Methods to Detect Habitable Atmospheres on the Terrestrial Exoplanet TRAPPIST-1 e

by

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Bachelor of Arts – Department of Astrophysical & Planetary Sciences

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Defense Copy

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Methods to Detect Habitable Atmospheres on the Terrestrial Exoplanet TRAPPIST-1 e

Thesis directed by Dr. Eric T. Wolf

In order to better direct future exoplanetary research, we must be able to accurately predict what telescopes like ~~JWST~~ will be able to detect. To this effect, NASA's Planetary Spectrum Generator can be used to simulate observations, both during exoplanet transits and at any time during an exoplanet's year. Such predictions allow us to ~~made~~ decisions about how to spend time on JWST and which techniques will allow for different types of science. In order to produce ~~accurate~~ results from the Planetary Spectrum Generator, climate models of the TRAPPIST-1 system are used to ~~understand how~~ atmospheres on tidally locked exoplanets might be different from ~~here on~~ Earth.

Climate model~~s~~ ~~run~~ by Eric Wolf indicate that there are two distinct types of exoplanet atmospheres; slow rotators and fast rotators. Slow rotators have large substellar clouds that remain constant over time. Fast rotators will have a significant Coriolis force, causing them to have much smaller substellar clouds ~~concentrated~~ to the east~~ern side.~~ Fast rotators therefore have an atmospheric emissivity that is dependent on the phase of its orbit, causing the total energy emitted by the planet to change relative to Earth over the exoplanet's year.

I have constructed a data pipeline that takes Eric Wolf's climate models as inputs, then send~~s~~ them to the planetary spectrum generator to produce spectra. This pipeline can use a number of climate models on a number of different planets and can be used to create transit spectra or thermal phase curves.

When studying terrestrial exoplanets, the most exiting cases are habitable planets. The TRAPPIST-1 system is currently the most intersting system, and TRAPPIST-1 e is likely the most habitable. The most effective methods for ~~detecting habitability from Earth~~ using JWST are the transit method and thermal phase curves. The transit method is the most popular method for

detecting exoplanets, and JWST will have high resolution spectrographs that will be able to detect many atmospheric species including CO_2 and H_2O. Additionally, accurate spectra ~~can~~ enable us to ~~determine~~ the partial pressure of CO_2 remotely.

Transit spectra can tell us a lot about the terminator profile of an atmosphere, but it cannot tell us about other parts of the planet's surface~~,~~ Thermal phase curves will observe the exoplanet over the course of its year, and ~~will~~ be able to detect ~~surface~~ features like the ~~shape~~ of the substellar cloud and ~~will~~ be able to detect if a planet has entered a runaway greenhouse effect or a ~~freezeout~~. Thermal phase curves will look dramatically different for fast rotators like TRAPPIST-1 e compared to slow rotators, and these results can only be simulated with global circulation models used in conjunction with line-by-line radiative transfer models. Future predictions for JWST should incorporate global circulation models into their predictions, and those models should be accurate to the exoplanets in question. Astronomers should also investigate thermal phase curves because they will be able to detect completely different features than transit spectra and will enable us to more effectively understand potentially habitable terrestrial exoplanets.

Dedication

To my Grandpa, Dr. Terry Flanagan

1938 – 2018

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Chapter 1

Introduction

Exoplanetary science is one of the most exciting fields in astrophysics, despite barely existing 20 years ago. Until the Kepler mission, it was thought that exoplanets were rare, but we have since estimated that approximately one third of F, G, and K stars have a terrestrial exoplanet (Traub, 2012). A majority of exoplanets are large gas giants that orbit extremely close to their host star, so called "Hot Jupiters." Although these planets are exotic and revolutionary for planetary formation theories, they couldn't possibly support life due to the lack of a surface and their extreme temperatures. More excitingly, we have found a number of terrestrial exoplanets which resemble Earth in mass, size, and most crucially, solar irradiance. These terrestrial exoplanets are the most likely candidates in the search for habitable worlds beyond Earth, and by extension, our most likely places to discover extraterrestrial life or a future home for humanity. To date, the list of exoplanets in the classical habitable zone is short, and few are close to Earth, but this will soon change with the recently launched Transiting Exoplanet Survey Satellite (TESS). TESS is expected discover thousands of exoplanets smaller than Neptune and dozens of Earth sized planets, and was optimized for finding planets that are closer to Earth (Ricker et al., 2014). In conjunction with the James Webb Space Telescope (JWST), we expect to have precise observations on a number of potentially habitable worlds in nearby star systems.

Exoplanets are likely tidally locked due to their close orbit to their host star (Turbet et al., 2018), meaning they don't rotate relative to their star. Tidally locked planets have a substellar point, which always gets direct sunlight, a terminator, which gets a perpetual sunset, and an antistellar side, which never receives direct sunlight. Our solar system contains no example of such a planet. Tidally locked planets behave so differently from any atmosphere ~~we've seen before,~~ that the only way to characterize their atmospheres is via global circulation models (GCMs). GCMs were invented for purposes like predicting the weather or climate change, and have proven useful for a number of different planets throughout the solar system (Way et al., 2018). Many astronomers have made predictions of what JWST will see on exoplanets, but most of these predictions assume that an exoplanet atmosphere can be similar to that of Earth (Fortney et al., 2018). However, ~~these~~ ~~models~~ demonstrate that exoplanets are very different than ~~what we would expect from~~ the Earth. For example, an exoplanet that receives approximately the same amount of sunlight as Earth, TRAPPIST-1 d, is less likely to be habitable than TRAPPIST-1 e, a planet that receives only 60% of the solar irradiance of Earth (Wolf, 2017).

With the launch of JWST on the horizon, it is essential that we know what to expect from our observations with it, and atmospheric models are our best method of putting constraints on our expectations. Simply assuming a tidally locked exoplanet will behave like Earth is unreasonable and can lead to inaccurate conclusions. Using GCMs for TRAPPIST-1 d, e, and f provided by Dr. Eric Wolf, we can ~~accurately predict~~ what the TRAPPIST-1 exoplanets ~~will~~ look like with regards to clouds features, distributions, precipitation, and temperature. NASA's Planetary Spectrum Generator (PSG) can generate spectra for these climate models, giving us accurate predictions of what JWST might be able to see (Villanueva et al., 2018). Using the PSG, we can determine which spectral features would be detectable with JWST and using signal to noise analysis, we will help the astrophysics community prioritize their time with JWST.

In addition to exoplanet spectra, GCMs allow us to study exoplanets using other methods, most notably thermal phase curves. A GCM provides global resolution of an exoplanet's surface and atmosphere, but only a small fraction of it is visible via the transit method. The PSG can allow us to measure the thermal emission of the surface of the planet as it rotates relative to the Earth over its year. Thermal phase curves measure the change in thermal brightness of an exoplanet as it orbits its star, and can be variable over time in a way that could be detected with JWST.

Thermal phase curves have the advantage of strong signal to noise due to large binning and long observation times. This technique serves as our best method of resolving ~~surface~~ features like clouds on exoplanets, and by extension, the planet's climate. Thermal phase curves and transit spectra provide two very unique methods of probing an exoplanet's atmosphere, and together, they will help JWST find habitable worlds beyond Earth.

In this thesis, I will ~~use GCMs to predict~~ both transit spectra and thermal phase curves several exoplanets, particularly TRAPPIST-1 e. In the following section, Chapter 2, I will explain the fundamentals of exoplanet research and exoplanet observations, with an emphasis on the variables significant to thermal phase curves and transits. In Chapter 3, I will show ~~Eric Wolf's~~ climate models, and particularly focus on the terminator atmosphere profile and the global cloud patterns. I will compare fast rotators, which have smaller clouds formations, and slow rotators, which have large, permanent cloud patterns, which is foundational to our results using thermal phase curves. In Chapter **??**, I will explain the data pipeline used and the PSG as a tool to simulate spectra. In Chapter **??**, I will show transit spectra results, analyze their behavior, and identify and measure prominent features. In Chapter **??**, I will do the equivalent analysis for thermal phase curves, and compare slow rotators versus fast rotators here. In Chapter **??**, I will conduct a noise analysis, and compare the signal to noise ratios of transits and thermal phase curves.

Chapter 2

Background

Isaac Newton was the first person to consider the possibility of exoplanets (Newton, 1846). It requires little more than a simple understanding of the solar system and Newtonian physics to consider the possibility that other stars may host their own planets. Any planet orbiting any star must obey Newton's version of Kepler's 3rd law,

$$T^2 = \frac{4\pi^2}{G\left(m_* + m_p\right)} a^3, \tag{2.1}$$

where T is the orbital period of the orbit, a is its semi-major axis, m_* is the mass of the star, and m_p is the mass of the planet. In addition, the small mass approximation where $m_* >> m_p$ simplifies equation 2.1 to

$$T^2 = \frac{4\pi^2}{G m_*} a^3, \tag{2.2}$$

which we can solve, even if the mass of the planet is unknown. If the orbital period of an exoplanet and the mass of the host star are known; the planet's semi-major axis can be calculated. Using the semi-major axis, the planet's solar irradiance can be calculated with

$$S_p = \sigma T_*^4 \frac{r_*^2}{a^2}, \tag{2.3}$$

where S_p is the solar irradiance for the exoplanet. This value can be calculated using only a few data points, and can be compared to the solar irradiance of Earth ($S_\oplus \approx 1361\,\mathrm{W\,m^{-2}}$). A simple narrative would be that if the $S_p \approx S_\oplus$, then the planet is Earth-like. This understanding defined exoplanetary knowledge for hundreds of years, and very little progress was made for a long time because of observational limitations.

The most traditional method for detecting an exoplanet is by directly imaging them, just like we do for stars; however, the math behind this isn't very promising. If a blackbody's flux is proportional to R^2T^4, then a 300K exoplanet with a radius of $1R_\oplus$ around a 3000K star with a radius of $0.17R_\odot$ would be $1/10,000,000^{\text{th}}$ as bright, which corresponds to a difference in 16 magnitudes. While observing two stars 16 magnitudes apart is certainly possible in optimal circumstances, it is virtually impossible to do in the case of exoplanets because an exoplanet and its host star are almost always within the diffraction limit of each other. Telescopes large enough to detect an exoplanet have existed for over a hundred years, but the primary limitation has always been the instrumentation. A photometric plate could never have detected an exoplanet.

This changed with the introduction of a type of digital camera called a CCD, where accurate photometry of dim objects can be done in minutes, not hours. Astronomers were now able to detect exoplanets with a new method, not by measuring the brightness of the planet, but by measuring the change in the brightness of the star. In 2003, the first exoplanet was detected by measuring the decrease in the star's brightness as the planet passed in front of its host star (Konacki et al., 2003). This became known as the "transit method," and to date, this method has detected more exoplanets than any other. The transit method only requires simple photometry, which can be done with significantly higher signal to noise than spectroscopy. Transits are usually found using relative photometry, meaning the brightness of a star during transit is compared to the brightness of other stars in the field. This means that measurements can be accurate despite the presence of systematic errors. In a transit, the measured signal is the decrease in the brightness of the star relative to its normal brightness, so the measured value is called transit depth, and can be given by

$$D = \frac{R_p^2}{R_*^2}, \tag{2.4}$$

where D is the transit depth, R_p is the planet radius, and R_* is the star radius. Using the above example of a $1R_\oplus$ planet around a $0.17R_\odot$ star, the transit depth would be 0.0028, or $3/1000^{th}$ the brightness of the star, which can be measured fairly reliably. The most observable exoplanets are large planets around small stars. Small stars are less likely to drown out the signal of a planet, and large planets are likely to create larger signals. A large planet around a small star would have a large transit depth. It is worth noting that transit depth is usually reported in parts per million (ppm) instead of as a decimal, as it will for the remainder of this thesis.

Other exoplanet detection methods have developed, such as gravitational lensing, radial velocity, and astrometry. However, all of these methods are fairly limited in both efficiency and scope. However, it is worth noting that the radial velocity method has become a very useful tool of measuring masses of planets that have already been detected via the transit method. With a combination of the two, planetary radius, mass, orbital distance, and solar irradiance can all be measured.

Unfortunately, there are some major limitations to the transit method. The most exciting exoplanets are terrestrial exoplanets are approximately $1R_{\oplus}$, approximately $1m_{\oplus}$, and have approximately $1S_{\oplus}$. For these planets in particular, the transit method has proven to be the most effective method. However, for large stars, smaller planet become impossible to detect as their transit depth is too small. With even the best scopes, it would be impossible to detect exoplanets around Sun-like stars. The Earth-Sun system has a transit depth of 84ppm, but we can barely see exoplanets with depths of 1000ppm. Another major limitation is that only a small number of exoplanets orbit in an observable plane. If we assume that an exoplanet can orbit in any random plane relative to Earth, and we can only detect it if its orbital plane is within $3°$, then $\sim 3\%$ of exoplanets can be detected from Earth. In reality, the actual cutoff of an "in plane" exoplanet is more complicated and depends on a number of other variables, but $3°$ is a good first-order estimate. Our ability to detect smaller transit depths will improve over time, but the inclination issue is an inherent limitation to the transit method. Only transiting exoplanets will be considered for the remainder of this thesis. It is worth noting that the conclusions made with transiting exoplanets can be easily generalized for non-transiting exoplanets because there is nothing unique about a transiting system other than its relation to Earth.

For transiting exoplanets, there are a few coordinate conventions that must be described explicitly. Firstly, there was the previously mentioned issue of the coordinate plane in which a planet rotates. The angular difference between the orbital plane and Earth is called the *inclination*, denoted here by θ. A visual example of inclination is given in Figure 2.1. There is also the position of the exoplanet in its orbit, which is called *orbital phase*. Conventionally, the phase where an exoplanet is perfectly behind its host star is set to $0°$ (an occultation, or sometimes a type-II transit), and the phase where an exoplanet is perfectly in the middle of a transit is set to $180°$ (also called a type-I transit). A visual explanation of phase is given in Figure 2.2. Surprisingly, it doesn't matter which direction the exoplanet orbits in as long as the convention is consistent. In this paper, the orbital phase will be called ϕ and will be to the left for $0° \leq \phi \leq 180°$ and to the right for $180° \leq \phi \leq 360°$

As has already been alluded to, a majority of exoplanets are found around small stars, mostly K-type and M-type stars. These stars are far redder than Sun-like stars, and emit far less light. This means that in order for a planet to receive similar TSI to Earth, it must be much closer to its parent star. Exoplanets are likely to be tidally locked, meaning that they rotate synchronously with their parent star. The Moon is tidally locked to the Earth, which is why we always see the same face of the Moon. In the case of the Moon, it still rotates relative to the Sun, ~~which means it will have roughly even surface temperatures~~. With exoplanets that are tidally locked relative to their parent stars, one half of the planet will get constant sunlight, and another side of the planet will never receive Sunlight. In this situation, a new set of useful terminology must be used to describe points on the planet. The point that is always facing the Sun is the substellar point. The point that is opposite to the substellar point is the antistellar point. The line that is equidistant from the substellar and antistellar point is called the terminator. The substellar point is equivalent to Earth at noon, when the sun is directly overhead; the antistellar point is equivalent to the Earth at midnight; and the terminator is equivalent to the Earth at Sunset and Sunrise.

Any point on a spherical object can be defined using two angles, and the most standard convention is latitude (δ) and longitude (λ), where the equator is defined as $\delta = 0°$, the North Pole is $\delta = 90°$, and the South pole is $\delta = -90°$. Longitude ranges from 0 to 360, and on Earth, the "zero point" is completely arbitrary~~, but for~~ tidally locked planets, the zero point ~~can~~ be conveniently aligned with the antistellar point, so the substellar point is at $(\lambda = 180°, \delta = 0°)$.

Of all the exoplanets discovered, the TRAPPIST-1 system ~~seems to be the most likely to support life~~. Around the star TRAPPIST-1, there are 7 exoplanets, named alphabetically from b to h. They are all roughly $1m_\oplus$ and $1R_\oplus$. TRAPPIST-1 is a very cool M-dwarf with a temperature of 2511K, at a distance of 12pc from Earth. TRAPPIST-1 b has a TSI of $3.8\text{S}_\oplus$, which is by any measure, too hot for anything even remotely close to life. TRAPPIST-1 h on the other end has a TSI of $0.13\text{S}_\oplus$, which must be far too cold to support life. Since both ends of the spectrum are covered, it's reasonable to hope that somewhere in the middle, one or two of the remaining 5 are similar enough to Earth to support life.

Using the work done by Turbet et al. (2018), it is reasonable to conclude that all the TRAPPIST-1 planets are tidally locked and have an eccentricity low enough to approximate it as 0. With the known parameters of the TRAPPIST-1 system found by Gillon et al. (2017), the next logical step is to run climate models to more accurately estimate habitability.

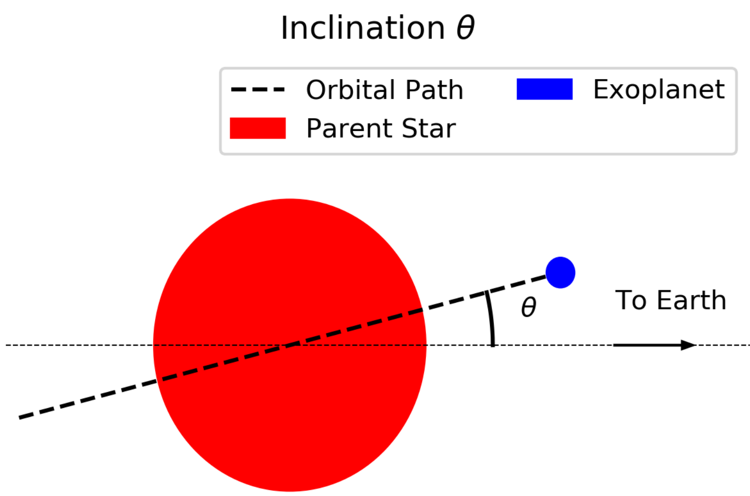

Figure 2.1: Simple depiction of inclination. Any possible exoplanet can be viewed from this angle, making inclination a universal tool for characterizing exoplanets. Typically, an exoplanet with an inclination of less than 3° can have a transit, although this isn't the most rigorous definition, and the actual value depends on planet size and star size. However, the closer to 90°, the better because that means longer transits and therefore better measurements.

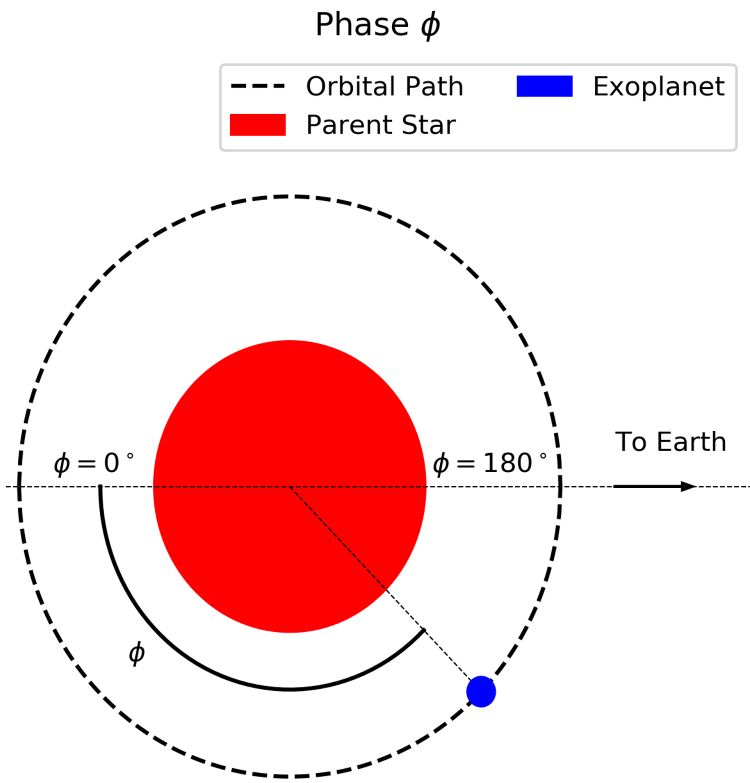

Figure 2.2: Simple depiction of phase. In this diagram viewing from above, phase first goes down, then up. The convention of phase can be defined relative to transits and occultations, and regardless of the direction of this convention, the math behind which latitudes face Earth remain constant.

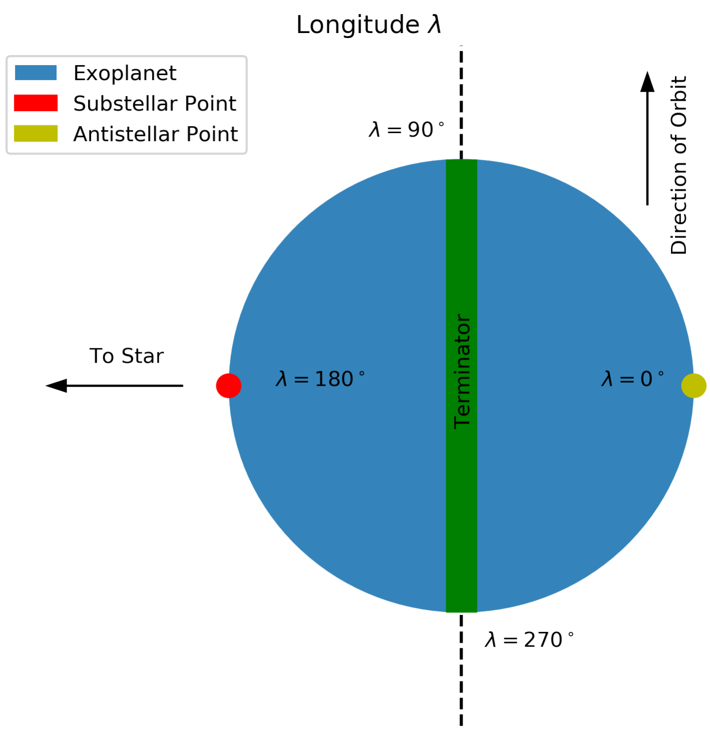

Figure 2.3: Simple depiction of longitude for a tidally locked planet. These longitudes are correct for any phase or inclination. Note that from Earth during a transit $\lambda = 0°$ when $\phi = 180°$, and they move in opposite directions.

Chapter 3

Climate Atmosphere Models

Al~~though I did not run any climate models myself, different atmospheric parameters will have dramatic impacts on transit spectra and thermal phase curves.~~ Therefore, it is important to ~~establish~~ the results of Eric Wolf's climate models in order to adequately understand any observation simulations derived from them. Many of the conclusions discussed here will have significant impacts on later sections. Transit spectra is sensitive to the atmospheric composition, and in order to characterize that sensitivity, many climate models with varying parameters must be tested. For thermal phase curves, ~~surface structures like~~ cloud are important. Climate models allow us to predict the ~~shape~~ of clouds in the TRAPPIST-1 system, giving us insight into what we would see from a thermal phase curve. Cloud distributions depend on the strength of the Coriolis force, which is determined by the rotational rate of the exoplanet.

Climate models have proven to be a very useful tool to accurately predict behavior of an atmosphere. A climate model uses fundamental physics like radiative transfer, convection, the Coriolis force, and other rules to predict the motion of air parcels iteratively through time. One ~~of the most~~ popular climate model~~s~~ is the ~~NOAA~~ ~~Climate Atmosphere Model 5 (CAM5)~~ (Neale et al., 2012). Using a modified version of ~~CAM5~~, Wolf (2017) was able to apply climate models to the tidally locked exoplanet of the TRAPPIST-1 system including TRAPPIST-1 d, TRAPPIST-1 e, and TRAPPIST-1 f. All of the climate models for TRAPPIST-1 d entered a runaway greenhouse, even in models without CO_2. ~~All of the models for TRAPPIST-1 f were extremely cold, even with extreme amounts of CO_2.~~ ~~TRAPPIST-1 e had several models which were very habitable, making~~

TRAPPIST-1 e the most promising candidate of the system for supporting life~~,~~ Although other cases will be considered, this paper will focus primarily on ~~the climate models run for~~ TRAPPIST-1 e.

Climate models can be used to determine the impacts of a variety of species in the atmosphere. In these models, fixed amounts of CO_2 and N_2 were given, ~~and~~ H_2O ~~varied over time~~ as determined ~~internally inside~~ ~~CAM5.~~ CO_2 will always tend to warm an atmosphere. This tendency ~~is known as~~ the greenhouse effect, and only molecules with 3 or more atoms will contribute to the greenhouse effect directly because they contain vibrational modes which can store energy levels that correspond to infrared wavelengths. 2-atom molecules like N_2 cannot contain vibrational modes, and thus cannot absorb or emit infrared light. However, adding N_2 to an atmospheric model will increase the pressure, which can impact the absorption of infrared light by CO_2~~.~~ Unlike atomic emission features, which absorb and emit at discrete wavelengths, molecular emission features are broad, and although they peak at a fixed wavelength, they will emit or absorb light for a large range of wavelengths around the peak wavelength. Increasing the pressure of a greenhouse gas has the tendency to broaden this emission feature, and therefore increase its efficacy as a greenhouse gas. For this reason, adding N_2 to an atmosphere can also increase the atmosphere's average temperature. H_2O, like CO_2, is a greenhouse gas and exhibits pressure-broadening behavior. More importantly, H_2O is not well mixed in an atmosphere, and may condense in liquid clouds, ice clouds, or vapor~~.~~ ~~The primary advantage of running a 3D climate model is to understand where~~ ~~H_2O~~ ~~will reside and what state it will be in, as well as its impact on warming.~~

A number of climate models have been run, and recently, Wolf has included CH_4, which is a stronger greenhouse gas than CO_2 or H_2O. All of the climate models are shown in Table 3.1. Of this list, many of the ~~atmospheric parameters~~ for TRAPPIST-1 e ~~are uninhabitable, due to a surface temperature that is either far too low or far too high~~. The Earth's mean atmospheric temperature is ~300K (Wang et al., 2005), and some of the models are able to get similar temperatures. From this list, the most interesting models are the 1barN_2, 0.2barCO_2, and 1barN_2, 0.4barCO_2 because they have ~~the most moderate terminator temperatures,~~ although some others also stand out as strong candidates for habitability.

Despite what Table 3.1 and Figure 3.1 suggest, habitability can be very complicated to define. Most of the details about habitability are questions of biology, ~~like how much CO_2 or CH_4 is safe in an atmosphere~~. Many finer details about habitability cannot be answered by these models due to many fundamental assumptions made in the construction of these models. All of these models use a global ocean but ignore ocean currents, which is a major method of heat transport. Many significant atmospheric species like O_2, O_3, N_2O, and others aren't included, despite their obvious significance in Earth's atmosphere. CO_2 abundance is set as a model parameter, but in reality, its abundance would be driven by geologic processes over timescales much longer than where CAM~~5~~ would be useful ~~(Neale et al., 2012).~~

In addition to climate models, many equations useful for Earth's atmosphere can help us describe the TRAPPIST-1 system. Anthropogenic climate change on Earth was predicted by Dr. Svante Arrhenius, who created an effective equation to predict the warming of an atmosphere, given an increase in CO_2. Arrhenius' rule is given as

$$\mathrm{T} = \alpha \ln\left(\frac{\mathrm{C}}{\mathrm{C}_0}\right) + T_0$$

where C is the current amount of CO_2 in the atmosphere, C_0 is the former amount of CO_2 in the atmosphere at a given time, and T_0 is the global atmospheric temperature at that time, α is a constant that depends on a number of things not considered in this model. For TRAPPIST-1 e, this equation can be very useful. In Figure 3.1, it can produce a reliable best fit line. A similar fit can be made for increasing N_2, and is shown in Figure 3.2.

So far, I have only examined the mean temperature of the terminator. For the purposes of transits, this is the only significant section of the atmosphere, but for thermal phase curves, spatial resolution is a necessity, largely due to the presence of a substellar cloud (Kopparapu et al., 2017). CAM~~5~~ models the atmosphere using a discrete number of points, making a 3D array of coordinates ~~where. There~~ are 72 longitudinal bins, 46 latitudinal bins, and 40 vertical bins. Each attribute of a model like temperature, cloud amount, etc. all have their own data cubes. In order

N_2 bar	CO_2 bar	CH_4 bar	H_2 bar	Surface Temperature K
0	0.25	0	0	221.1
0	0.5	0	0	257.3
0	1	0	0	298.5
0	2	0	0	332.3
0.9	0	0	0.1	217.9
1	0	0	0	207.5
1	0.0004	0	0	221.9
1	0.0004	1.7×10^{-6}	0	225.2
1	0.01	0	0	242.4
1	0.1	0	0	267.0
1	0.2	0	0	279.1
1	0.4	0	0	298.8
1	1	0	0	330.1
1.5	0.1	0	0	280.8
1.5	0.2	0	0	294.4
2	0.1	0	0	286.3
2	0.2	0	0	307.0
4	0.1	0	0	319.9
4	0.2	0	0	332.4
10	0.2	0	0	358.2

Table 3.1: TRAPPIST-1 e Models and Species Abundances. Each row represents a single climate model of TRAPPIST-1 e, with each column showing the amount of a given species in that model. The surface temperatures are an average of the 3 longitudes closest to the terminator.

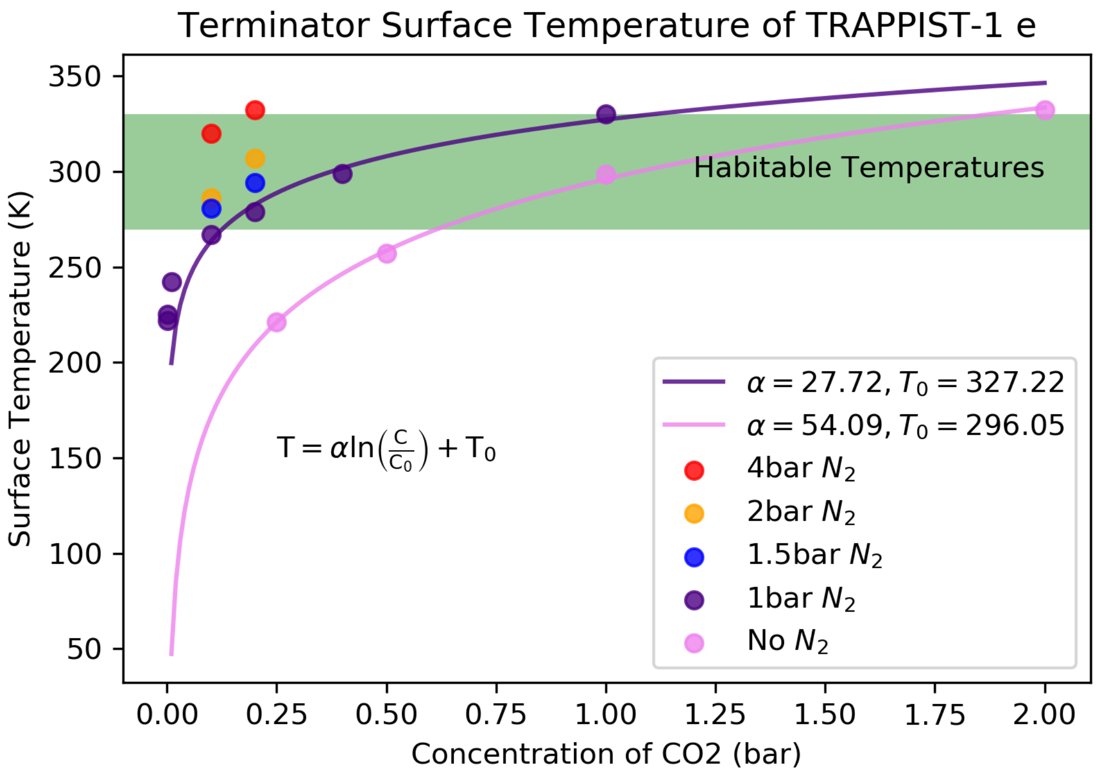

Figure 3.1: Terminator surface temperature versus CO_2 partial pressure. Most of the models in Table 3.1 are shown here to more accurately demonstrate the relationship between CO_2 and warming. Both CO_2 and N_2 can contribute significantly to the warming of the planet, but they do so differently because N_2 is not a greenhouse gas. In this diagram, the "habitable zone" is between ~~290K and 310K~~, but there is no rigorous math behind that range. It is just a general estimate of where the most likely habitable worlds would likely be.

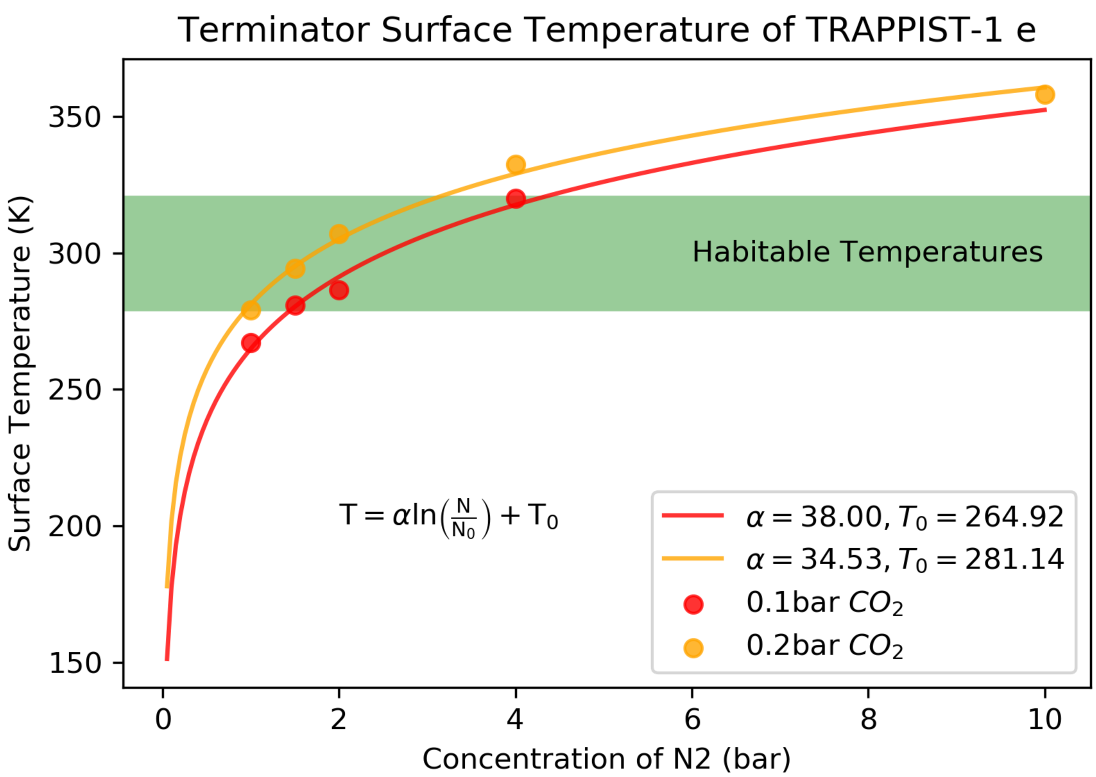

Figure 3.2: Terminator surface temperature versus N_2 partial pressure. Similarly to Figure 3.1, logarithmic best fit lines match the data well, although the fit is noticably better for CO_2 than N_2.

to display the data, it must be reduced from a 3D set. A useful method of displaying data like cloud abundance is using a column density. Each vertical layer of the atmosphere has a different cloud abundance, but we're mostly concerned with the total cloud abundance, which would be the sum of all the different layers. This more closely represents what the clouds would look like from a distant observer. Figures 3.3 and 3.5 are both column densities of liquid cloud abundance and precipitation.

Since ~~exoplanets~~ are tidally locked ~~and~~ ~~don't~~ have a ~~day-night~~ cycle, ~~one might assume that they wouldn't have a strong Coriolis force, which depends on the rotational frequency of the planet.~~ The acceleration due to the Coriolis force is given as $a_C = 2\mathbf{v} \times \mathbf{\Omega}$, where $\mathbf{v}$ is the velocity of a particle and $\mathbf{\Omega}$ is the rotational frequency of the planet. Earth has a rotational frequency of $2\pi/24$hr, so the Coriolis force plays a major role in atmospheric physics. TRAPPIST-1 e has no rotation relative to the ~~sun~~, but because its year is only 6 days (Gillon et al., 2017), it will have an angular frequency of $2\pi/6$d, which is significantly less than Earth's, but still strong enough to ~~be significant~~. The effects of TRAPPIST-1 e's Coriolis force can be clearly seen in Figure 3.3. The substellar cloud is fairly small, and is concentrated to the east, while the western substellar point has little to no clouds.

Kopparapu et al. (2017) has run models on other exoplanets ~~with Eric Wolf~~, including some ~~imaginary~~ exoplanets ~~with idealized~~ parameters such as stellar temperature and orbital period. These models can easily be put into two categories, fast rotators and slow rotators. An extended orbital period means that the Coriolis force is much weaker, which produces a completely different shape for its substellar cloud. ~~Almost half the planet~~ is covered by clouds, and the substellar cloud is fairly symmetric from the east and west. According to Kopparapu et al. (2017), the boundary between a fast rotator and a slow rotator is between 7 and 20 days. Fast rotators like TRAPPIST-1 e have small substellar clouds, concentrated to the east. Slow rotators (like the 44 day one shown in Figure 3.4 have large substellar clouds that are highly symmetric and cover most of the planet's day side.

In addition to surface features, one of the most useful tools to describe a planetary atmosphere

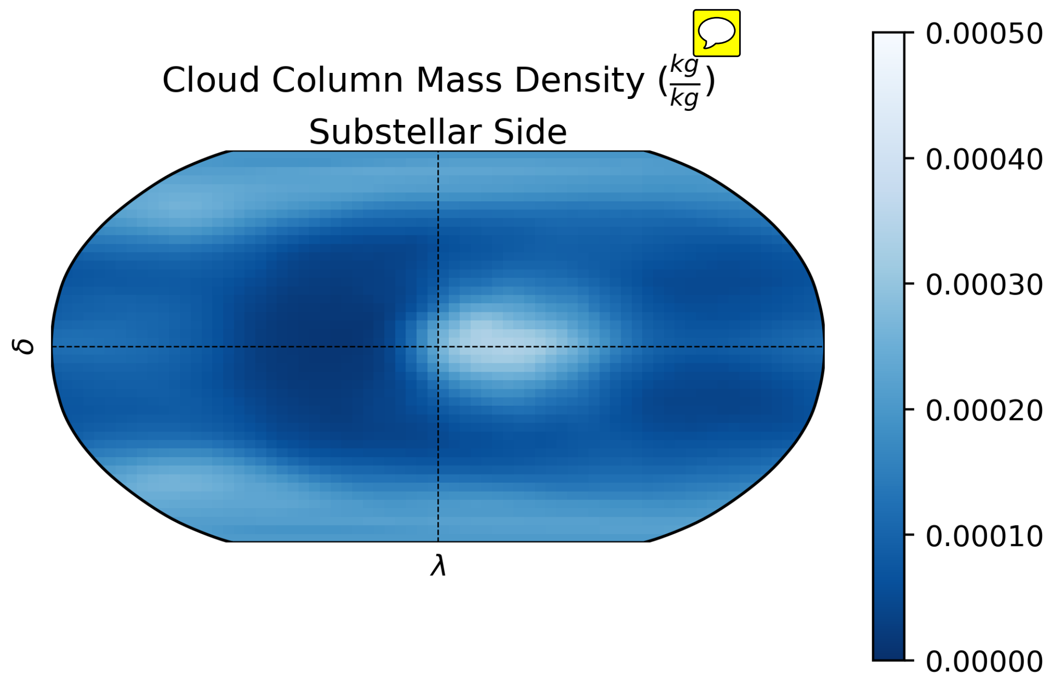

Figure 3.3: Cloud Column Density of TRAPPIST-1 e with 1bar N_2 0.4bar CO_2. In this image, white represents very dense clouds, and blue represents few to no clouds. For the substellar point, there are strong clouds, particularly on the eastern side. Surprisingly, right next to the substellar point is also the region with the least amount of clouds. This is due to the planet's rotation, which causes a Coriolis force that produces asymetric substellar clouds. In CAM5, clouds are measured as mass densities of the cloud particle mass in each grid point divided by the total mass inside that grid point, which is where the units of $\frac{kg}{kg}$ come from. When summing the column, the units don't change.

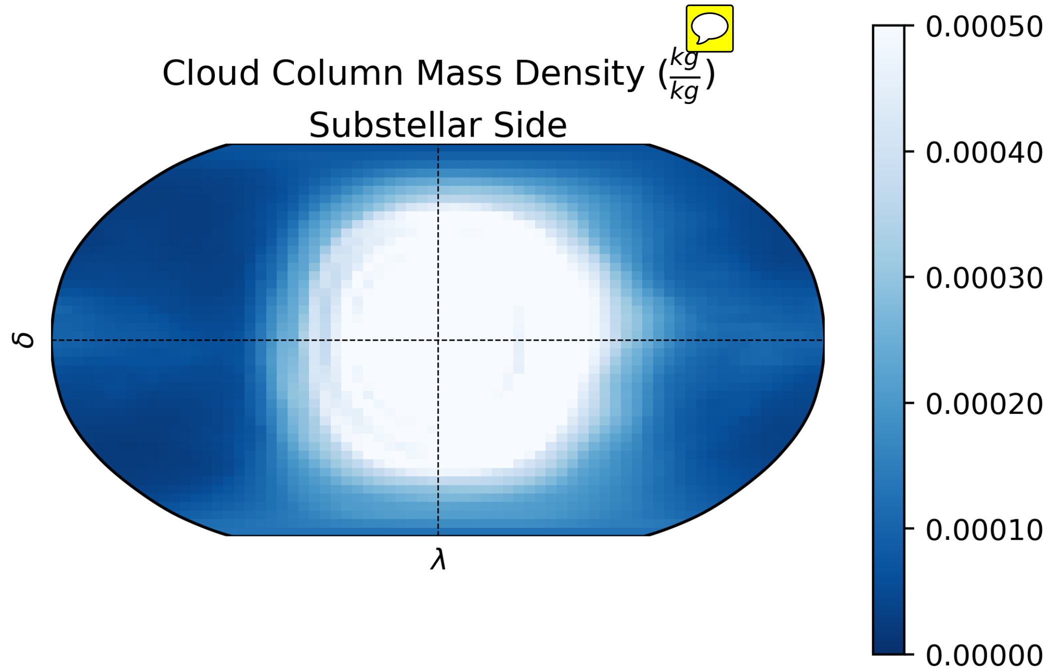

Figure 3.4: Cloud Column density of a slow rotator. The planet used here is a slow rotator with an orbital period of 44 days. In this case, it received significantly more solar energy from TRAPPIST-1 e, which will cause it to be extremely warm and therefore have much stronger clouds than TRAPPIST-1 e. The absolute scaling of the cloud amount is less important than the shape of the clouds. Here, the clouds are extremely symmetrical and large. This is a dramatic difference from the behavior of the TRAPPIST-1 e model in Figure 3.3.

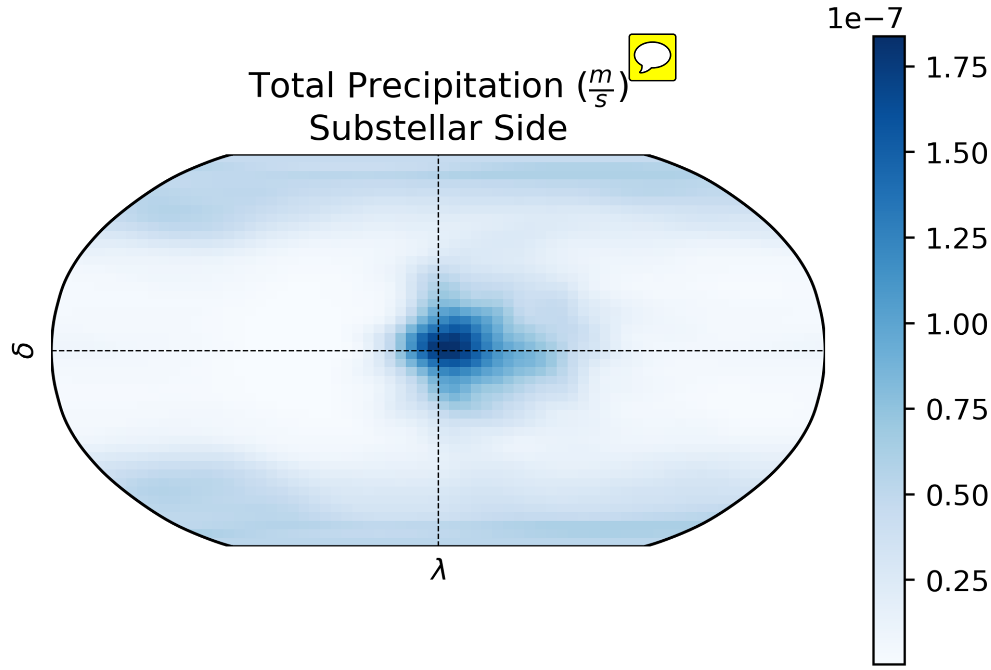

Figure 3.5: ~~Total Column~~ Precipitation of TRAPPIST-1 e with 1bar N_2 0.4bar CO_2. In this image, blue represents high amounts of precipitation and white represents little to no precipitation. From Figure 3.3, we can conclude there is a persistent substellar cloud, but in order to determine if there's actually rain reaching the surface, one must also check its precipitation since the presence of clouds doesn't always mean there must be rain. There does appear to be very localized substellar rain indicated by the blue dot, but the rest of the planet only has marginal amounts of rain in comparison.

is its profile. During an exoplanet transit, light will pass through the atmosphere, and the lower atmosphere will be too opaque, and little light will make it through, but the upper atmosphere will be much less dense, allowing more light through. This means that atmospheric features that are close to the planet's surface would be much harder or impossible to detect compared to upper atmosphere features. According to Figure 3.6, a majority of the clouds are concentrated in the lower atmosphere, meaning that H_2O will be harder to see in an exoplanet transit than CO_2 which is well mixed at all levels of the atmosphere. From Figure 3.6, a thermal inversion close to the surface can also be seen, meaning that the temperature goes up with height for a brief period. This has the effect of stabilizing the atmosphere and on Earth, can cause pollution to be trapped near the surface (Fortelli et al., 2016). In this plot, the effective temperature is given, which is what the temperature of the planet's surface would be if it had no atmosphere, and is given by the equation

$$\mathrm{T}_e = \sqrt[4]{\frac{\mathrm{S}(1-\alpha)}{4\sigma}}$$

where T_e is the equilibrium temperature, S is the solar irradiance, α is the albedo, and σ is the Stefan-Boltzmann constant. The shape of an atmosphere's profile is significant for a

While these models are extremely illustrative of many details about the TRAPPIST-1 e atmosphere, there are a number of noteworthy assumptions that limit our understanding. These models don't include O_2, which is a vital element for living organisms. Adding O_2 would dramatically complicate the models because it would require the addition of O_3 as well, a major greenhouse gas and the primary species in the stratosphere. These TRAPPIST-1 e models ~~don't~~ include a stratosphere, which would be a second thermal inversion higher up in the atmosphere. These models are long term models run over 40 years, and they only have enough resolution to determine general surface features. Unlike a weather forecast model; these models cannot accurately predict small weather features in the TRAPPIST-1 e atmosphere, the models are only useful for general, long-term trends. These climate models ~~don't~~ include any trace atmospheric species, most notably N_2O, but there are many more species that could be detected during a transit from a telescope.

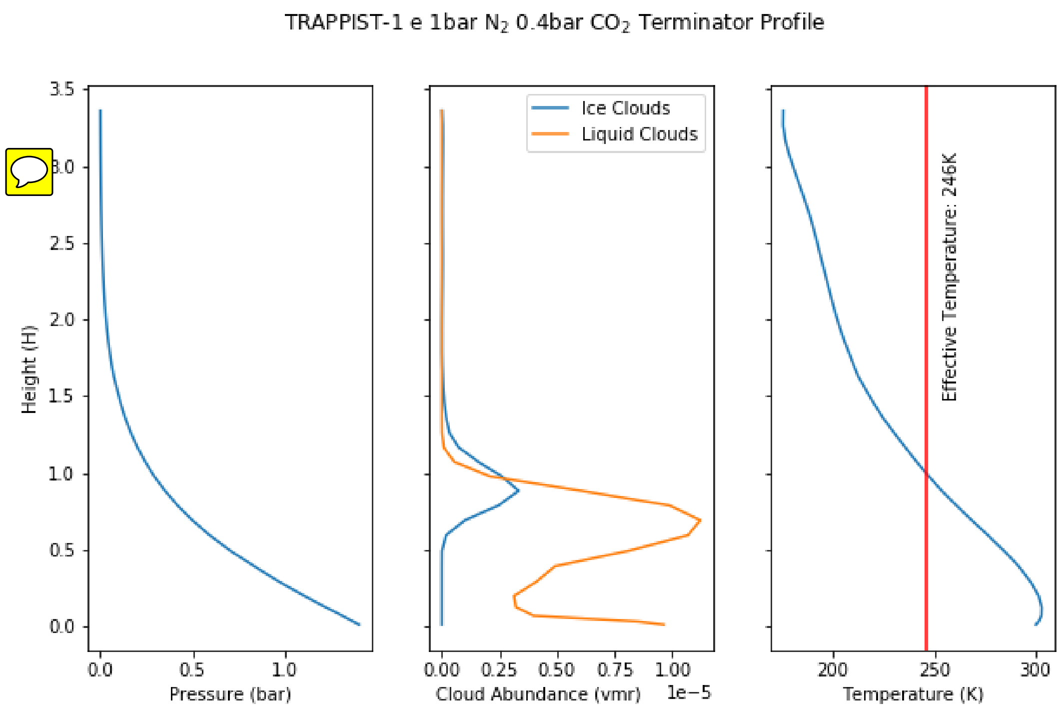

Figure 3.6: Profile of TRAPPIST-1 e with 1bar N_2 0.4bar CO_2.

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