#### ABSTRACT

### Exoplanet Habitability and an Analysis of Gliese 436 b

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Exoplanets are planets that orbit stars other than the Sun. Many scientists have postulated that life may exist on these extra solar bodies. Earth-like exoplanets are the ideal target for habitability. The most important factor to consider when analyzing habitability is the existence of liquid water. Liquid water is most likely to exist if an exoplanet orbits within a star's habitable zone. Density is another important factor, because exoplanets with a similar density to earth are targets for further habitability research. In order to apply these concepts, the exoplanet Gliese 436 b was observed using the Paul and Jane Meyer Observatory during a transit of its host star. A light curve was plotted from the images taken in order to determine the radius and density of Gliese 436 b. A habitability zone calculation was also performed. Using this information, a determination on the habitability of Gliese 436 b was made.

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# EXOPLANET HABITABILITY AND AN ANALYSIS OF GLIESE 436 B

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By

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#### CHAPTER ONE

#### Introduction

Is there another world in the universe that could meet the biological requirements to host life? Apart from the Earth, no celestial body has been found to harbor any form of life. Yet the potential for finding habitable bodies in the universe increased with the discovery of 51 Pegasi b by Mayor and Queloz.<sup>1</sup> As such, many astronomers now look to exoplanents as the most probable location for life to exist beyond Earth. In 2014, the Kepler Spacecraft had catalogued over 3,500 exoplanets since the mission first started in 2009.<sup>2</sup> With 100 of these exoplanets found to be in the host star's habitable zone, exoplanets indeed provide an increase in the amount of potentially habitable bodies known to astronomers.<sup>2</sup> The issue then becomes combining the physical data found for an exoplanet with the biological limitations for the existence of life.

### Exoplanets and Detection Methods

Just what exactly are exoplanets though? Simply stated, they are planets that orbit other stars besides the sun.<sup>3</sup> This simple definition is explained by the fact that the field of exoplanetology is quite young. Only twenty years have passed since the first journal article was written about 51 Pegasi b.<sup>1</sup> Since this discovery though, the methods of discovery and analysis have increased dramatically. 51 Pegasi b was discovered utilizing the radial velocity method.<sup>4</sup> When an exoplanet orbits a host star, the position of the star will change slightly around the center of mass in regards to both objects.<sup>4</sup> This change in position can be measured by Doppler spectroscopy in order to produce a sine curve that

represents the orbit of an exoplanet around the host star.<sup>1</sup> While this is an effective method of exoplanet discovery, the limitation is that exoplanets with Jupiter-like or greater mass will be more easily discovered.<sup>5</sup> These greater mass exoplanets will have larger gravitational pull on the host star, thus causing more Doppler movement to be recorded.<sup>5</sup>

Another method of exoplanet discovery is direct imagery. In this method, images of a host star are captured and then analyzed for the presence of other celestial bodies.<sup>6</sup> Again, this method favors exoplanets with Jupiter-like masses and exoplanets with large semi-major axis's on the order of tens of astronomical units.<sup>6</sup> This method can enable atmospheric data to be taken from an exoplanet, a key step in analyzing habitability.<sup>6</sup> The limitations of this method are the low angular separation of the exoplanet and host star along with the generally extreme luminosity difference between these two bodies.<sup>6</sup> Due to these limitations, it is unlikely that a potentially habitable exoplanet would be found by this method of discovery.

While direct imagery takes images of a host star, gravitational lensing is a detection method that is utilized when two stars are lined up almost perfectly.<sup>4</sup> The foreground star's orbiting exoplanet will cause a deviation in the expected magnifying lens curve from the light of the background star.<sup>7</sup> This method is best suited for identifying exoplanets with masses between Earth's and Jupiter's and a semi-major axis of about 1-5 AU around the foreground star.<sup>7</sup> It should be evident that the limitation for this detection method is the need for two stars to line up almost perfectly when looked at from Earth. This phenomenon is not seen with every potential host star in the universe, as the number of exoplanets discovered by this method is less than other methodologies.<sup>4</sup>

The most substantial method of exoplanet discovery though is the transit method.<sup>4</sup> This is the methodology utilized to analyze the exoplanet observed for this paper. It is also the detection method utilized by the Kepler spacecraft, which is currently searching for habitable exoplanets in the Milky Way.<sup>8</sup> The transit method is similar to an eclipse of the moon. An exoplanet orbits in front of its host star as viewed from earth.<sup>8</sup> A photon counting camera can then detect the decrease in perceived brightness from the host star.<sup>9</sup> A light curve is then produced to show brightness over time.<sup>8</sup> From this light curve, an exoplanet's radius and density can be determined in order to provide observers with an idea of the physical composition of the exoplanet.<sup>9</sup> This is an important determination when searching for habitable exoplanets as rocky planets are the primary candidates for future research.

The Kepler spacecraft and other missions searching for exoplanets constantly monitor stars for detectable decreases and then increases in light flux that produce a light curve.<sup>8</sup> Researchers can then analyze the data obtained in order to assess an exoplanet's probability for habitability.<sup>8</sup> The main limitation for this method is that larger exoplanets have greater disparities between then maximum and minimum light flux on the light curve. However, advancements in light capturing cameras and the Kepler Spacecraft have made it easier to detect Earth-like planets in both composition and size.<sup>8</sup>

The transit method can also be used to determine the time duration of an exoplanet's orbit. The most simplified way of accomplishing this is to record the time between two transit events from the same exoplanet. This data can then be extrapolated to determine the semi-major axis of an exoplanet's orbit, a key factor in determining if an exoplanet lies in a host star's habitable zone. The habitable zone of a host star, or Goldie

Locks Zone as it is known to most of the public, is the region where liquid water can occur.<sup>10</sup> If an exoplanet exists outside of this orbital radius around a host star, then life is unlikely to exist as the energy from the host star is either too great or too little to keep the exoplanet's temperature conducive for life. This definition assumes that no geothermal or other heat producing processes can provide sustainable temperatures for life outside of a star's habitable zone.

#### Exoplanet Habitability Requirements

After finding an exoplanet through one of the various detection methods listed previously, the next step is to determine if this planet could in fact be habitable to life. It is important to note that this paper does not seek to prove the existence of life beyond Earth. Instead, the focus of this research is to analyze the habitability of exoplanets observed.

For starters, the first condition that must be met for an exoplanet to be habitable is the possibility that liquid water can exist.<sup>10</sup> As such, certain conditions need to be observed for an exoplanet to be considered habitable. The temperature on the exoplanet needs to be sustainable for liquid water (roughly 0-113°C).<sup>10</sup> The atmospheric pressure needs to be greater than 100 MPa so that water does not become water vapor due lack of pressure in the atmosphere.<sup>10</sup>

If these conditions for liquid water can be met, the next step is to look for what are known as the "building blocks of life." In looking at organisms on earth, it seems that the only element required for life to exist is carbon.<sup>11</sup> Carbon's abundance in the earth's solar system makes astrobiologists believe that this may not be a significant limiting factor.<sup>11</sup> Other elements that may be a requirement for life include phosphorous, sulfur,

and nitrogen with nitrogen most likely being the most important of the three due to its presence in DNA and proteins.<sup>11</sup> Remember that without the presence of water though, these building blocks will not lead to the development of life.

Along with water and these building blocks, UV radiation and greenhouse gases must be considered. If too much radiation reaches the exoplanet's surface, then molecular formation necessary for life, such as proteins and DNA, can be easily broken down.<sup>10</sup> Greenhouse gases also allow for stability if they are in equilibrium with volcanic activity on the exoplanet.<sup>12</sup> This is an effect of the carbon-silicate cycle which regulates the amount of carbon dioxide present in the atmosphere.<sup>12</sup> At higher temperatures, the amount of carbon dioxide decreases as weathering on the surface of a planet occurs faster.<sup>12</sup> At cooler temperatures, the amount of carbon dioxide increases without volcanic activity.<sup>12</sup> The amount of variation in temperature between the two extremes of this cycle greatly affects if an exoplanet can sustain the conditions necessary for life.

What is important to note about all these different factors for life to exist is that it takes very precise ranges of multiple variables for life to exist. It is entirely possible that life could evolve via a different process somewhere else in the universe. However, since the earth is the only known place where life exists in the universe, astronomers and astrobiologists focus their efforts on earth-like conditions and life development.

## Potential Biomarkers for Life

Since life cannot be directly seen on exoplanets from earth, biomarkers in an exoplanet's atmosphere must be observed in order to imply that life may already exist. There are three general classifications of biomarkers that could exist in an exoplanet's atmosphere. The first class of biomarkers includes nitrous oxide and oxygen as these are important molecules in the life cycle on earth.<sup>13</sup> While important, an atmospheric spectroscopy indicating the presence of either of these molecules does not provide substantial evidence to life's existence as these molecules can be produced through non-biological means.<sup>13</sup>

The second class of molecules to search for is metabolic reaction products such as methane.<sup>13</sup> As with the first class of biomarkers though, many false positives in an exoplanet's atmosphere can occur due to the fact that methane can be produced through non-biological means.<sup>13</sup>

The third class of biomarkers offers the most hope for a way to detect life by spectroscopy. Molecules such as DMS and methanethiol are biological markers outside of the basic metabolic processes or life-building components of life.<sup>13</sup> The presence of these molecules would provide evidence to the existence of life because these molecules are not abundant in abiotic processes.<sup>13</sup> However, it should be noted that, on Earth, these molecules are not highly abundant in the atmosphere.<sup>13</sup> As such, it can be very difficult to even observe the presence of these molecules on a spectroscopy readout.<sup>13</sup> Even if this class of molecules were discovered on an exoplanet though, a high amount of the first and second class biomarkers would need to be viewed on a spectroscopy readout in order to provide stronger evidence of potential life on the exoplanet in question.

## Estimated Number of Exoplanets

The number of estimated habitable worlds in the Milky Way is 40-49 billion.<sup>14</sup> In the entire universe, the estimated number is 4.2-5.3 trillion.<sup>14</sup> This is an astonishing amount of potential celestial bodies to observe and analyze for the potential housing of life. Yet even present day technology limits the amount of exoplanets that can be

observed to no more than a few thousand.<sup>3</sup> Even still, the field of exoplanetology continues to grow and expand as more and more excitement is raised with the potential of what lies beyond the earth.

#### CHAPTER TWO

#### Methods and Materials

In order to properly assess habitability as presented in the previous chapter, an exoplanet was observed and analyzed to confirm properties measured by other astronomers. After completing an observing run of a specific exoplanet during transit of the host star, an assessment was made on the potential habitability of the exoplanet. It should be noted that the exoplanet observed is not an ideal candidate for habitability. This is because the experimental tools available limited the amount of exoplanets that could potentially be observed. However, even without an ideal exoplanet, a habitability analysis was still applied.

#### Gliese 436 b

The exoplanet observed for this experiment was Gliese 436 b. Astronomers discovered this exoplanet by the radial velocity method in 2004 at the University of California Berkley.<sup>15</sup> The Neptune-like exoplanet's mass was measured to have a mass of 21 times that of Earth's with an orbital period of 2.644 days.<sup>15</sup> This mass has since been updated to be  $22.2 \pm 1.0$  times the mass of the earth.<sup>16</sup> The temperature on Gliese 436 b is reported to be  $712 \pm 36$  K.<sup>16</sup> The radius of the exoplanet is reported to be  $4.327 \pm 0.183$  times that of the Earth.<sup>16</sup> It has an orbital period around its host star of 2.643882 +0.000060/-0.000058 days and semi-major axis of  $0.0291\pm 0.0004$  AU.<sup>16,17</sup>

The host star, Gliese 436, is a M2.5 V star, also known more commonly as a red dwarf star, and reported to have a mass of  $0.41 \pm 0.05$  times the mass of the sun and a

radius of 0.42 times the sun.<sup>15,18</sup> It has an apparent visual magnitude of 10.67 and an absolute magnitude of 10.63.<sup>15</sup> The luminosity of the star is reported to be 0.025 that of the Sun.<sup>15</sup> The age of the star is estimated to be between 7.41 and 11.05 billion years.<sup>19</sup>

### Materials for Observation and Analysis

The telescope used to observe Gliese 436 b was the Paul and Jane Meyer Observatory. The location of the telescope is given in the table below.

Longitude	97 deg 40 min 24.7 sec west
Latitude	31 deg 40 min 47.7 sec north
Elevation	Approximately 1000 feet

Table 1: Location and Elevation for Paul and Jane Meyer Observatory<sup>20</sup>

The 24-inch telescope is equipped with a CDC camera to take and save images.<sup>20</sup> For this experiment, the telescope and camera were controlled remotely from the Baylor University Science Building.

After capturing images, the computer program AstroImageJ was utilized to obtain a light curve from images taken during the observing run. AstroImageJ is an ImageJ program developed by the University of Louisville that includes astronomy plugins and installed macros for analysis of astronomical images.<sup>21</sup>

### Methods for Collecting and Processing Data

The observed transit of Gliese 436 b took place on March 28, 2015. The predicted ingress was determined to be 12:44am Central Standard Time (Barycentric

Julian Date of 2457109.739493) and the predicted egress to be 1:30am (BJD of 2457109.770833).<sup>22</sup>

In order to check for weather anomalies and other extenuating factors that could alter light reaching the CDC camera, comparison stars were monitored for consistent reception of data during the transit. The CDC camera was set to take images every thirty seconds starting about one hour before and after the transit period. At the completion of the transit, thirty flat, dark 10, dark 30, and bias images were taken.

After the observing run, master flatfield, dark, and bias images were created using AstroImageJ by averaging each individual flat, dark10, dark 30, and bias image together respectively. These images were utilized in order to correct for the number of pixels in each image taken during the transit.<sup>23</sup> The master dark image was subtracted from all the transit images.<sup>23</sup> These images were then divided by the master flatfield image. Bias image were then also subtracted to produce the final, corrected transit images.

After all transit images were corrected for, AstroImageJ was utilized in order to develop a light flux and magnitude for each observing image utilizing the multiple aperture photometry tool. This was done in order to allow for simultaneous processing of both the target star and comparison stars' light flux and magnitude. AstroImageJ was then utilized to produce the light curve measuring magnitude versus time for the transit run. This light curve was then used to determine the radius of Gliese 436 b by the change in magnitude of Gliese 436. Utilizing this experimentally determined radius, the density of the exoplanet was determined by using a mass reported in the available literature.

The data collected from the light curve was compared to the current data on Gliese 436 b in the literature. No atmospheric data was collected.

After determining the radius and density of Gliese 436 b, the habitability of Gliese 436 b was analyzed by computing the habitable zone of Gliese 436. This was accomplished by taking the luminosity of Gliese 436 and semi-major axis of Gliese 436 b from available literature.

## CHAPTER THREE

## Analysis

# Literature and Experimental Comparison Values

The table below lists relevant values that were not experimentally determined for in this paper but are necessary for calculations about Gliese 436 b.

Period of Orbit for Gliese 436 b <sup>17</sup>	2.643882 +0.000060/-0.000058 d
Semi-Major Axis of Orbit for Gliese 436 b <sup>16</sup>	0.0291±0.0004 AU
Mass of Gliese 436 b <sup>16</sup>	$22.2\pm1.0~M_{Earth}$
Temperature of Gliese 436 b <sup>16</sup>	712 ± 36 K
Luminosity of Gliese 436 <sup>15</sup>	0.025 L <sub>Sun</sub>
Radius of Gliese 436 <sup>18</sup>	0.42 R <sub>Sun</sub>

## Table 2: Relevant Data Taken from Literature

The table below lists data taken from the available literature that was used as a

comparison for experimentally determined data.

Radius of Gliese 436 b	$4.327 \pm 0.183 R_{\text{Earth}}$
Density of Gliese 436 b	1510 kg m <sup>-3</sup>

Table 3: Experimentally Compared Data<sup>16</sup>

# Star Field of Gliese 436

The following images are pictures of the star field of Gliese 436. The right ascension of Gliese 436 is  $11^{h}42^{m}10.55^{s}$  and the declination is  $+26^{\circ} 42' 23.6537$ .<sup>24</sup>







Figure 2: Star Field Image of Gliese 436 with Annotation for Light Curve

#### Light Curves for the Transit of Gliese 436 b



The following figures are the light curves plotted for the transit of Gliese 436 b.

Figure 3: Light Curve for the Transit of Gliese 436 b

Figure 3 shows the plot of relative magnitude versus time. The red curve represents the light detected by the CDC camera for the target star, Gliese 436. The dip in the curve is when Gliese 436 b transited in front of Gliese 436. This caused the decrease in magnitude detected. The approximate depth of the curve above is 0.008±0.001.

The black line plot represents the background flux detected by the CDC camera. This line shows the variability in light flux that occurs due to the Earth's atmosphere or other background sources.



Figure 4: Light Curve for the Transit of Gliese 436 b Including Comparison Stars

Figure 4 shows the same curves as Figure 3 with the addition of the three comparison stars taken from the star field of Gliese 436. The light curves of the comparison stars represent a control for the light curve of Gliese 436. These comparison stars cannot be variable stars in order to be effective controls. Since the three curves do not illustrate any significant differences, no outside adjustments need to be made to the light curve of Gliese 436.

#### Radius of Gliese 436 b

Utilizing the decrease in magnitude obtained from the light curve, the radius of Gliese 436 b can be experimentally determined. Firstly, the relationship between magnitude and flux is presented in the following equation:

$$m_{GJ436} - m_{\Delta GJ436b} = -2.5 \log\left(\frac{F_{GJ436}}{F_{GJ436b}}\right) \tag{1}$$

where  $m_{GJ436}$  is the relative magnitude of the host star,  $m_{\Delta GJ436b}$  is the absolute value of the decrease in relative magnitude of Gliese 436 during mid-transit caused by Gliese 436 b,  $F_{GJ436}$  is the light flux from the host star, and  $F_{GJ436b}$  is the light curve dip during at the mid-transit caused by Gliese 436 b.<sup>25</sup>

While this equation is needed to establish the relationship between relative magnitude and flux, the inverse relationship is needed in order to determine the radius of Gliese 436 b. This is given in the following equation:

$$\frac{F_{GJ436b}}{F_{GJ436}} = 10^{\frac{m_{GJ436} - m_{\Delta GJ436b}}{2.5}}$$
(2)

where the variables are the same as in equation  $1.^{25}$ 

Using equation 2, the values of 0 for  $m_{GJ436}$  and  $0.008\pm0.001$  for  $m_{\Delta GJ436b}$  are used to solve for the ratio of light flux during transit from Gliese 436 to light flux of Gliese 436 without a transit occurring. A result of  $0.993\pm0.001$  occurs for the ratio of  $F_{GJ436b}$  to  $F_{GJ436}$ .

Now that a light flux ratio between transit and non-transit flux has been determined, the radius of Gliese 436 b can be calculated using the following equation:

$$1 - \left(\frac{F_{GJ436b}}{F_{GJ436}}\right) = \left(\frac{R_{GJ436b}}{R_{GJ436}}\right)^2 \tag{3}$$

where  $R_{GJ436b}$  is the radius of Gliese 436b,  $R_{GJ436}$  is the radius of the host star, Gliese 436, and all other variables are the same as in equation 1 and 2.<sup>23</sup> The assumption made in this equation is that the entire diameter of Gliese 436 b passes in front of the host star during transit. The  $1 - (\frac{F_{GJ436b}}{F_{GJ436}})$  portion of this equation is used in order to calculate for the decrease in light flux that is caused by Gliese 436 b transiting in front of Gliese 436. From here, the equation can be solved for  $R_{GJ436b}$ :

$$R_{GJ436b} = \sqrt{(R_{GJ436})^2 \left[1 - (\frac{F_{GJ436b}}{F_{GJ436}})\right]}$$
(4)

The value of  $R_{GJ436}$  is taken from Table 2 and the same value for the ratio of  $F_{GJ436b}$  to  $F_{GJ436}$  is used that was calculated for in equation 2.

After utilizing these values, the radius of Gliese 436 b is calculated to be approximately  $24,400 \pm 1,700$  km or  $3.83 \pm 0.27$  R<sub>earth</sub>. This value is slightly below the accepted range from literature values for the radius of Gliese 436 b with a percent error of 11.5%.

#### Density of Gliese 436 b

Utilizing the radius determined from the light curve, the mean density of Gliese 436 b can be determined through the following equation:

$$D = \frac{M}{\frac{4}{3}\pi R_{GJ436b}^{3}}$$
(5)

where D is the mean density of Gliese 436 b, M is the reported mass of Gliese 436 b, and  $R_{GJ436b}$  is the experimentally determined radius of Gliese 436 b.<sup>26</sup> The assumption made in this equation is that Gliese 436 b is a perfect sphere so that the volume of a sphere formula can be used.

The reported mass of Gliese 436 b is 22.2 times the mass of the earth or  $1.32 \times 10^{26}$ kg.<sup>15,30</sup> The experimentally determined radius for Gliese 436 b is 24,400 km ± 1,700 km.

After completing the calculation, the experimentally determined density of Gliese 436 b is approximately  $2,170 \pm 450$  kg m<sup>-3</sup>. This value is higher than the value from the literature by a percent error of 43.8%.

#### Habitable Zone of Gliese 436

As mentioned previously, Gliese 436 is a red dwarf star with a luminosity of 0.025 times the luminosity of the sun.<sup>15</sup> Utilizing this luminosity; the habitable zone of Gliese 436 can be determined. The assumption that is made for this determination is that liquid water must be able to exist on an exoplanet in order for life to exist.<sup>27</sup> Therefore, the temperature range that needs to be determined is between 0-113°C.<sup>11</sup>

In order to make this calculation, the two equations for flux are utilized. The first equation:

$$F = \sigma_{SB} T^4 \tag{6}$$

calculates flux, or the energy per area time, by utilizing the Stephan-Boltzmann constant,  $\sigma_{SB}$ , and temperature, T.<sup>27</sup> The second equation:

$$\mathbf{F} = \mathbf{L} / (4\pi \mathbf{r}^2) \tag{7}$$

where L is the luminosity of the host star, Gliese 436, and r is the distance from the host star.<sup>27</sup>

Since both of these equations are equal to flux, they can be set equal to each other in order to calculate the habitable zone.

$$\sigma_{\rm SB} T^4 = L / (4\pi r^2) \tag{8}$$

This equation can then be rearranged in order to solve for the distances from the host star where the temperature allows for liquid water to exist.

$$\mathbf{r} = \sqrt{L/(4\pi\sigma_{SB}T^4)} \tag{9}$$

Equation nine must be utilized twice since the habitable zone is a range around a host star. For both calculations, L is equal to 0.025 the luminosity of the Sun or  $9.6 \times 10^{24}$ W.<sup>15,28</sup> The two temperatures utilized are 273.15K and 386.15K. Kelvin must

be used since the Stephan-Boltzmann constant utilizes Kelvin in order to account for temperature.<sup>27</sup>

After using these values and constants, the equation yields a habitable zone of  $2.5 \times 10^{10}$  m to  $4.9 \times 10^{10}$  m or approximately 0.17 AU to 0.33 AU from Gliese 436.

Using this habitable zone range, it can be shown if Gliese 436 b lies within a habitable range from the host star. The semi-major axis of Gliese 436 b is 0.0291±0.0004 AU.<sup>16</sup> From this data; it is clear that Gliese 436 b does not orbit within the habitable zone of Gliese 436. Therefore, Gliese 436 b is not an ideal candidate for exoplanet habitability.

It should be noted that this habitable zone range is primarily based upon the temperature at which liquid water can exist on an exoplanet.<sup>10</sup> This calculation does not include the effects of albedo, or light reflection. An exoplanet with a higher albedo will be cooler than an exoplanet with a lower albedo.<sup>27</sup> A second consideration that is not taken into effect is the greenhouse effect. As seen with Venus, the greenhouse effect can dramatically increase temperature even when an orbiting body may or may not be in the water temperature habitable zone.<sup>27</sup>

#### CHAPTER FOUR

#### Discussion

### Experimental Results

The experimental results for Gliese 436 b's radius and density did not fall within the accepted, comparison values from the literature available. The radius value was closer to the accepted value than the density. The density of Gliese 436 b will be discussed further in a later section.

The primary reason for error was that only one transit run was completed for this exoplanet. With only one transit run, the experimentally determined data is limited by atmospheric and other background factors that occurred on the observing night. If multiple transit runs were attempted, then data could have been compared and averaged in order to determine if the one observing run was an anomaly. If consistent data occurred that was outside the accepted range for the radius of Gliese 436 b, then more questions could be asked about current measurements. An increased number of transits would also allow for determinations on the precision of the telescope and CDC camera used.

In regards to this specific transit observation, atmospheric variability must be considered. As seen in Figures 3 and 4, the atmospheric background was quite variable. During the predicted transit, the atmospheric background varies by a relative magnitude of 0.005, a large margin when the relative curve dip is only 0.008±0.001 in Figure 3.

The comparison stars do provide evidence that atmospheric effects did not have extreme effects though. Each of the three curves representing the comparison stars in Figure 4 do not vary to a significant degree to justify removing the data from consideration for this paper.

The final possibility is more theoretical. It has been proposed that another exoplanet orbits Gliese 436 in order to account for the orbit of Gliese 436 b.<sup>29</sup> If this exoplanet had also transited with Gliese 436 at the same time, this would explain the increased radius findings for this experiment. Unfortunately, this does not seem likely as Gliese 436 b and the hypothetical exoplanet would have to orbit Gliese 436 at roughly the same position in orbit. What may be more likely is that a moon orbits Gliese 436 b. However, there is no evidence to suggest a moon orbits Gliese 436 b.

### Habitability of Gliese 436 b

Gliese 436 b is not an ideal exoplanet candidate for habitability. The two primary factors that lead to this conclusion are the exoplanet's density and orbit around Gliese 436. Gliese 436 b's density implies an overall composition more similar to that of Neptune than Earth from the literature.<sup>30</sup> The experimentally determined density implies that Gliese 436 b is slightly more dense than Neptune, but still less than half the density of Earth.<sup>30</sup> Since most life in the universe theories are based upon life on Earth, an exoplanet with a density similar to a gas giant is not ideal. It should be noted that just because Gliese 436 b's density is not similar to Earth's does not disprove that life may exist on this exoplanet. Gliese 436 is believed to have a rocky core surrounded by "hot ice" and a surrounding atmosphere of hydrogen and helium.<sup>31</sup> It is believed that pressure, gravity, and tidal effects aid in allowing ice to exist on Gliese 436 b even with the exceptionally high temperatures present.<sup>31</sup>

The next piece of evidence that implies Gliese 436 b is not ideal for habitability is its orbit. As shown in the analysis chapter, Gliese 436 b lies too close to Gliese 436 to be within the habitable zone range. This implies that the expected temperature of Gliese 436 b is too high for liquid water to exist. This presents a problem since life as it is known on Earth requires liquid water.<sup>10</sup>

Finally, the actual temperature of Gliese 436 b confirms the evidence previously stated. The temperature of the exoplanet is around 712 K, too high for even the possibility of liquid water existing.<sup>16</sup> Even if a solid surface does exist; the temperature is still too hot for life to feasibly exist on Gliese 436 b. A greenhouse effect from the atmosphere is hypothesized to be increasing the temperature of Gliese 436 b given its orbit around the host star.<sup>31</sup>

#### Habitability Around other Red Dwarfs

M type stars, or red dwarfs, are a new focus for exoplanet habitability. It is estimated that red dwarfs constitute 90% of stars in elliptical galaxies.<sup>32</sup> Based upon the probabilities given previously in this paper; a large number of exoplanets may then be orbiting around these types of stars in the universe.<sup>14</sup> While many of these exoplanets may be tidally locked, cloud formation may make it possible for the temperature to be equibrilated around the exoplanet.<sup>33</sup> This would then solve for the problem of one side of an orbiting body being incredibly hot, while the other side is incredibly cold.<sup>33</sup> As stated previously, temperature is crucial when analyzing an exoplanet for habitability.

Perhaps the most hopeful evidence for increasing the search around red dwarf stars is their lifespan. Red dwarfs have less mass than stars similar to the sun.<sup>34</sup> They also utilize less of the hydrogen in their core for nuclear reaction; which explains their lower luminosity.<sup>34</sup> Both these reasons lead to the conclusion that red dwarf stars would provide more than enough time for orbiting exoplanets to develop the necessary processes for life.

#### Improvements for This Experiment

As previously mentioned, the transit of Gliese 436 b should be observed and plotted multiple times in order to have a significant amount of data to use when determining the radius of an exoplanet. These extra observing runs should also have at least some runs that are predicted to be back-to-back transits so that an experimental period can be calculated for as well.

The orbital radius can also be experimentally determined using Kepler's Third Law:

$$P^2 = \left[\frac{4\pi^2}{G(M+m)}\right] a^3 \tag{10}$$

where P is the period of the exoplanet, G is the universal gravitational constant, M is the mass of the host star, m is the mass of the exoplanet, and a is the semi-major axis.<sup>26</sup> The back-to-back transits would allow for the time between transits to be determined, and thus a value for P to be found. M can be found either from the literature or experimentally using a mass to luminosity relationship.<sup>26</sup> The exoplanet's mass can be ignored since it is assumed to be significantly smaller than the mass of the host star.<sup>26</sup>

An exoplanet's mass can be determined experimentally using the radial velocity method.<sup>26</sup> Red and blue fluctuations can allow for a determination as to the force of gravity from the host star.<sup>26</sup> Using Newton's Law of Gravity:

$$F_G = G \frac{Mm}{r^2} \tag{11}$$

where  $F_G$  is the force of gravity, G is the universal gravitational constant, M is the mass of the host star, m is the mass of the exoplanet, and r is the semi-major axis of the exoplanet's orbit around the host star.<sup>26</sup>

Lastly, an atmospheric spectroscopy would allow for analysis of the atmosphere to determine what compounds or elements make up the exoplanet's atmosphere.

If available resources and tools can be utilized, then this experiment can included all these methods in order to find experimentally determined values for many of the numbers from the literature available on Gliese 436 b.

### Future of Exoplanet Habitability Experimentation

At the present time, research into habitable exoplanets is limited to stars that can be observed with telescopes from earth or orbiting the earth. Although there is an estimated 4.2-5.3 trillion habitable exoplanets in the universe, only a small fraction of those can currently be studied.<sup>8,14</sup> This is because data has to be taken from individual stars in order to obtain useful information about exoplanet(s) orbiting the star. Therefore, distant stars and galaxies are precluded from having information obtained about individual exoplanets. It will take new methods or technologies in order to drastically increase the number of exoplanets discovered from the 3500 currently discovered by the Kepler Spacecraft.<sup>3</sup>

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