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Searching for Trends in the Atmospheres of Exoplanets

Wynter Broussard, Hielen Enyew, Shushmitha Radjaram, Rachel Ren, Manasa Yadavalli
Physical Sciences Division
University of Washington, Bothell
Bothell, Washington 98011 USA

Faculty Advisor: Prof. Paola Rodriguez Hidalgo, Dr. Stephen Kane

Abstract

The field of exoplanets has been experiencing rapid growth alongside the technological advances that have been made since exoplanets were first discovered in the 1990's. Several of the more than 4150 exoplanets which have been discovered so far have had their upper atmospheres probed with transmission spectroscopy. This form of spectroscopy uses the difference between the spectra of a star which is being transited by an exoplanet, and the spectra of the star when the exoplanet is being eclipsed, to characterize the exoplanet's upper atmosphere. The goal of this research is to gather previously published data in order to characterize potential trends relating exoplanets' physical properties to their atmospheric compositions. This research has focused on, among other classes, hot Jupiters with periods of less than 3.5 Earth days and with radii between one and three times the radius of Jupiter. There were 191 exoplanets within this parameter space, 24 of which had published spectral data in the wavelength range of 3000 - 9000 Å. No clear trends have been found relating the physical properties of the exoplanets in this search to the presence of sodium and/or potassium in their atmospheres. This type of study is important for future exoplanet missions.

Keywords: Exoplanets, Spectroscopy, Atmospheres

1. Introduction

As of June 2020, more than 4,150 extrasolar planets (planets orbiting a star other than our sun, hereafter referred to as exoplanets) have been confirmed[1]. Since the discovery of the first exoplanets in the 90's, the field of exoplanets has grown rapidly. Fifty-one of those confirmed exoplanets have been detected by the Transiting Exoplanet Survey Satellite (TESS), which launched in April 2018, and there are nearly 2,000 more TESS candidates waiting to be confirmed. This is exciting news: with TESS's ability to search the entire sky for transiting exoplanets, the number of confirmed exoplanets will grow quicker than ever before. Moreover, the field will become even more exciting in the near future with the expected launch of the James Webb Space Telescope (JWST), which will target the exoplanets identified by TESS in follow-up atmospheric studies[2,3].

In 2001, the exoplanet HD 209458b became the first exoplanet outside our solar system to have its atmosphere measured. A team of researchers used the technique of transmission spectroscopy to detect atomic sodium, confirming theoretical models which predicted sodium would be present in the atmosphere of this exoplanet[4,5].

Currently, a limited number of the confirmed exoplanets have published spectral data of their atmospheres. These data, acquired through transmission spectroscopy, are taken during the transit of the exoplanet (figure 1). As an exoplanet makes its transit, stellar radiation passes through the thin upper atmosphere of the exoplanet. Depending on the composition of the exoplanet's atmosphere, that radiation will either be blocked or transmitted at different wavelengths. If a particular element is present in the atmosphere of an exoplanet, stellar radiation will be blocked by the atmosphere at the wavelength that is unique to that element. By blocking more light, the radius of the exoplanet will appear larger at that particular wavelength where an element is being absorbed.

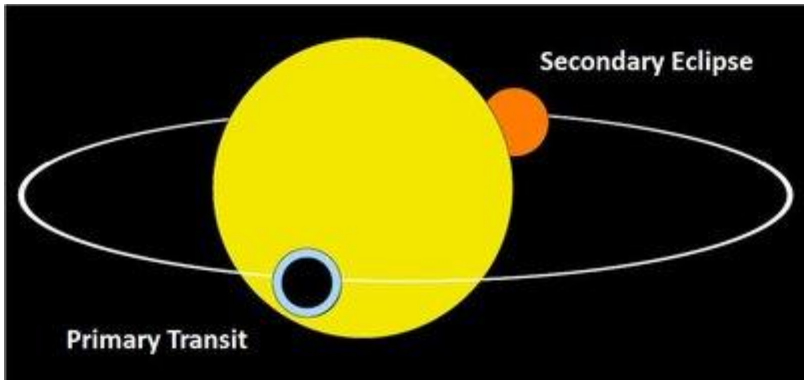

Figure 1. Diagram of an exoplanet's transit. Image courtesy of Sara Seager (MIT).

As an exoplanet makes its transit (labelled primary transit), it passes between the Earth and its host star. Then, it is eclipsed by the host star, so that the host star is between the exoplanet and the Earth (labelled secondary eclipse).

Two spectra are taken: one of the exoplanet-star combination during the exoplanet's transit, and another of the star alone when the exoplanet is being eclipsed. The exoplanet's spectrum will show in the difference between the in-transit spectrum and the eclipse spectrum: this transmission spectrum will show the change in radius of the exoplanet with respect to the radius of the star (R_p/R_*) as a function of wavelength. Thus, we can know the composition of an exoplanet by measuring it with transmission spectroscopy[6].

Exoplanets with short periods and large radii are ideal to study with transmission spectroscopy. An exoplanet's orbital period is the time it takes for it to make one complete revolution about its host star. Thus, exoplanets with short periods also transit more frequently, and can be observed more frequently. Likewise, exoplanets with very large radii are favored because they block a large fraction of stellar flux that they block is larger than the fluctuations in the instrument which is collecting data, the noise of the interstellar medium, and the variability in flux of the host star. In other words, they have a very high signal to noise ratio.

Hot Jupiters are gas giant exoplanets which have a mass roughly greater than or equal to the mass of Jupiter, and are located close to their host star[6]. Due to their close stellar proximity, hot Jupiters have very high temperatures. This combination of large mass, stellar proximity, and hot temperature also means that these exoplanets have bloated atmospheres, which allow large amounts of stellar radiation to pass through. The more stellar radiation that can pass through an exoplanet's atmosphere, the more apparent the exoplanet's absorption features will be, meaning hot Jupiters are ideal exoplanets for transmission spectroscopy[2,6].

Exoplanet atmospheres evolve with the exoplanet as it forms, so it is expected that the exoplanets which have evolved to have similar physical and orbital properties will also have similar atmospheric compositions. Although the number of atmospheric characterizations is growing, few studies have been conducted with the purpose of analyzing the available data to determine if there are any trends relating exoplanet atmospheric compositions to their physical and orbital properties[7,8]. This is the goal of our research.

Originally, this search focused on hot Jupiters with periods from one to three Earth days, and with radii between one and two times the radius of Jupiter[9]. There were 78 exoplanets in this data set, which used the updated list of exoplanets from February 2017[9]. After conducting a thorough literature search, only 17 of the 78 were found to have published transmission spectroscopy data. Of the 17 exoplanets with published transmission spectroscopy data, only 8 had published that data in the overlapping wavelength range of 4800 - 9000 Å[9]. Two exoplanets out of the 8 with usable spectra had detected atmospheric absorption, and the two exoplanets which showed atmospheric absorption were in the middle of the parameter space, thus no trends could be characterized in this search[9]. In the current search, the parameter space of interest was expanded to include exoplanets with periods of up to three and a half Earth days: this expansion more than doubled the number of exoplanets in the search space, from 78 exoplanets to 191.

Section 2 details the methods used in this research, and includes a summary of limitations. Section 3 contains a description of the data and an analysis of the statistical significance of any findings. A discussion of these findings in the context of future exoplanet missions is included in section 4. Section 5 includes a conclusion and future work.

2. Methodology

2.1 Data & Methods

The Habitable Zone Gallery (HZG)[1], created by Dr. Stephen Kane and Dr. Dawn Gelino, is a website which gathers names and physical parameters (such as mass, orbital period, radius, eccentricity and argument at periastron) from the NASA Exoplanet Data Explorer (EDE)[2] and it calculates (1) the extent of the habitable zone around each star, (2) the percentage of time each exoplanet spends in its stars' habitable zone, and (3) the equilibrium temperatures for the exoplanet at periastron (when it is closest to its host star) and at apastron (when it is furthest away from its host star), either assuming the atmosphere is completely efficient at redistributing heat (the 'well-mixed' model), or assuming it is completely inefficient at redistributing heat (the 'hot-dayside' model)[10]. These calculations can be completed as long as the luminosity of the host star is known, and the exoplanet-star separation is known. Stellar luminosity can be approximated with the stellar radius effective temperature; exoplanet-star separation can be found with the semimajor axis and eccentricity of the exoplanet's orbit.

Our research focuses on the following physical properties: mass, radius, density, period, and temperature. Exoplanetary mass, radius, and density are all defined in terms of Jupiter: 1 M_j , 1 R_j, and 1 ρ_j are equal to the mass of Jupiter, the radius of Jupiter, and the average density of Jupiter, respectively. Exoplanet mass can be directly measured or estimated as a minimum mass, which can be calculated from orbital parameters and the mass of the host star. The mass values provided in the HZG are those for which the NASA EDE has provided an accurate estimate of the exoplanets' mass. Average density is a straightforward calculation; for this physical parameter, the author wrote a code which took each exoplanet's M_j and R_j and returned a value for the average density of the exoplanet in terms of the average density of Jupiter, ρ_j.

The HZG calculates the four equilibrium temperatures mentioned previously, measured in Kelvin. The differences between the four temperatures is not very large. For the purpose of this search, the equilibrium temperature calculated at periastron using the hot-dayside model has been used because it provides the hottest estimate for the exoplanets in this search.

A python code, written by Troy Maloney and Kassandra Weber, took data provided by the HZG and returned the names of the exoplanets within the desired parameter space[11,9]. The expanded search included 191 exoplanets. Of these 191 exoplanets, 27 had published spectral data, and 24 of those exoplanets had published spectral data in the overlapping wavelength range of 3000 - 9000 Å. The 24 exoplanets, and their parameters, have been included in Table 1.

To determine if an exoplanet has a particular element in its atmosphere, the conclusions of those who authored the papers have been used. If an exoplanet has only one paper with published transmission spectroscopy data available, the conclusions of that paper are followed. When there are multiple papers available for an exoplanet, a set of criteria is used to evaluate the available literature for each exoplanet. These criteria allow each author's conclusion to be taken into account, while assigning the most weight to the most recently published paper.

The criteria first take into account the significance of the detection/nondetection of a particular element in each paper. Sigma (σ) represents the signal to noise ratio of an observation, and it is used to determine the significance of a detection. A larger value for σ means that the element's signal coming from the exoplanet atmosphere was stronger than the sources of noise, indicating that the detection is more significant. For a detection to be made the value of R_p/R_* must be at least 1σ higher than the noise. To result in a conclusive detection, a σ value of greater than 2.5σ is necessary.

For this research, if all published literature find an element to be present in the atmosphere of an exoplanet at a significance of at least 2.5σ, definite absorption is concluded. If disagreement is found in the literature, the exoplanet can still be determined to have definite absorption if the most recently published paper finds evidence of the element at a significance of greater than 3σ, or if there is evidence of time-varying hazes which periodically obstruct an observation, as is the case with the exoplanet HD 189733b[12,13,14,15]. Otherwise, the exoplanet may still be determined to have potential absorption if the papers generally find that absorption is present at a significance from 1-2.9σ, or if the authors do not explicitly make a conclusion about the presence or absence of an element, but the feature can be clearly seen in the exoplanet's transmission spectrum.

Of the 24 exoplanets with previously published atmospheric data, 9 show potential or definite absorption. The exoplanets are as follows:

- Definite sodium and definite potassium: WASP-103b
- Definite sodium and potential potassium: HD 189733b, WASP-19b, WASP-52b, and WASP-96b
- Potential sodium: WASP-4b and WASP-121b
- Definite potassium: WASP-31b
- Potential potassium: WASP-6b

Table 1. The 24 exoplanets with overlapping spectral data, with their physical parameters included.

Planet	Period (Days)	Radius (Rj)	Temperature (K)	Mass (Mj)	Average Density (ρj)
CoRoT-1b	1.5	1.49	1741	1.03	0.31
HAT-P-23b	1.2	1.09	2057	1.34	1.03
HAT-P-32b	2.2	1.86	1782	0.83	0.13
HD189733b	2.2	1.13	1203	1.13	0.78
Qatar-1b	1.4	1.143	1418	1.294	0.87
Qatar-2b	1.3	1.254	1348	1.494	1.26
TrES-3b	1.3	1.336	1640	1.91	0.80
WASP-103b	0.9	1.528	2508	1.49	0.42
WASP-12b	1.1	1.82	2582	1.183	0.20
WASP-121b	1.3	1.865	2354	1.183	0.18
WASP-19b	0.8	1.392	2100	1.069	0.40
WASP-31b	3.4	1.549	1574	0.478	0.13
WASP-33b	1.2	1.06	2649	1.17	0.98
WASP-36b	1.5	1.327	1738	2.361	1.01
WASP-4b	1.3	1.33	1670	1.18	0.50
WASP-45b	3.1	1.14	1197	1.04	0.70
WASP-46b	1.4	1.174	1639	1.91	1.18
WASP-48b	2.1	1.5	2032	0.8	0.24
WASP-49b	2.8	1.11	1370	0.37	0.27
WASP-52b	1.7	1.27	1299	0.46	0.22
WASP-6b	3.4	1.03	1185	0.37	0.34

WASP-74b	2.1	1.36	1916	0.72	0.29
WASP-96b	3.4	1.2	1286	0.48	0.28
WASP-98b	3	1.144	1170	0.922	0.62

2.2 Limitations

The main limitations in the methods of this research come from how the literature search is conducted. To search for papers with previously published transmission spectroscopy data, several search terms are used to cover the range of ways authors may write up their results in an abstract. For instance, when searching for papers for the exoplanet WASP-103b, search terms were included for each way the exoplanet name might have been written (WASP-103b, WASP 103b, or WASP-103 b) as well as a search term for each of the different ways the use of transmission spectroscopy may have been indicated (transmission spectroscopy, transmission spectra, transmission spectrum, etc.). However, if an author does not include any of these terms in their abstract, papers with information about some of the exoplanets in the sample may have been missed.

In terms of the data found in the literature, there are a number of factors which limit the study of exoplanet atmospheres, thus limiting this research. First, many of the studies suffer from low spectral resolution, and the resulting data are not clear enough to make a conclusive detection[16,17,18,19,20,21]. Second, the dynamic natures of the exoplanet atmospheres themselves act as limitations, as seen with the atmosphere of HD 189733b, for which sodium detections can be made only when time-varying hazes are not obscuring the sodium feature[12,13,14,15]. Just like the Earth's atmosphere has changing weather patterns and cloud covers due to varying atmospheric conditions, time-evolving conditions in hot Jupiters can determine whether or not a feature can be observed.

3. Analysis

The Kolmogorov-Smirnov test (K-S test) is a nonparametric statistical test which can be used to compare two samples in order to determine the probability that the samples were drawn from the same parent population. The K-S test was used for each of the individual physical and orbital parameters, to test whether the distribution of physical properties for exoplanets with absorption is the same for all the exoplanets in our search, to see if the distributions are statistically different. To conduct this test, four types of lists were created: (1) 10 lists, five for each of the physical properties of the 9 exoplanets with potential and/or definite absorption of sodium, and five for each of the physical properties of the 9 exoplanets with potential and/or definite absorption of potassium (2) 10 lists, five for each of the physical properties of the five exoplanets with definite sodium absorption, and five for each of the physical properties of the two exoplanets with definite potassium absorption, (3) 5 lists, one for each of the physical properties of all 24 exoplanets, and (4) 5 lists, one for each of the physical properties of all 191 exoplanets in the search space. The K-S test determines the probability that any two of these distributions came from the same population; a p-value smaller than 0.03 would reject the hypothesis that they come from the same population, and it would indicate a trend.

The test was conducted forty times: comparing lists 1 with 3, 1 with 4, 2 with 3, and 2 with 4. By conducting this test, no significant trends were found relating the presence of sodium and/or potassium in an exoplanet's atmosphere to their mass, radius, average density, period, or equilibrium temperature. This is the case whether or not the test was conducted for exoplanets with only definite absorption, or for exoplanets with potential and/or definite absorption. Likewise, the test resulted in no significant trends when using just the 24 exoplanets with previously published literature, and when using all 191 exoplanets in our search space. The smallest p-value found was 0.054, although the average for all the p-values was 0.57.

These results indicate that the 9 exoplanets with absorption are a random sample, drawn from the same population of all exoplanets in the HZG with both period and radius data. In other words, any of the exoplanets in the search could have been found to have potassium/sodium absorption; there is nothing significant about the individual physical properties of the 9 exoplanets which showed absorption.

Having found no significant trends relating potassium/sodium absorption to a single parameter within our current sample, trends relating potassium/sodium absorption to combinations of parameters were investigated. By plotting each combination of parameters, as shown in figure 2, we can accomplish this qualitatively. By visually inspecting figure 2, it seems that there is no clear connection between an exoplanet's sodium or potassium absorption status and where it appears within the figure. Exoplanets determined to have definite or potential absorption of potassium and/or sodium are spread out throughout this figure, thus no trend can be concluded from visual inspection. However, in order to have the same rigorous results as with single-parameter trends, a method of adapting the K-S test so that it could be utilized to conduct a 2-dimensional test was investigated.

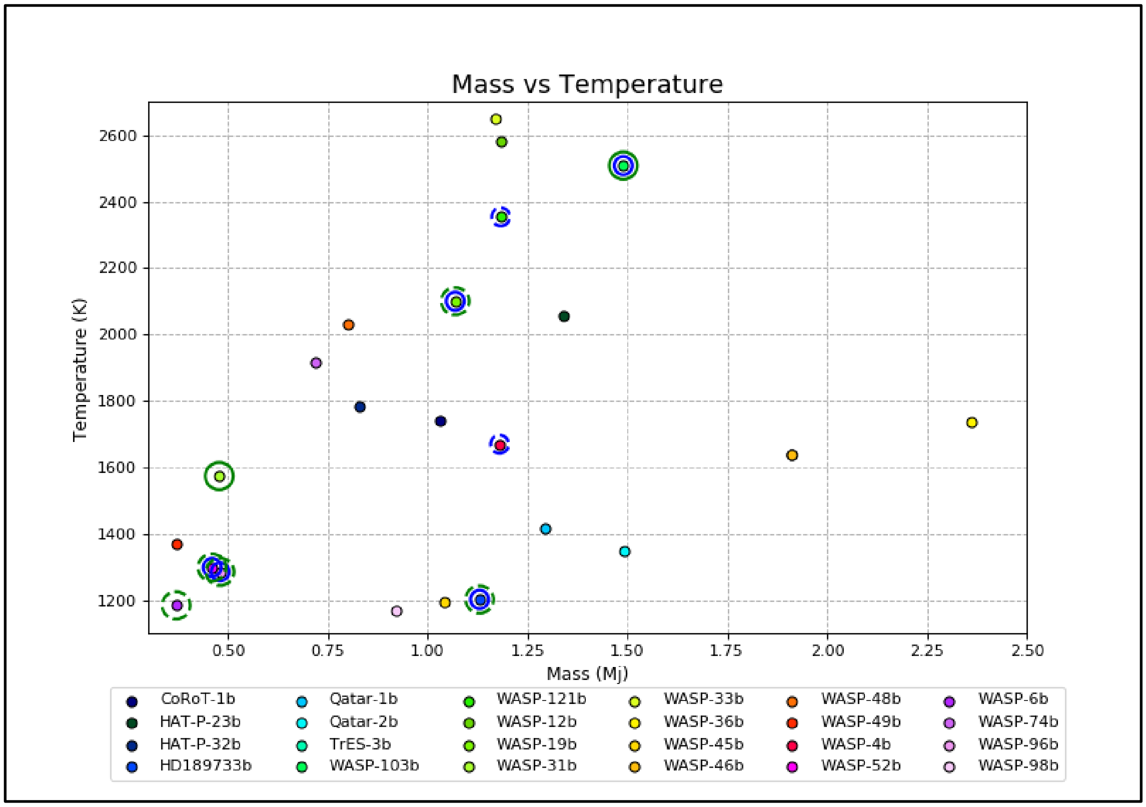

Figure 2. Plot of mass vs. temperature of the 24 exoplanets in this search.

This plot shows the mass vs temperature values of the 24 exoplanets included in this search. The 9 exoplanets which show absorption are indicated with circles: a blue circle for sodium absorption, green for potassium absorption. A solid circle represents definite absorption, whereas a dashed circle represents potential absorption.

To conduct the 2-dimensional K-S test, we used a code created by Github user syrte[3]. To conduct this test, four types of lists were created: (1) 15 lists, five for each of the physical properties of the 9 exoplanets with potential and/or definite absorption of sodium, five for each of the physical properties of the 9 exoplanets with potential and/or definite absorption of potassium, and five lists for each of the physical properties of the 9 exoplanets with potential and/or definite absorption of potassium and/or sodium (2) 15 lists, five for each of the physical properties of the five exoplanets with definite sodium absorption, five for each of the physical properties of the two exoplanets with definite potassium absorption, and five lists for each of the physical properties of the one exoplanet which had both definite potassium absorption and definite sodium absorption (3) 5 lists, one for each of the physical properties of all 24 exoplanets, and (4) 5 lists, one for each of the physical properties of all 191 exoplanets in the search space. Although the atmospheric compositions of all 191 exoplanets in the search space is largely unknown, the fourth type of list was included to determine if the exoplanets with published atmospheric data occupied a particular part of the search space as a whole.

The test was conducted sixty times: comparing lists 1 with 3, 1 with 4, 2 with 3, and 2 with 4. By conducting this test, no significant trends were found within our current sample which relate the presence of sodium and/or potassium in an exoplanet's atmosphere to any combination of their mass, radius, average density, period, or equilibrium temperature. This is the case whether or not the test was conducted for exoplanets with only potential absorption, or for exoplanets with potential and/or definite absorption. Likewise, the test resulted in no significant trends when using just the 24 exoplanets with previously published literature, and when using all 191 exoplanets in our search space. The smallest p-value found was 0.042, although the average for all the p-values was 0.45.

4. Discussion

A previous study, conducted by Sing et al., compared water absorptions in the spectra of 10 hot Jupiters and found that, when present in an exoplanet's atmosphere, clouds and hazes weaken the spectral strength of water[7]. The exoplanets in their study have similar radii to ours (0.96 - 1.89 R_j), masses (0.21 - 1.40 M_j), and orbital periods (0.79 - 4.46 days); indeed, there is an overlap of 5 exoplanets between our study and the study conducted by Sing et al.[7] In their study, out of 5 cases with absorption due to water, 4 also showed sodium absorption, and the R_p/R_* values for both absorption features seemed to be correlated with each other (see Figure 1 in Sing et al., 2016).

However, another study conducted by Wellbanks et al. analysed the absorption features of water, sodium, and potassium in their study of 19 hot Jupiters, including the 10 studied in the aforementioned study by Sing et al.[7,8] They found that there was a one-to-one correlation between the relative abundances of sodium and potassium, but this was not the case for water/potassium relative abundances[18]. With our future work set to include absorption due to water, we hope to find results which clarify the relations between water and other metals in the atmospheres of hot Jupiter exoplanets.

This research has explored the relationship between the individual physical parameters of the exoplanets in this search and their atmospheric absorption, and the relationship between combinations of physical parameters and atmospheric absorption. No significant trends have been observed in our current sample of exoplanets. With only 9 of the 24 exoplanets in this search showing potential and/or definite absorption, this research may still be limited in the ability to recognize trends by small sample size.

As is the case with our research, both Sing et al. and Wellbanks et al. suggest that they have small numbers, and larger studies need to be carried out to reach any conclusions[7,8]. In particular, Sing et al. stated that future studies will benefit from atmospheric surveys which are able to differentiate exoplanets with cloudy atmospheres from those with clear atmospheres; then, exoplanets with clear atmospheres could be targeted for further study, which would allow us to determine valuable constraints on hot Jupiter formation models[7]. New exoplanet surveys, such as the JWST, will need to decide which previously observed exoplanets get follow-up observations. Finding a trend relating the atmospheric compositions of exoplanets to their physical parameters could help inform researchers about their target selections, and may be a factor in deciding which exoplanets are selected for those follow-up observations.

5. Conclusion

This research has explored the relationships between the physical parameters and atmospheric compositions of hot Jupiters with periods of up to 3.5 Earth days, and radii between one and two times the radius of Jupiter. No clear trends have been found relating the physical properties of the exoplanets in this search to the presence of sodium and/or potassium in their atmospheres, neither in individual magnitudes nor in combinations of them. The number of exoplanets with transmission spectral data is still small; of the original 191 in this search, only 24 had published spectral data in the wavelength range studied. Of those, only 9 showed potential or definite potassium and/or sodium absorption..

Future work includes uploading these results to the Habitable Zone Gallery so the scientific community can have easy access to them. Additionally, this search will be expanded to include more exoplanets, hopefully increasing the number of exoplanets found to show absorption. The wavelength region of interest will also be expanded to include wavelengths from 3000 - 17000 Å; in this wavelength range, atmospheric features from potassium, sodium, and water can be seen. Investigating this wavelength region further will help clarify the relationships between atmospheric absorption features, as well as provide insight for future exoplanet missions.

6. Acknowledgements

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8. Endnotes

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