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

by

D. Gatlin

Bachelor of Arts – Department of Astrophysical & Planetary Sciences

Undergraduate Honors Thesis

Defense Copy

Thesis Defense Committee:

Eric T. Wolf	Advisor	Atmospheric and Oceanic Sciences
Prof. Ann-Marie Madigan	Honors Council Representative	Astrophysical and Planetary Sciences
Prof. David Brain	External Faculty Member	Astrophysical and Planetary Sciences
Prof. Daniel Jones	External Faculty Member	Arts and Sciences Honors Program

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Methods to Detect of Habitable Atmospheres on the Terrestrial Exoplanet TRAPPIST-1 e
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has been approved for the Department of Astrophysical and Planetary Science

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Dr. Eric T. Wolf

Prof. Ann-Marie Madigan

Prof. David Brain

Prof. Daniel Jones

Date ____________________

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Gatlin, D. (B.A., Astrophysics)

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

Thesis directed by Dr. Eric T. Wolf

Often the abstract will be long enough to require more than one page, in which case the macro "\OnePageChapter" should *not* be used.

But this one isn't, so it should.

Dedication

To my Grandpa, Dr. Terry Flanagan

Acknowledgements

In the fourth grade, I received a book on astronomy for Christmas. This book started me down the path I'm now on. To this day, I don't remember who gave me the book, only that they were in my extended family. Ever since then, I've been dedicated to a career in astropysics. It would not have been possible without the early support of my family and my father, who acquired a small telescope that we often used on the roof.

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Introduction

Exoplanets 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 $\sim 1/3^{rd}$ of F, G, and K stars have a terrestrial planet(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, they couldn't possibly support life. 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 launch of the 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.

It is known that exoplanets are likely to be tidally locked, 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. 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. However, these 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. These models have demonstrated that exoplanets are very different than what we would expect from the Earth, and 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 atmosphere 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, accurate predictions can be made about what these exoplanets look like. With these models, in conjunction with NASA's Planetary Spectrum Generator (PSG), spectra can be generated for exoplanets, giving us accurate predictions of what we will be able to see using JWST(Villanueva et al., 2018). Using this transit simulator, analysis can be done on the observable spectral features that JWST can detect, and signal to noise analysis will help the astrophysics community help 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, allowing for much more than a transit profile. 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. So-called thermal phase curves measure the change in thermal brightness of an exoplanet as it orbits its star, and can be variable 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, I will explain the background of exoplanet research, with an emphasis on the variables significant to thermal phase curves and transits. In section 2, 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. In section 3, I will explain the data pipeline used and the PSG as a tool to simulate spectra. In section 4, I will show transit spectra results, analyze their behavior, and identify and measure prominent features. In section 5, I will do the equivalent analysis for thermal phase curves, and compare slow rotators versus fast rotators here. In section 6, 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. Once he understood the concept of orbital mechanics and how a planet must orbit and that stars just like the Sun, but further away, it becomes intuitive to ask if those stars also have planets orbiting them. Even then, several things were known. 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 and 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 the math to

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

which makes the equation solvable, 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, its semi-major axis can be calculated. Using the semi-major axis, the planet's total solar irradiance (TSI) can be calculated with

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

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

Different observations techniques and different planets can have dramatically different signal strengths. 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. The most traditional idea of seeing an exoplanet is that we could see it the same way we see stars. In principle, if telescopes were large enough, we could detect exoplanets by directly imaging them, however, the math behind this doesn't seem 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 is certainly possible in optimal circumstances, it's virtually impossible to do because an exoplanet and its host star are almost always within the diffration 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 CCDs, where accurate photometry of dim objects can be done in minutes, not hours. Astronomers only started becoming serious about detecting exoplanets with a new method, detecting transits not by measuring the brightness of the planet, but by measuring 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 is 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. 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 have proved to be 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 TSI 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 a TSI comparable to that of Earth. For these planets in particular, the transit method has proven to be the most reliable and effective detection method. 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 even terrestrial exoplanets have a transit depth of at least 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 $\sim 3°$, then $\sim 3\%$ of exoplanets can be detected from Earth. Our ability to detect smaller transit depths will improve over time, but the inclination issue is an inherent to the transit method. For the remainder of this thesis, only transiting exoplanets will be considered. 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 $180°$. 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 like this 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 $3.8\mathrm{S}_\oplus$, 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 $0.13\mathrm{S}_\oplus$, 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.

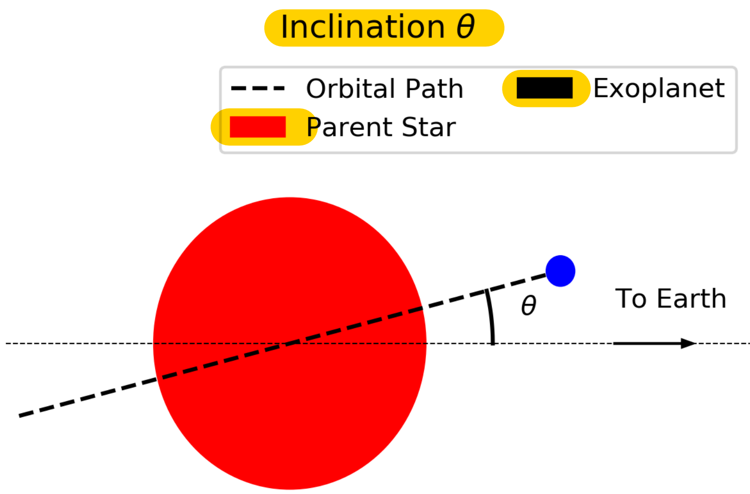

Figure 2.1: This is a simple depiction of what inclination represents physically. Any possible exoplanet can be viewed from this angle, making inclination a universal tool for characterizing exoplanets. Typically, an exoplanet with an inclination of less than 3° can have a transit, although this isn't 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.

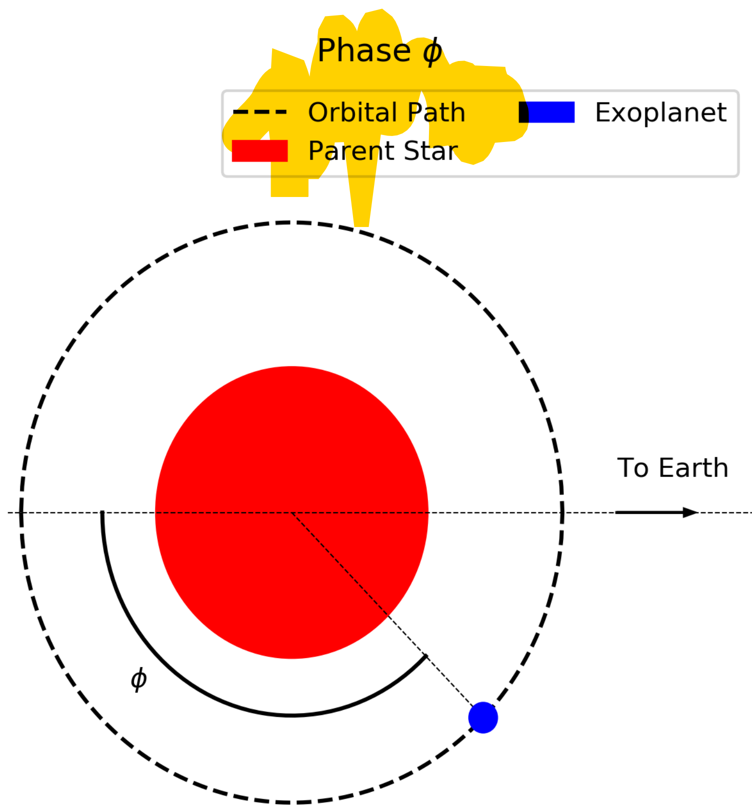

Figure 2.2: This is a simple depiction of what phase represents physically. In this diagram viewing from above, phase first goes down, then up. The convention of phase can be defined relative to transits and occultations, and regardless of the direction of this convention, the math behind which latitudes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

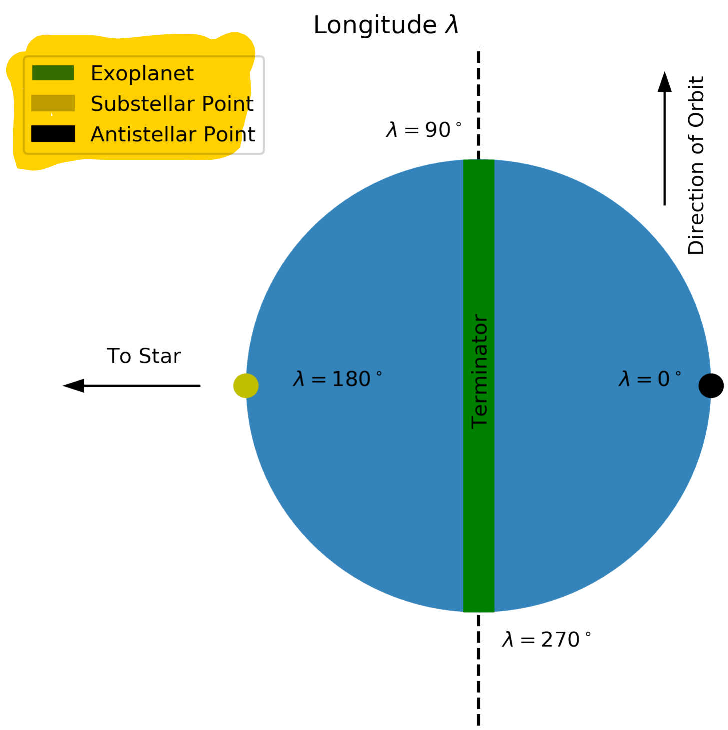

Figure 2.3: This is a simple depiction of what longitude represents physically for a tidally locked planet. These longitudes are correct for any phase or inclination. Note that from Earth during a transit $\lambda = 0°$ when $\phi = 180°$, and they move in opposite directions.

Chapter 3

Climate Atmosphere Models

In order to accurately predict behavior of an atmosphere, climate models have proven to be a very useful tool. A climate model uses fundamental physics like radiative transfer, convection, advection, and other rules to predict the motion of air parcels iteratively through time. These models are extremely complex, how and why they work is beyond the scope of this paper. Using a modified version of the NOAA Climate Atmosphere Model 5 (CAM5)i(Neale et al., 2012), 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 and is by far the most promising candidate of the 3 for supporting life. Although other cases will be considered, this paper will focus primarily on the climate models run for TRAPPIST-1 e.

In these models, fixed amounts of CO_2 and N_2 were given, and H_2O was set to vary in ways determined by CAM5. CO_2 is a greenhouse gas, and will always tend to warm an atmosphere due to its 3-atom molecular structure, which tends to prevent infrared radiation from leaving 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 which 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 is also a greenhouse gas like CO_2, and also exhibits pressure-broadening behavior, but 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.

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 get well within the habitable range of 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. A lot of these 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, and also ignore ocean currents. 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 CAM5 would be useful(Neale et al., 2012).

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 on each side.

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 which can change due to a number of other things. 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). CAM5 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. This means that each attribute of a model like temperature, cloud amount, etc. all have their own data cubes. In order 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 amount of clouds, which would be the sum of all the different layers. This more closely represents what the clouds would look like from space. Figures 3.3 and 3.4 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 infer 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 no rotation relative to the sun, but because it's year is only 6 days(Gillon et al., 2017), it will have an angular frequency

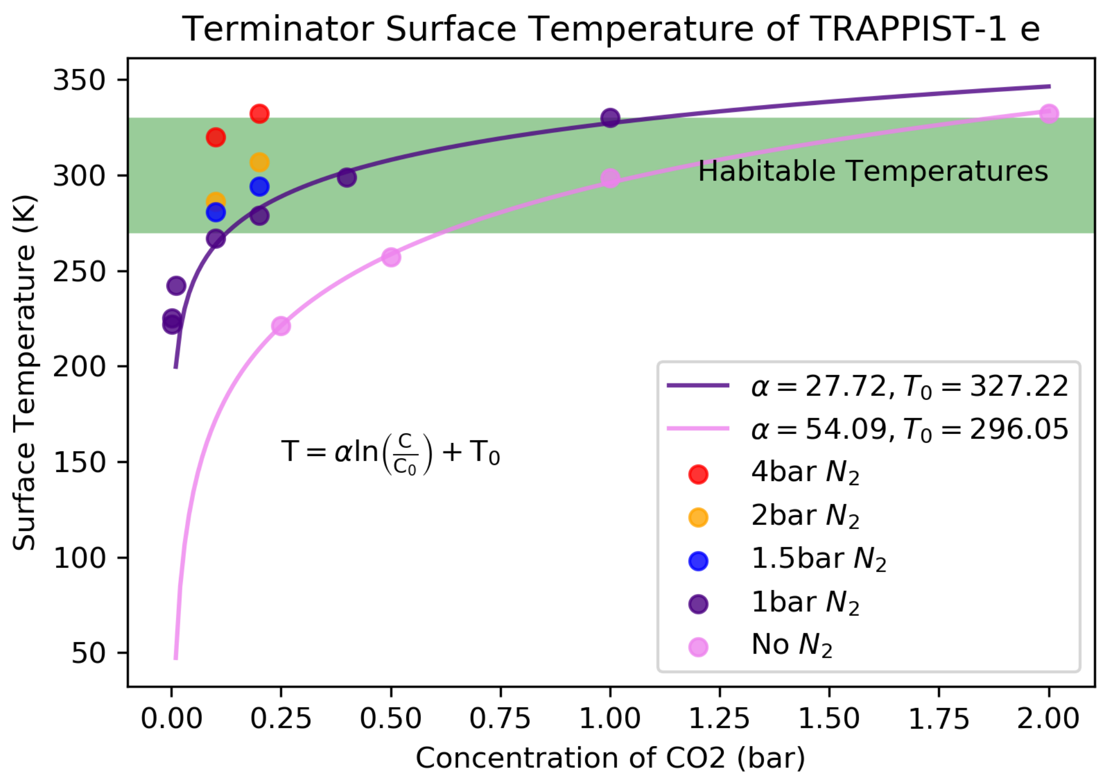

Figure 3.1: Terminator surface temperature versus CO_2 partial pressure. Most of the models in Table 3.1 are shown here to more accurately demonstrate the relationship between CO_2 and warming. Both CO_2 and N_2 can contribute significantly to the warming of the planet, but they do so differently because 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.

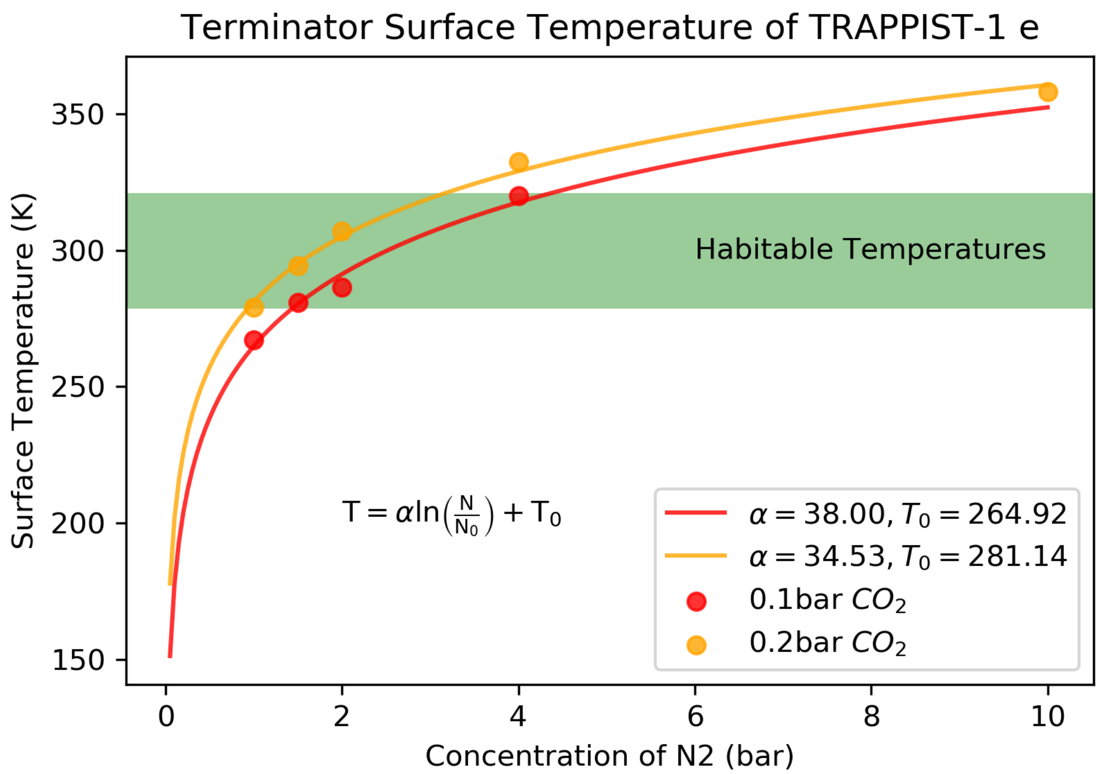

Figure 3.2: Terminator surface temperature versus N_2 partial pressure. Similarly to Figure 3.1, logarithmic best fit lines match the data well, although the fit is noticably better for CO_2 than N_2.

of $2\pi/6$d, which is significantly less than Earth's, but still strong enough to be significant. From the results of these climate models, the effects of TRAPPIST-1 e's coriolis force can be clearly seen. The substellar cloud is fairly small, and is concentrated to the east, while the western substellar point has little to no clouds.

? has run models on other exoplanets, including (whatever the name of this planet is that my advisor hasn't sent me yet), which orbits a much larger star than TRAPPIST-1, allowing the exoplanet to orbit at a farther distance, therefore decreasing its orbital period. The extended orbital period means that the coriolis force is much weaker, which produces a completely different shape for its substellar cloud. Almost have the planet is covered by clouds, and the cloud is fairly symmetric from the east and west. According to **?**, tidally locked exoplanets fall into two categories; fast rotators and slow rotators. Fast rotators like TRAPPIST-1 e have small substellar clouds and a strong coriolis force. Slow rotators like (whatever the name of this planet is) have large substellar clouds and a weak coriolis force.

In addition to surface features, one of the most useful tools to describe a planetary atmosphere 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 3.5, 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 3.5, 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

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

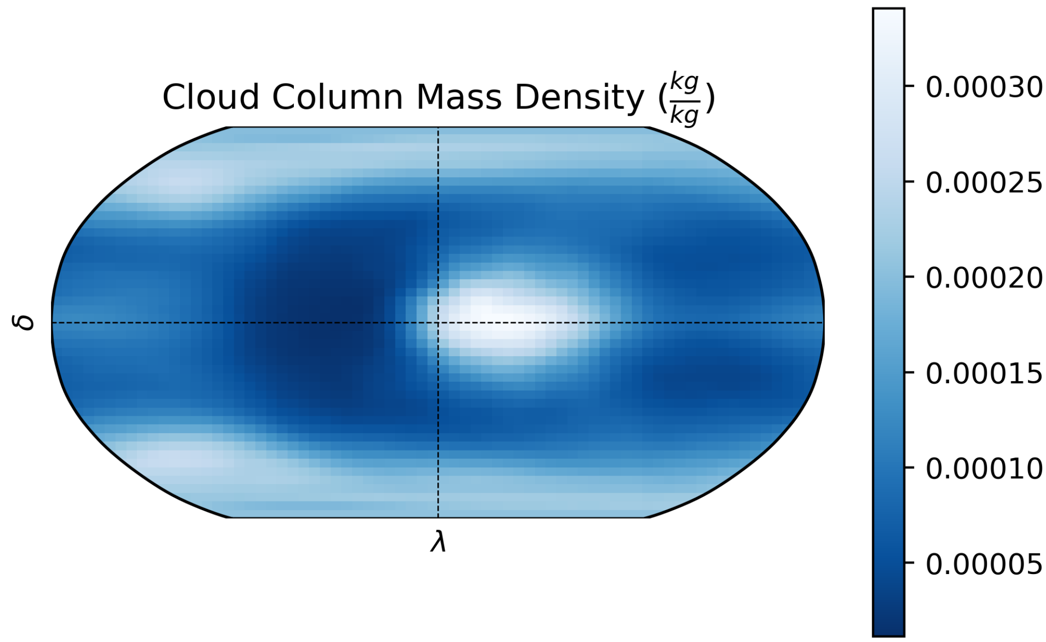

Figure 3.3: Cloud Column Density of TRAPPIST-1 e with 1bar N_2 0.4bar CO_2. In this image, white represents lots of clouds, and blue represents few clouds. For the substellar point, there are strong clouds, particularly on the eastern side. Surprisingly, right next to the substellar point is also the 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.

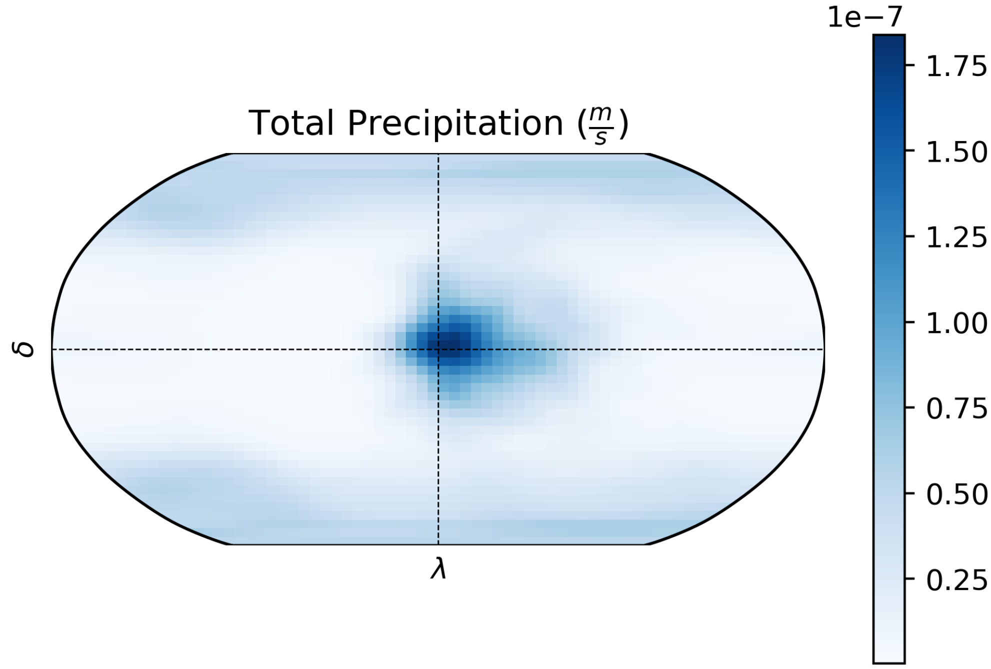

Figure 3.4: Total Column Precipitation of TRAPPIST-1 e with 1bar N_2 0.4bar CO_2. In this image, blue represents high amounts of precipitation and white represents little to no precipitation. From Figure 3.3, we can conclude there is a persistent substellar cloud, but in order to determine if there's 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, but the rest of the planet only has marginal amounts of rain in comparison.

where T_e is the equilibrium temperature, S is the solar irradiance, α is the albedo, and σ is the Stefan-Boltzmann constant.

While these models are extremely illustrative of many details about the TRAPPIST-1 e atmosphere, there are a number of noteworthy limitations 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.

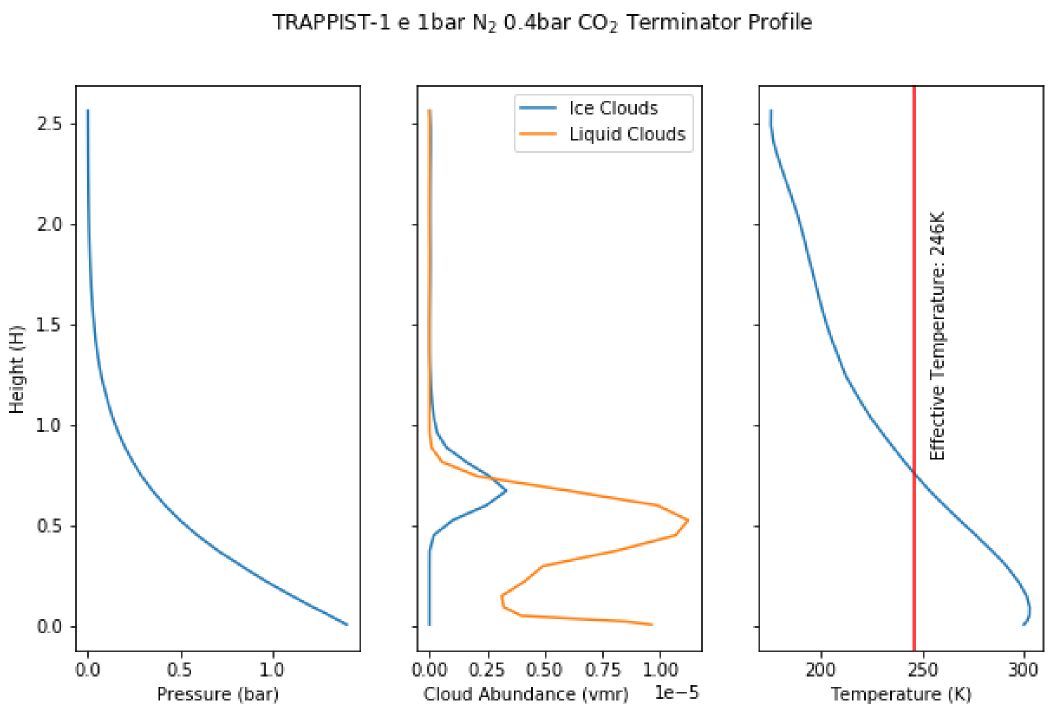

Figure 3.5: Profile of TRAPPIST-1 e with 1bar N_2 0.4bar CO_2.

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