TRAPPIST-1 e Atmosphere Detection Methods

by

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TRAPPIST-1 e Atmosphere Detection Methods

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

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. This is dedicated to them.

Acknowledgements

A special thanks to my grandpa, the first person to introduce me to physics.

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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 there are ≈100 billion exoplanets just in the Milky Way (Woo, 2013). 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.

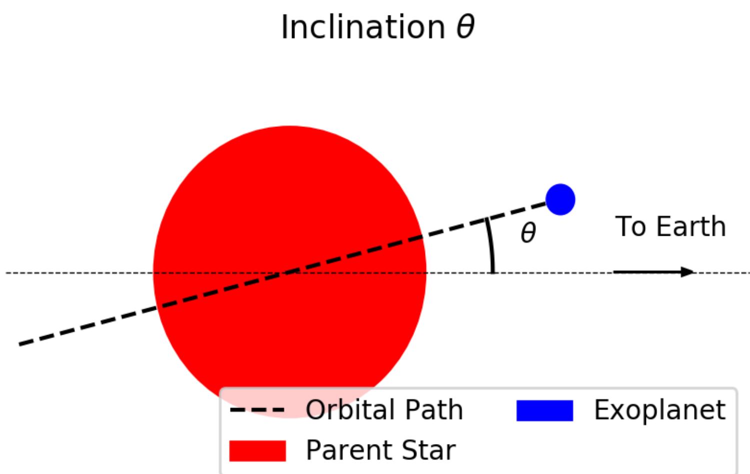

Figure 2.1: This is a simple depiction of what inclination represents physically. Any possible exoplanet can be viewed from this angle, making inclination a universal tool for characterizing exoplanets. Typically, an exoplanet with an inclination of less than 3° can have a transit, although this isn't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

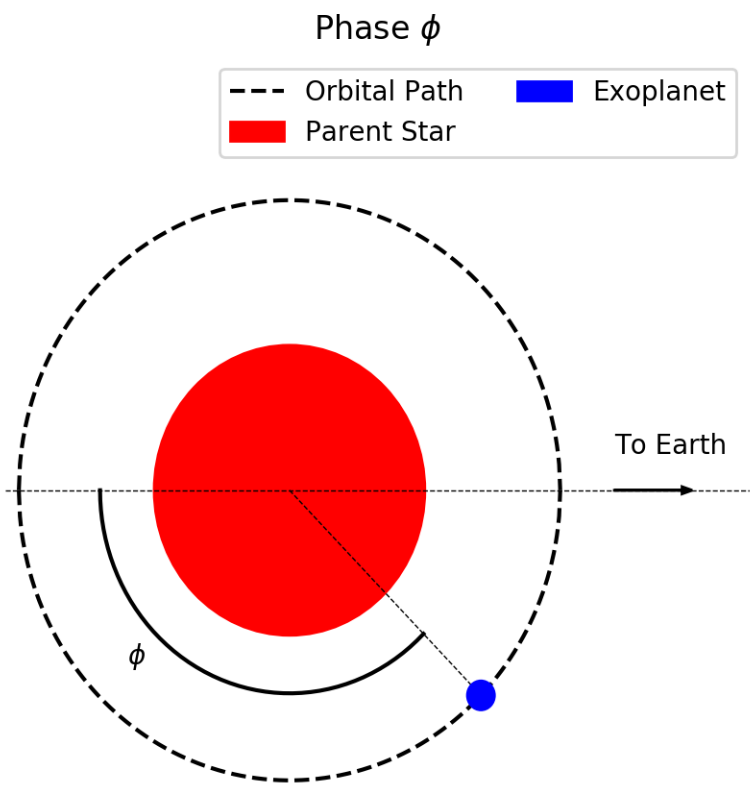

Figure 2.2: This is a simple depiction of what phase represents physically. In this diagram viewing from above, phase first goes down, then up. The convention of phase can be defined relative to transits and occultations, and regardless of the direction of this convention, the math behind which latitudes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

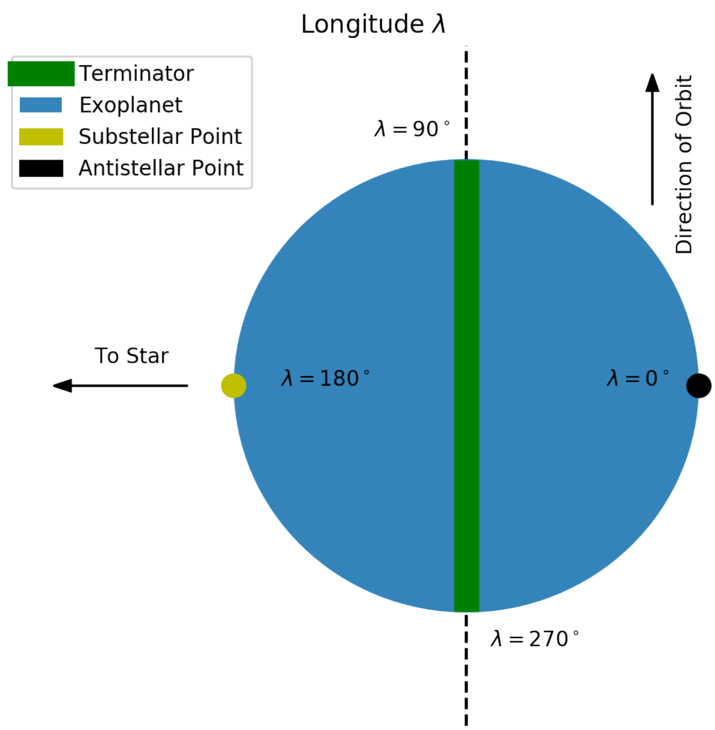

Figure 2.3: This is a simple depiction of what longitude represents physically for a tidally locked planet. These longitudes are correct for any phase or inclination. Note that from Earth during a transit $\lambda = 0°$ when $\phi = 180°$, and they move in opposite directions.

Chapter 3

Climate Atmosphere Models

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