chemical composition of the atmosphere, and to some extent, the surface as well. This is called transmission spectroscopy (See section 3.2), which observes the stellar light, passing through the planet’s atmosphere.

When it comes to the method, the planet can either be in front of the star, which is called a primary eclipse; or the planet can be behind the star, which is called a secondary eclipse. The third configuration is the phase curve. Phase curves are the time when the planet is between the two eclipses. The primary eclipse has been explained above, wherein the planet’s radius, density and atmospheric composition can be found. During secondary eclipses, the planet’s radiation can be measured. The star’s intensity is subtracted during the eclipse. The planet’s signal remains and a surface temperature is inferred. Light’s colour directly relates to temperature. However, sometimes it is possible an exoplanet’s orbit doesn’t allow for secondary eclipses to occur as viewed from Earth. Detecting secondary eclipses are relatively harder than detecting transits, because firstly orbits of planets are often elliptical, resulting in the possibility of temperature change. Second, given planets contribute barely to radiation to the total radiation emitted from a star, it is much harder to detect this radiative contribution, as compared to measuring the stellar light and transits. Records from Kepler’s mission were used in order to determine the minute changes taking place in the radiation, which in turn allowed them to detect tiny changes in radiation.

As discussed above, knowing the chemical composition of planets can only be done once information about other planetary features are known. An example, radial velocity and transits are interconnected, and both required for density. Together several methods are interconnected to find new details about the planet.

Delving deeper into chemical compositions, it is important to understand the type of atmosphere exoplanets might have. There are several layers and various processes occurring in different layers of an atmosphere. This subsection has determined the importance of radius and density. Furthermore, direct imaging provides valuable insights about the exoplanet's surface temperature, presence of clouds and chemical composition (Traub and Oppenheimer, 2010).

2.3. Direct Imaging

The Direct Imaging method is the only direct exoplanet detection method. This means, it is the only method that involves taking a picture of an exoplanet. As observed in the transit and RV method, only the photons are studied and assumptions (These are still specific assumptions) about a planet are made. In planetary systems, the brightness of the star engulfs the planet, by a factor exceeding millions.

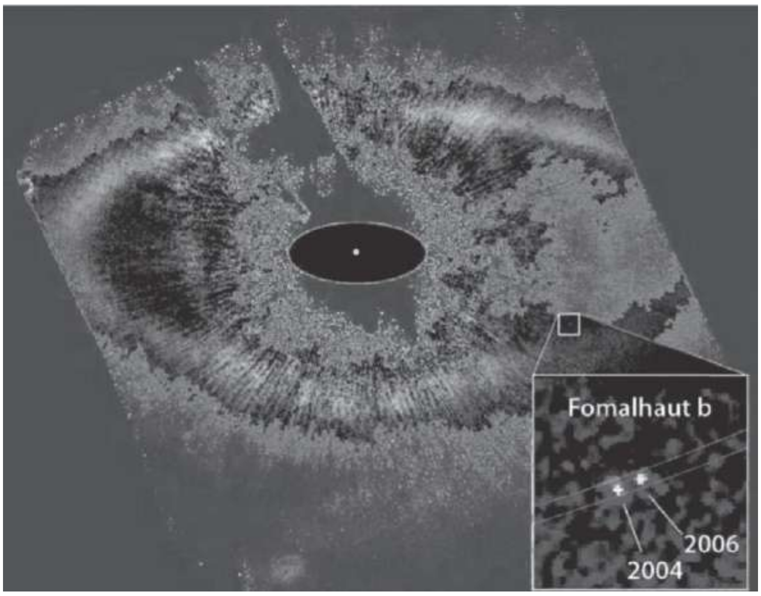

Figure 4: A direct image of Fomalhaut b using a coronagraph, within a dust disk of the star Fomalhaut. As observed, the centre is the host star, surrounding it a planetary disk, where Fomalhaut b orbits. The single pixel image is zoomed in to show the planet. *Traub, W.A. & Oppenheimer, B.R. 2010.*

Direct imaging is an extremely sensitive and difficult survey to conduct. Usually, pictures of planets are extremely blurred. The first directly imaged planet; Fomalhaut b, is one-pixel large in the image taken. In figure 4, Fomalhaut b is observed as a tiny white dot, which when zoomed in does not look much like a planet. In direct imaging, coronagraphs are used to remove the excess starlight which hide the exoplanets. Direct imaging works best for planets which have large orbits, are large themselves and have high temperatures to emit a greater amount of infrared radiation. In the case of Fomalhaut B, the planet orbits around 110 AU from Fomalhaut, which is why it was easier to detect than other planets, because the glare of the starlight did not completely conceal the planet. Most planets detected via direct imaging are most likely gas giants, given that accretion launches less dense particles further out into space. Hot Jupiters as well, though never directly imaged, may be in the future due to their high temperatures (Traub and Oppenheimer, 2010).

Direct imaging is not a largely-scaled survey, due to the fact that there are several constraints that are essential to detecting an exoplanet. Due to the brightness problem, certain stars are targeted, such as sub-brown and brown dwarfs. First, the method involves observing stars larger than the sun, brighter and hotter (Howard, 2011), which allows protoplanetary disks to be farther from the star (This directly means that the habitable zone of the star is further away from the star). Second, targeting young stars indicates planets are young as well. Ergo, their temperatures from formation are still high, making their infrared signatures to be detected far more accurately. Last, most direct imaging observations are made in the infrared to decrease the contrast in brightness between the two celestial bodies. It is believed in H-alpha (A deep red visible line with a wavelength of 656.28 nm in air. Hydrogen's energy level drops from its 3^{rd} to 2^{nd} lowest level.) these contrasts can be far better.

Coronagraphs are essential components in direct imaging. These are telescopic attachments which are designed to observe the stellar corona of stars. The stellar corona varies depending on the brightness of the star, as these can stretch up to millions of kilometers. Solar coronagraphs eliminate the stellar light in order to study the sun's corona. Although, stellar coronagraphs eliminate this light in order to detect planets, other stars as well as debris and planetary disks.

Inside the coronagraph, there are many lenses and mirrors to focus onto the light of the star. Once the light enters, several mirrors reflect the light onto a computer to receive an image. When the light from a star is first received, the light has distortions. The light shows a star in the centre with concentric circles which is scattered light as a result of diffraction. Once the coronagraph is activated, a coronagraph mask, is used, which is designed to redirect the unblocked starlight to the edges of the beam. There is a dark central region in the mask that conducts this. The light then travels through a Lyot stop which blocks the excess light on the side, getting rid of the concentric circles. This blocks up to 98.5% of the stellar light. Given that the telescopes are angled to be directly in line the with star, planetary light enters the telescope at different angles. The light misses the central region of the mask and then travels through the centre of the Lyot stop and can be transferred to a computer to display the image. Although due to the distortions caused by imperfections, certain areas of the image have smears of light. The use of deformable mirrors can alter the distortions and correct the beam in order to get rid of the blobs, revealing the planets. Often, telescopes observe the light in infrared wavelengths, as brightness ratios are significantly ordered. For example, Jupiter's brightness is a billionth of the Sun's in the visible range of light, but only 1% of the sun's brightness in infrared range.

Stellar light when observed has absorption features which convey details about a planet's chemical composition. Along with that, the thermal signatures and orbital radius of the planet conveys the surface temperatures of the exoplanet. Using details from an image, the radius of an exoplanet can be determined with an estimate. Ratios are compared between the sizes to find these properties.

3. Spectroscopic Methods

Spectroscopy is the study of the interaction between electromagnetic radiation and matter. Spectroscopy plays a vital role in understanding the chemical composition of exoplanet. Via spectroscopic surveys, characterizing planets, atmospheres and conducting the hunt for life and habitability is initiated. Within spectroscopy there are many methods of understanding exoplanetary compositions. Spectroscopy uses light from other stars to be reflected onto the planet, in order to understand not only its chemical composition, but atmospheric processes as well. Different molecules are required to absorb different wavelengths of light in order to receive the energy they need to jump from one energy level to another. These absorptions can be shown, producing a spectrum of certain molecules, or several in one spectrum. The most successful method of spectroscopy in exoplanetary studies has been transmission spectroscopy. Other methods include high-dispersion, high-resolution and infrared spectroscopy.

3.1. Transmission/Transit Spectroscopy

Transmission spectroscopy is the most successful method in understanding surface and atmospheric compositions. As the name suggests, this method is directly related to transits. When the light from an incoming star is disturbed by a transit, telescopes detect the light which has passed through the exoplanet's atmosphere, allowing us to observe the spectrum with different absorption/emission features.

As mentioned before, transits have three configurations (Madhusudhan, 2019). The primary eclipse, secondary eclipse and phase curves. Each form produces a different spectrum. When a primary eclipse occurs, the stellar light passes through the atmosphere and causes the light to have absorption features. Different compounds and substances can be identified based on the location of absorption. In the event of a secondary eclipse, emission spectra are produced, from dayside atmospheres of the planet. Whilst this phenomenon occurs, or before it, a combined spectrum is measured between the star and planet. In order to individually observe the spectra of the planet, the stellar light is subtracted, therefore revealing only the planetary light. Typically, the observations produce emission and reflection spectrum, because there are elements of radiative energy as well. During a phase curve, the light measured is of different stages in the planet's day-night cycle, out which each spectra offers different insights upon the atmospheric properties (Madhusudhan, 2019), making it highly useful for atmospheric characterization.

Transit spectroscopy, typically in a primary eclipse, causes the spectrum to be primarily for the day-night terminator. Aside from chemical composition, ionic species can be found and details about the planet's temperature can be determined from the scale height (Atmospherically, it indicates the vertical height of pressure dropping), because pressure implies temperature based on which molecules are present in the terminator region. Typically, the detections of O_2, H_2O, TiO, CH_4, HCN, CO_2 (Madhusudhan, 2019. Snellen, 2014. Quanz, 2019. Tinetti et al. 2010) are made in exoplanetary atmospheres using transmission spectroscopy. At times, if exoplanetary atmospheres have clouds, they can disrupt the light and have an effect upon absorption and emission features. Although, inferring the presence of clouds and hazes are

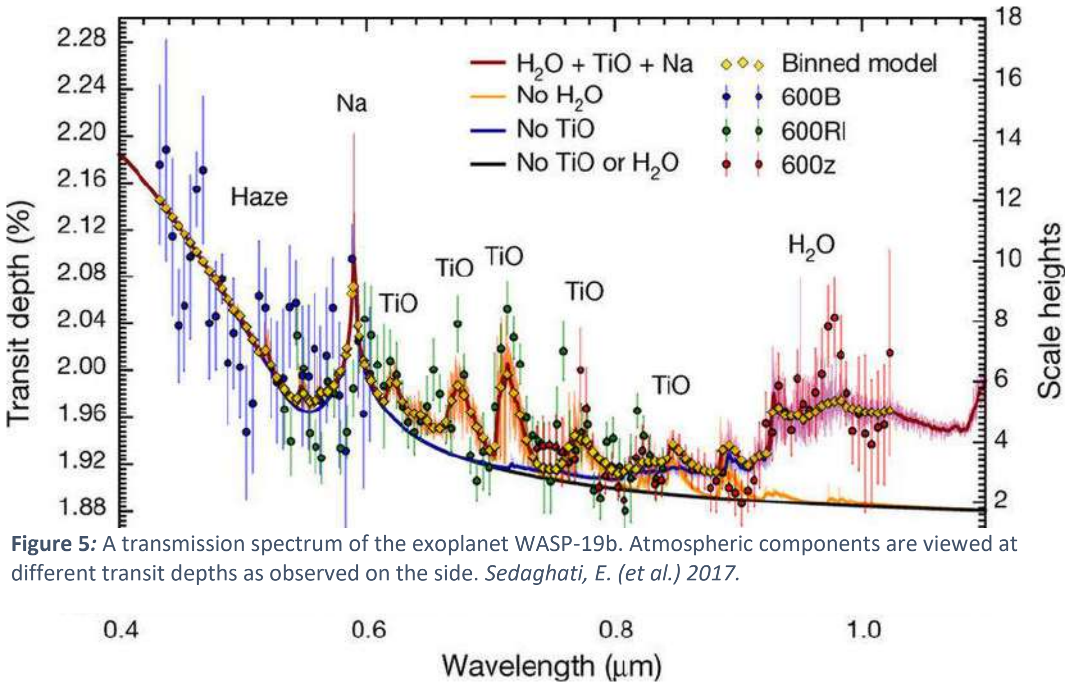

Figure 5*:* A transmission spectrum of the exoplanet WASP-19b. Atmospheric components are viewed at different transit depths as observed on the side. *Sedaghati, E. (et al.) 2017.*

important for atmospheric characterization and conditions on a planet. The applications of scattering such as Rayleigh and Mie, stamp identifiable features in optical transmission, proposing the existence of clouds in the atmosphere.

Emission spectra, received from secondary eclipses contain information about the temperature structures of the exoplanet and offer details about the chemical composition of the planet’s dayside. Emissions of planets are usually measured in between 1nm and 100nm, but due to difference in flux of the two bodies, the light is observed in infrared wavelengths in order to understand chemical composition and temperatures from secondary eclipses.

Phase curves, also provide necessary details about chemical composition. These spectra contribute to atmospheric characterization as well (See section 4.2), in describing energy transport and temperature distribution around the atmosphere (Madhusudhan, 2019). Atmospheric dynamics, being essential in understanding physiochemical processes and other processes in atmospheres can be derived via the phase curves.

3.2. High-Dispersion Spectroscopy

High-dispersion spectroscopy is proving to be a highly effective spectroscopic method for characterizing exoplanets as well as their atmospheres. Resolutions reach up to around 100,000 (Birkby, 2018) in this method, causing molecular bands to be separated into tens of individual lines. Molecular bands are often present quite close together, causing them to be perceived as a continuous spectrum, but high-dispersion spectroscopy avoids that. The increase in resolution allows absorption features to be made more prominent, hence allowing further analyses to be done. The first exoplanet's atmosphere measured via this spectroscopic method was HD209458b, in order to detect CO. The band was dispersed into several individual lines, with different shifts in wavelength due to gravitational wobbles.

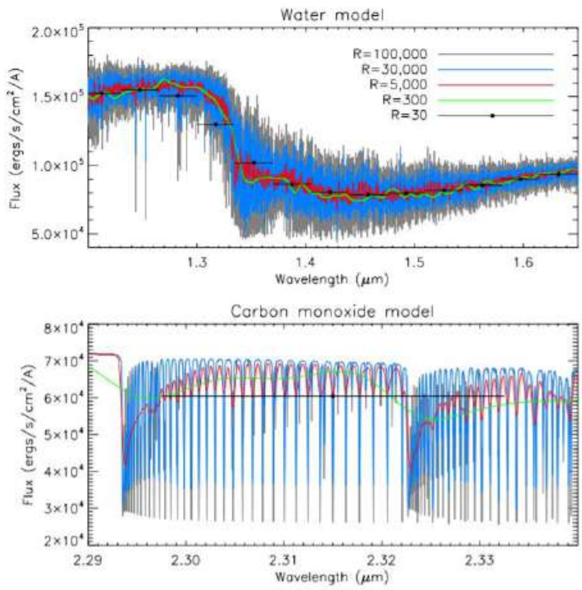

Figure 6: Different spectral resolutions shown on a spectrum of water and carbon monoxide. This diagram aims shows the effect of resolution on understanding molecular features. At a resolution of 30, the models are shown only with individual black lines. With increasing resolution, the models and their spectral features become much denser. *Birkby, J. L. 2018.*

High-dispersion spectroscopy often measures hot Jupiters in close orbits, as double line spectroscopic binaries. The effect of large planets such as these cause spectral lines to be doppler shifted (Birkby, 2018). Double line spectroscopic binaries are binary star systems, where each star is too close to each other and causes the spectrum's spectral lines/features to be shown twice. Intentionally treating the planet-star system proves to be effective, because thermal emissions of the hot Jupiter, thermal inversions and molecular abundances can be found, relative to the star (Crossfield, 2015). Each of these factors are key in atmospheric characterization. Certain telescopes are designed to follow the high-res approach in order to detect thermal emissions. Atmospherically, looking at molecular abundances and studying their lines are essential in understanding chemical composition as well, aside from simply characterizing the atmosphere. High-dispersion spectroscopy suits well for studying directly imaged planets. Most of these exoplanets are observed at medium resolution. As a result, inferences about the planet's thermal structure are made.

Oxygen detection is essential in the search for life. Oxygen's molecular band, which has 50 strong lines, allows its detection to be suitable for high-dispersion spectroscopy (Snellen, 2014). In twin-Earths these could be detected as possible biomarkers using the method. Red-dwarfs (hosts of the exo-Earths) are much fainter than other stars of planets such as hot Jupiters.

In order to detect oxygen, larger telescope receiving areas are used, larger than the Very Large Telescope's (VLT) eight meter receiving area.

3.3. Infrared Spectroscopy

Infrared spectroscopy is another major branch in spectroscopy. It is the study of the interaction between matter and infrared light. It can be used to identify substances and their states of matter as well. Infrared spectra are composed of reflected/scattered flux (Peaks in UV/NIR/Visible) and thermal emission, as electromagnetic waves at greater wavelengths (Encrenaz, 2014). Infrared spectroscopy is often used as infrared light and spectra offer the most details about molecules in the atmosphere based on thermal emissions and inversions. As mentioned above, infrared light is used in areas such as direct imaging and other observational areas as planet-

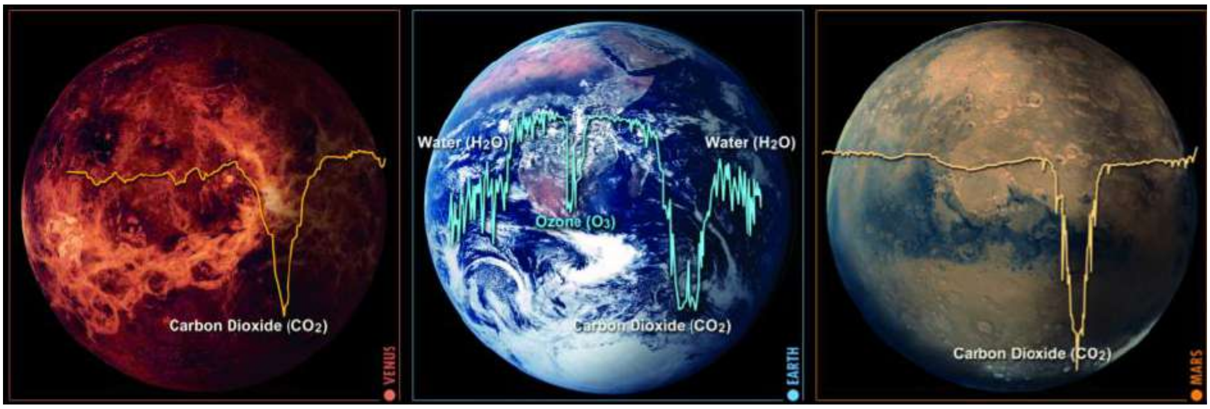

Figure 7: This figure shows infrared thermal emissions from different rocky planets, within our solar system. Provided that Mars and Venus have abundances in carbon dioxide, their spectra show features only for that certain compound, but for Earth, given the many different abundances such as water, ozone and carbon dioxide, there are far more features on the same spectrum. *Quanz, S. P. 2019.*

star brightness ratios drastically change.

On the Spitzer-IRS (Infrared Spectrograph), emission spectra were received of hot Jupiters which showed the presence of H_2O in their atmospheres. There were several noise-disturbances, which denied there is water within the wavelength region of 7-14.5 μm (Tinetti et al. 2012). Although, using further investigation, it was found water was present in the emission spectrum using the IRS on Spitzer, in the 1μm region in the hot Jupiter HD209458b.

Ultimately, infrared spectroscopy allows for the detection of similar, or the same molecules in exoplanetary atmospheres as transmission and high-dispersion spectroscopy. As observed in figure 7, infrared spectroscopy proves to be efficient in determining the molecular abundances, across planetary atmospheres. Given these are thermal emissions, temperature details are found as well as atmospheric components, which are useful for characterization.

4. Exoplanet and Atmospheric Characterization

Spectroscopy has shown to be extremely important and effective in providing essential details about a planet's atmospheric properties and chemical composition. Once this information is received, it is put to use. These details can be used classify exoplanets. Post this, characterising and defining its atmospheric properties layer by layer conveys tens more details about the exoplanet.

4.1. Characterizing and Classifying Exoplanets

Exoplanets have different compositions and sizes, which means there are several types of exoplanets. Due to different effects such as orbital radii, chemical composition and temperature, exoplanets must be classified into certain groups. There are 4 major groups of exoplanets; Gas giants, Neptunian, super-Earth and terrestrial. Each of these groups have several sub-categories. Additionally, there are some theoretical planets as well.

4.1.1. Terrestrial Planets

Terrestrial/Telluric/Rocky planets, are planets which are composed of silicate-minerals and metals. They have hot molten cores, solid surfaces and possibly some moons. These predictions are made on the basis of current knowledge about Mercury, Venus, Earth and Mars, which are all rocky. They may also have different surface features like mountains and volcanoes. Most exoplanets discovered have found to be gas-giants, due to the fact that they're large and easier to observe/detect. Although, several smaller exoplanets have shown to be terrestrial due to their compositions observed via spectroscopy. A terrestrial exoplanet is classified as a terrestrial planet if it has around the same mass as the Earth, or even lesser. Planets that are twice the size of Earth, may be rocky, but are classified as super-Earths, because they're much larger. Within the terrestrial group, there are carbon, water, sub-Earth and lava. There are some hypothetical terrestrials as well such as coreless (Non-metallic) and desert planets. There are different theoretical ideas regarding how these sub-categories of terrestrial planets might have come into existence. For example, it is believed lava planets must exist due to some sort of collision with another planet or might be orbiting dangerously close to its parent star. Examples of terrestrial exoplanets include, CoRoT-7b, GJ 1214 b, Kepler-42b.

4.1.2. Gas Giants

Gas giants are planets comprised of hydrogen and helium. As the name suggests, they're made of gas, so they don't have a solid surface on which something can land on. It is just swirls of gas above a solid core. Gas giants have varying sizes and types, and their distances can vary as well from its host. Mentioned above, hot Jupiters are quite abundant. They are Jupiter-like planets, which have orbital periods of approximately 10 days. Types of gas giants include, hot Jupiters, helium planets, super-Jupiters and puffy-Jupiters. Examples include 51 Pegasi b, Kelt-9b and Kepler-7b.

4.1.3. Neptunian

Neptunian planets are planets that have similar sizes as Uranus and Neptune. Chemically, they are composed of hydrogen and helium. Most of these objects are 17 M ⊕. Sub-categories such as mini-Neptunes have varying mass of between 2-10 M ⊕. These planets also have water, methane and ammonia as ices. Neptunian exoplanets often have clouds which block lots of light, but some planets have been found to have clear skies, such as HAT-P-11b. The primary set of Neptunian exoplanets include hot-Neptune, Ice giant and mini-Neptune. Examples include Gliese 436b and Kepler-138d.

4.2. Characterizing Exoplanetary Atmospheres

There are a vast number of processes taking place in an atmosphere. Atmospheres have different layers (Earth's has 4 different layers, each with different processes and properties) and each can be studied using different wavelengths of light and spectroscopic studies, as observed in figure 8. UV, Infrared and Optical each have different depths of penetration into the atmosphere which contribute to the characterization of exoplanetary atmospheres.

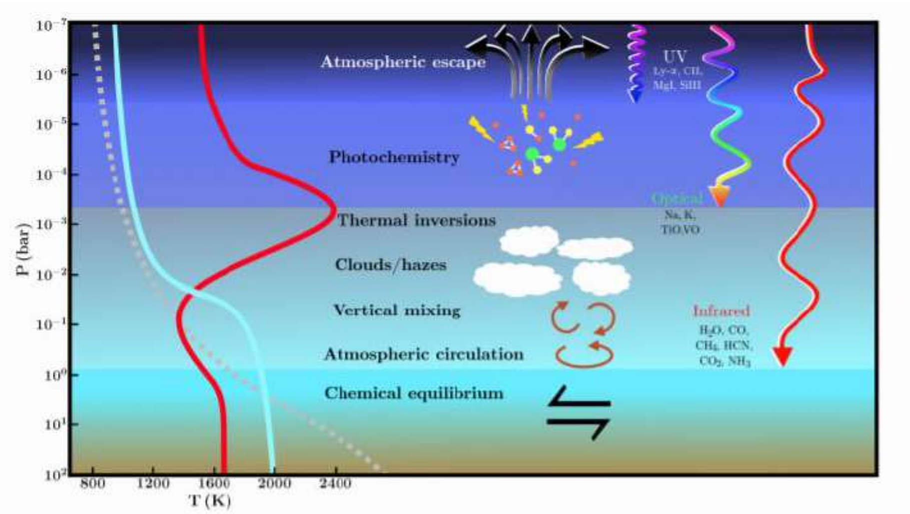

Figure 8: This figure shows the different penetration depths of light in an atmosphere. The lines on the left show thermal invasions. Each penetration depth of light corresponds to what each light is able to detect and understand in a planet's atmosphere. *Madhusudhan, N. 2019.*

There are different molecules and molecular and ionic species in different regions of the atmosphere. Understanding where they are located is necessary in characterizing the planet's atmosphere. Different molecules can absorb different wavelengths of light and some are observed best in a certain wavelength. Atomic and ionic species are best seen in the UV. Water, carbon monoxide and methane are some molecules observed in infrared light and for visible, titanium oxide is observed well (Madhusudhan, 2019). Ionic species are best detected in UV, because these atomic species and ionic species are present in the exosphere and regions where photochemistry occurs. As layers reach closer to the surface, there are different molecules and species present in that atmosphere. Infrared spectrographs report results of the presence of several species including ammonia, helium, hydrogen, methane and water.

Another major aspect of characterization is the detection of chemical abundances. As the name suggests, these are the abundances of certain chemicals relative to others in their surroundings or atmosphere. This provides details about potential biosignatures (See section 5.2) or general knowledge about a planet's composition. Within the detections of chemical abundances, there are observational constraints. Using different spectroscopic methods, we are able to determine an atmosphere's abundances. Transmission spectroscopy in NIR and visible, can identify between abundances and clouds. Several precise measurements are carried out to do so. Emission spectra, similarly differentiate between abundances and temperature profiles. Commonly detected abundances, are of H_2O and CO, in hot-Jupiters and other planets with certain observational bands in infrared. It is important to look at the climate of an exoplanet. Observing clouds/hazes, energy transfer, radiative properties and structure is important.

Radiation can be absorbed or reflected. Reflected radiation is in the form of longwave radiation as infrared rays, which can be absorbed by greenhouse molecules, hence diffusing across the atmosphere. Cooler, upper layers of the atmosphere release thermal energy to maintain an equilibrium with the absorbed shortwave radiation which heats up the ground (Cowan et al. 2015). Via this effect, a planet's climate can be determined using these radiative properties and looking at emitted heat.

Temperature structures propose details about radiative processes and chemical processes. Pressure-Temperature profiles are measured via thermal emission spectra. The spectra emit brightness in terms of temperature, and pressure/altitude with respect to the photosphere at that certain wavelength (Madhusudhan, 2019). Due to this factor, most P-T profiles are obtained via them on the dayside of primarily hot Jupiters. Based on how irradiated a planet a profile is obtain. It was observed from this study that irradiated hot Jupiters have thermal inversions, and the most irradiated showed isothermal profiles (This is a profile where temperature remains constant). These lay foundations for not only atmospheric characterization, but understanding whether planets are habitable, generally understanding the composition of atmospheres and looking at different types of climates across the universe.

Clouds also play an important role. Keeping radiation cycles aside, the presence of clouds results in observable temperature changes, and has weather effects as well. The detection of clouds made via transmission spectroscopy is done when their presence hides certain features of otherwise prominently detected molecules (Madhusudhan, 2019). There are other cases of observing clouds in reflection spectra and direct images (Using spectral features in the infrared) as well. Often, detecting H_2O molecules, as mentioned above, there may be a degeneracy between its detection and clouds. Using atmospheric retrieval methods and other studies, we can study about cloud fractions across a planet and cloud top pressure. Clouds themselves also have different compositions. In brown-dwarfs, clouds can be made up of aluminates and silicates as well (Crossfield, 2015).

Within atmospheric characterization there are other aspects such as atmospheric escape which is the loss of atmospheric gases escaping the atmosphere itself into outer space. Another aspect is atmospheric dynamics, which is a study of motion systems from a meteorological perspective. This looks at hurricanes, storms, tornadoes and jet streams.

5. Biosignatures and Habitability

A major aspect in exoplanetary sciences is the hunt for life. So far, we have minimal, if at all evidence for life outside Earth. A Biosignature is a sign of biological life in the form of a certain phenomenon or a molecule, isotope or element. Whereas habitability is a measurement or inference as to whether a planet may be able to support Earth life.

5.1. Habitability

The first step in knowing or inferring whether a planet is habitable is whether it is in the habitable zone of a planetary system. The habitable zone is an area where a planet allows water to be in its liquid form. This has to do with the size, brightness and temperature of a star, and the orbital radius, composition and size of the planet. Using existing knowledge, of the thousands of exoplanets discovered, a handful are rocky planets which are potentially habitable. Most habitable stars have been found to be orbiting low-mass stars (Late-K and Late-M type) to avoid having overly, blistering temperatures affecting where a habitable zone lies. Additionally, these types of stars offer excellent planet-star ratios in areas such as flux, it is easier to study their atmospheres and receive transmission spectra from them (Madhusudhan, 2019).

Firstly, looking at composition of the planet, there must be water. Second, there should be other substances suitable for life such as CO_2 and CH_4. Furthermore, determining whether the atmosphere is able to protect the planet from UV rays and is thick enough to allow us to breathe is essential. Additionally, atmospheric dynamics must be able to host an organism. If there are too many violent storms and endless cyclones, it does not make the planet liveable. Knowing the mass and temperature of the star, allows one to determine where the habitable zone lies. Studying the orbital radii of exoplanets determines if its in the habitability zones. Within our own solar system, once the sun expands and becomes a red giant, Europa (Moon of Jupiter) is predicted to fall into the habitable zone, and the frozen oceans of water, will melt and turn into liquid water.

Atmospherically, it is predicted that a planet is habitable if it has an N_2-CO_2-H_2O type atmosphere (Seager, 2013). It is estimated a habitable zone could lie in between 0.5AU to 10AU for planets orbiting a sun-like star or larger. Looking at water, it is majorly abundant in rocky planets, hot Jupiters and Neptunian objects. While claimed that water is present, its confirmation for abundances has not been done, hence denying whether any planet is truly habitable at this point (Tinetti et al. 2012).

The aforementioned paragraphs state that habitable zone varies based on sizes of the star and planet. In the TRAPPIST-1 star system, 3 of its planets are believed to be habitable. TRAPPIST-1 is only 0.089 solar masses, and has half the sun's surface temperature. TRAPPIST-1e has an orbital radius of only 0.02817AU. A result such as this shows that it is a ratio-based system when compared to Earth's habitable zone.

5.2. Biosignatures

Across the thousands of exoplanets studied, a biosignature has never been detected. Biosignatures apply several constraints which make them quite hard to detect. On Earth, the most abundant biosignatures are Oxygen, Ozone, Nitrous oxide and Methane (Madhusudhan, 2019. Seager, 2013).

Regarding the constraints applied by biosignatures, it is important to look at three areas. One, in the process of detecting biosignatures, there can’t be any false-positives. This means there can’t be an abiotic mechanism producing the indication. For example, while oxygen is a biosignature, it can still be produced by an effect of natural, non-living phenomena. Some naturally occur, without life such as water, carbon dioxide and nitrogen and some are produced geologically, like methane and hydrogen sulphide. Two, the signature must have the ability to be detected easily, indicating it is present and effectively proves the presence of an organism. Finally, it is important to make sure the biosignature is detected as a molecular/chemical abundance, which confirms the results and proves there are several organisms roaming the planet. Another constraint, but not a major one, is dependant on whether that organism produces the same biosignatures. It is also possible that the stellar environment affects the detection and number of biosignatures.

The search for life, is expanding constantly. While there is no defined evidence for extra-terrestrial life or a biosignature for that matter, there are many opportunities and the search has barely scratched the surface.

6. Conclusion

Exoplanetary sciences have several major goals, such as understanding details about planet, looking for life and many more. The evolution of receiving this knowledge has continuously grown since the first confirmed exoplanet discovery in 1992. Understanding the chemical composition of exoplanets have shown several unexpected bodies. There are many different types of planets and possible structures for planets. This paper has explored the detection of exoplanets using methods such as radial velocity and transit photometry which have explained to us tens of unknown variables of a planet. Spectroscopy has shown us different types of molecules and substances than can be present in exoplanetary atmospheres as well as how their atmospheres are composed and tell us about the chemical composition of exoplanets and different physical and chemical processes taking place in atmospheres. Despite these stellar limitations, these methods have grown to become efficient for current technology and the expanse of our knowledge.

Exoplanetary sciences are said to heavily evolve in the near future. The launch of new telescopes such as JWST, WFIRST and Starshade Rendezvous (Quanz et al. 2019). Each of these telescopes aim to observe different features and collect various sets of data, varying from direct images of planets to discovering potentially habitable exoplanets. Eventually, the launch of the Exo-Earth interferometer will be on the hunt for life in 2035.

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