SEARCHING FOR TRENDS IN THE ATMOSPHERES OF EXOPLANETS

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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. More than 4,100 exoplanets have been confirmed, and that number will only continue to grow (NASA Exoplanet Archive). Several of these exoplanets have had their upper atmospheres probed with transmission spectroscopy. The goal of our research is to gather previously published transmission spectroscopy data in order to characterize trends relating exoplanets physical properties to their atmospheric compositions. We have studied 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 planets within this parameter space. We will present our results on the 24 exoplanets with spectral data in the wavelength range of 3000 - 9000 Å.

1. Introduction

In 2001, sodium was detected in the atmosphere of the exoplanet HD 209458b, making it the first planet outside our solar system for which an atmospheric measurement had been made (Charbonneau et al. 2002). This detection confirmed theoretical models which predicted sodium to be present in the atmosphere of this exoplanet (Seager & Sasselov, 2000).

Since this detection, a limited but growing number of the more than 4,100 exoplanets we have confirmed to date have published atmospheric data. These data are acquired through transmission spectroscopy. As an exoplanet transits its host star, the radius of the planet will appear to be larger at the particular wavelength where that element is being absorbed, because more stellar radiation is being blocked by the planet. We can directly measure the radius of a transiting exoplanet through transit photometry, collecting the total amount of light coming from a planet-star combination while the planet is transiting, and when the planet is being eclipsed by its host star. The dip in total flux caused by the transit of the exoplanet can be used to directly calculate the radius of an exoplanet. When we know the radius of the planet independent of wavelength, we can then use transmission spectroscopy.

As an exoplanet makes its transit, passing between the Earth and its host star, stellar radiation passes through the thin upper atmosphere of the exoplanet, allowing the spectral features of the planet to appear where the emitted stellar radiation is absorbed by the exoplanet's atmosphere passes through the planet's atmosphere. A spectrum is taken of the planet-star combination. Then, as the exoplanet is eclipsed by the star, a spectrum of the star alone is obtained. The planet's spectrum will show in the difference between the in-transit spectrum and the eclipse spectrum. This transmission spectrum shows how the radius of the planet changes with respect to the radius of the star: R_p/R_*, which changes as a function of wavelength. If a particular element is present

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in the atmosphere of an exoplanet, light passing through the exoplanet's atmosphere at that wavelength will be absorbed: it will not reach the observer on Earth. Thus, we can know the composition of an exoplanet by measuring it with transmission spectroscopy.

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 (Sing et al. 2016; Wellbanks et al. 2019). This is the goal of our research.

Our research so far has focused on hot Jupiters. 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 (Seager, 2010). This generally means that the planet is less than 0.1 astronomical units (AU; the average distance from the Earth to the sun), which also means hot Jupiters have very short periods (Seager, 2010). The period of an exoplanet is the time it takes to make a full orbit of its host star, measured in Earth days; hot Jupiters typically have periods of less than 10 days. 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; these atmospheres 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 planet's absorption features will be, meaning hot Jupiters are ideal planets for transmission spectroscopy.

In this paper, we describe the results of our search for trends relating their physical and orbital properties to the presence of sodium and potassium in their atmospheres. In section 2, we describe the physical and orbital parameters we are interested in, how we obtain our data, and the planets we have worked with. In section 3 we present our analysis and results; we will discuss which of the planets in our search showed absorption, and present an analysis on our results. Section 4 provides a discussion of how our results fit into the broader picture of the field of exoplanets. In section 5, we will present our conclusions and plans for future work.

2. Methods and Data

2.1 The Habitable Zone Gallery

The Habitable Zone Gallery (HZG), 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) and it calculates (1) the extent of the habitable zone around each star, (2) the percentage of time each planet spends in its stars' habitable zone, and (3) the equilibrium temperatures for the planet 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; Kane & Gelino 2012). These calculations can be completed as long as the luminosity of the host star is known, and the planet-star separation is known. Stellar luminosity can be approximated with the stellar radius effective temperature; planet-star separation can be found with the semimajor axis and eccentricity of the planet's orbit.

2.2 Planetary Information

For the purpose of our search, the planetary physical properties we are interested in are: mass, radius, density, period, and temperature.

Planetary 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 from, 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 actual mass, so for the planets in our search we have only used actual mass. Average density is a straightforward calculation; for this physical parameter, we have written a code which takes each planet's M_j and R_j and returns a value for the average density of the planet in terms of the average density of Jupiter, ρ_j.

The HZG calculates the four equilibrium temperatures mentioned in section 2.1, measured in Kelvin. The differences between the four temperatures is not very large. For the planets in our search, we used the equilibrium temperature calculated at periastron using the hot-dayside model. We expect this temperature to provide the best approximation for the conditions of the exoplanet atmospheres when they are being observed via transmission spectroscopy.

2.3 Data

A Python script, written by Troy Maloney and Kassandra Weber, takes HZG data and returns the names and physical information of the planets within the desired parameter space (Weber et al. 2019). In the original data set, we searched for planets with radii from 1 - 2 R_j, and with periods of up to 3 Earth days. There were 78 planets in this data set, which used the updated HZG data from February 2017 (Weber et al. 2019). For all of the planets in our study, the percentage of time they spend in it's stars' habitable zone is zero since they are hot Jupiters.

We conducted a comprehensive literature search for published data on the atmospheric compositions of the 78 planets in our data set. Of those 78 planets, only 15 had published transmission spectroscopy data, and only 8 had published that data in the overlapping wavelength range of 4800 - 9000 Å (Weber et al. 2019). One out of the 8 planets with usable spectra had detected atmospheric sodium absorption; WASP-52b. However, one data

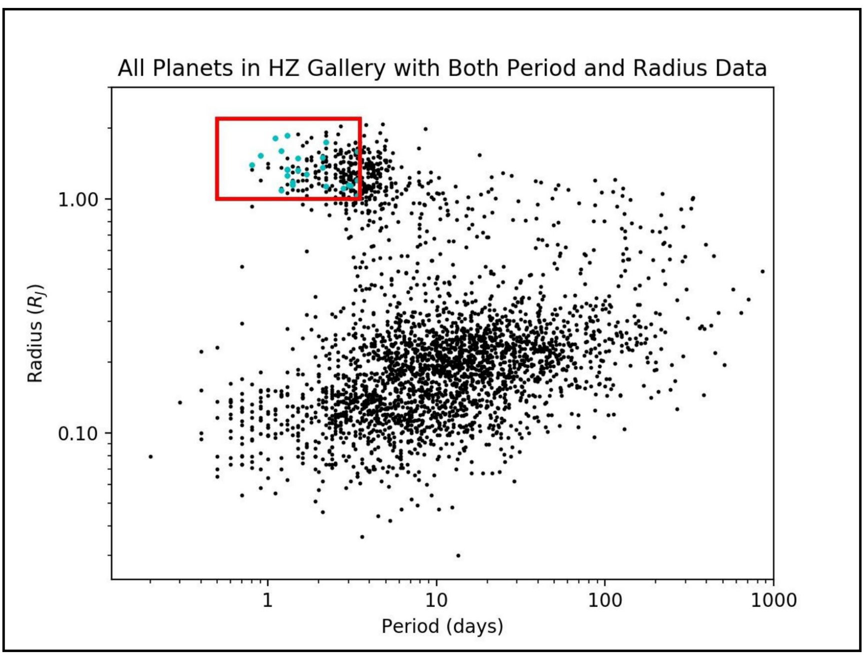


Figure 1. All planets in the habitable zone gallery, with the planets in our search lying within the red box. The 24 planets with published spectra from 3000 - 9000 Å are colored blue.

Table 1. 24 planets with overlapping spectral data, with physical parameters from the HZG included.

Planet	Period (Days)	Radius (Rj)	Mass (Mj)	Temperature (K)	Average Density (pj)
CoRoT-1b	1.5	1.49	1.03	1741	0.31137
HAT-P-23b	1.2	1.09	1.34	2057	1.03473
HAT-P-32b	2.2	1.86	0.83	1782	0.12899
HD189733b	2.2	1.13	1.13	1203	0.78315
Qatar-1b	1.4	1.143	1.294	1418	0.86655
Qatar-2b	1.3	1.254	2.494	1348	1.26475
TrES-3b	1.3	1.336	1.91	1640	0.80097
WASP-4b	1.3	1.33	1.18	1670	0.50156
WASP-6b	3.4	1.03	0.37	1185	3386
WASP-12b	1.1	1.82	1.183	2582	0.19623
WASP-19b	0.8	1.392	1.069	2100	0.39633
WASP-31b	3.4	1.549	0.478	1574	0.12861
WASP-33b	1.2	1.06	1.17	2649	0.98235
WASP-36b	1.5	1.327	2.361	1738	1.01038
WASP-45b	3.1	1.14	1.04	1197	0.70197
WASP-46b	1.4	1.174	1.91	1639	1.1804
WASP-48b	2.1	1.5	0.8	2032	0.23704
WASP-49b	2.8	1.11	0.37	1370	0.27054
WASP-52b	1.7	1.27	0.46	1299	0.22457
WASP-74b	2.1	1.36	0.72	1916	0.28623
WASP-96b	3.4	1.2	0.48	1286	0.27778
WASP-98b	3	1.144	0.922	1170	0.61582
WASP-103b	0.9	1.528	1.49	2508	0.41765
WASP-121b	1.3	1.865	1.183	2354	0.18237

point is not sufficient for determining a trend, thus no trends could not be characterized in this search (Weber et al. 2019).

Our present work has expanded the search space to include planets with periods of up to 3.5 Earth days, and we have used the updated HZG data from February 2019. There are 191 planets in this data set. Of these 191 planets, 27 had published spectral data, and 24 of those planets had published spectral data in the wavelength range of 3000 - 9000 Å. Figure 1 shows the 24 planets colored in blue; a list of the planets and their parameters has been included in Table 1.

2.4 Limitations

With respect to our methods, the main limitations come from how we conduct the literature search. We are looking for published papers with transmission spectroscopy data for every planet in our search box; to accomplish this, we must use several search terms which cover the range of ways the planets might be written in the abstract. For instance, when searching for papers for the planet WASP-103b, we had to include search terms for every way the planet name might be written (WASP-103b, WASP 103b, or WASP-103 b) as well as a search term for each of the different ways the author might indicate the use of transmission spectroscopy (transmission spectroscopy, transmission spectra, transmission spectrum, etc.). However, if an author does not include any of these terms in their abstract, we might miss papers with information about some of the planets in our sample.

In terms of the data found in the literature, there are a number of factors which limit the study of exoplanet atmospheres, which in turn limits our research. First, many of the studies suffer from low spectral resolution, and the resulting data are not clear enough to make a conclusive detection (Mancini et al. 2013;

Huitson et al. 2013; Louden et al., 2017; Delrez et al., 2018; Evans et al., 2018; May et al., 2018). 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 (see section 3.1.1). Just like our own atmosphere has changing weather patterns and cloud covers due to varying atmospheric conditions, time-evolving conditions in the hot Jupiters we study can determine whether or not a feature can be observed.

3. Analysis & Results

3.1 Previously Published Data

Below, we present our results for the nine planets out of the 24 with published transmission spectra in our wavelength range of interest which show potential or definite sodium and/or potassium absorption. To conclude definite absorption, we follow the conclusions made by the authors who published the transmission spectroscopy data we have used. When there are multiple papers available for a planet, we take the conclusions of each author into account, and assign the most weight to the most recently published paper.

In a transmission spectrum, sodium absorption can be seen around 5890 Å; potassium absorption can be seen around 7665 Å. For a detection of either element to be seen in the transmission spectrum, the planetary radius must be larger than the radius found via transit photometry. However, a planet may have an increased radius around these wavelengths without resulting in a detection; transmission spectroscopy is frequently low in resolution, and there is often noise contaminating the data. There are many different sources which can create noisy data, including instrumental errors and variability of the host star. For a detection to be made, the signal from the planet must be stronger than the noise.

To determine the significance of a detection we use sigma (σ), which represents the signal to noise ratio. A large value for σ means that the signal from the exoplanet atmosphere was stronger than the sources of noise, indicating that the detection is more significant. Error bars for the values of R_p/R_* are typically given at the 1σ level. For a detection to be made, the radius of the planet at the wavelength of interest must be elevated at least 1σ above the surrounding points; to be significant, the radius should be even greater than just a 1σ increase.

Of the 24 planets with previously published atmospheric data, 9 show potential or definite absorption. The planets 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

Below we discuss how these classifications were made based on the information in the literature for the planets with definite or potential absorption:

3.1.1 HD 189733b

This exoplanet shows conclusive sodium absorption and potential potassium absorption, at least at times since at other times hazes prevent absorption.

Sodium: Pino et al. combined high-resolution and low-resolution spectroscopy to study the atmosphere of this exoplanet in more depth, and found evidence for definite sodium absorption (2018). Previously, Redfield et al. made the first detection of sodium in this planet's atmosphere (2008), however later, Sing et al. found that the transmission spectrum of HD 189733b was dominated by a global haze obscuring any alkali metal absorption features (2011). Huitson et al. also found sodium in HD 189733b's atmosphere at a significance of 9σ (2012). Pont et al. found a relatively flat transmission spectrum; however, they noted that a strong core of sodium could be seen (2013).

Potassium: Pino et al. did not make a detection of potassium, though they mentioned this feature may be present in the spectrum, smeared out due to the low resolution of the Advanced Camera for Surveys, an HST instrument, at that wavelength (Pino et al. 2018). Pont et al. found a relatively flat transmission spectrum, noting that a strong core of potassium was possible (2013).

3.1.2 WASP-4b

This exoplanet shows potential sodium absorption.

Sodium: Huitson et al. found evidence for sodium absorption at a significance of 2σ: too low to be a conclusive detection, but significant enough to suggest potential sodium (2017).

3.1.3 WASP-6b

For exoplanet WASP-6b, there is potential sodium absorption

Sodium: Nikolov et al. specified that while there is no indication of wide absorption features of sodium, there is tentative evidence for potential sodium at a significance level of 1.2σ (2015). Previously Jordan et al. found no evidence for sodium absorption, and concluded that higher resolution observations would be needed (2013).

3.1.4 WASP-19b

This exoplanet shows definite sodium absorption and potential potassium absorption.

Sodium: Most recently, Sedaghati et al. reported a 3.9σ detection of sodium in the atmosphere of WASP-19b (2017). Previously available literature featured data which were too low in resolution, or had too many uncertainties, to ame a detection of sodium (Mancini et al. 2013; Huitson et al. 2013; Sedaghati et al. 2015).

Potassium: Sedeghati et al. determined that potassium was moderately favored by the data, but could not make a detection (2017).

3.1.5 WASP-31b

This exoplanet shows conclusive potassium absorption.

Potassium: Potassium in WASP-31b was first detected by the Hubble Space Telescope in 2015 (Sing et al.). This detection was made at a significance of 4.3σ (Sing et al., 2015). In 2017, Gibson et al. presented a different method for concluding potassium absorption (2017). Using the ground-based Very Large Telescope (VLT), the potassium absorption recovered by the HST was ruled out. Instead, Gibson et al. combined the transmission spectrum produced by the HST with the spectrum they obtained using the VLT; in doing so, they were able to conclude a 2.2σ detection of potassium (2017).

3.1.6 WASP-52b

The exoplanet WASP-52b has definite sodium absorption and potential potassium absorption.

Sodium: In 2018, Alam et al. was able to detect sodium at a significance of 2.3σ in the atmosphere of WASP-52b. This exoplanet's first detection of atmospheric sodium came from Chen et al. in 2017. May et al. and Louden et al. searched for this feature, but could not conclude a detection due to the low resolution of their data (2018; 2017).

Potassium: Chen et al. found potassium at a significance of 2.2σ, which they determined was not high enough to make a conclusive detection, but is still suggestive of potential potassium (2018).

3.1.7 WASP-96b

We can conclude definite sodium and potential potassium for this exoplanet.

Sodium: Nikolov et al. could clearly resolve sodium in their transmission spectra, and determined the element to be present in the atmosphere of WASP-96b (2018).

Potassium: Nikolov et al. made a small detection of potassium, at a level just below statistical significance; thus, no definite conclusion of potassium could be made (2018).

3.1.8 WASP-103b

This planet shows definite sodium and definite potassium absorption.

Sodium: In 2017, Lendl et al. were able to find strong signs of potassium in the atmosphere of WASP-103b. Because of WASP-103b's large mass, the amplitude of the sodium feature was expected to be small; despite this, Lendl et al. were able to detect a signal of sodium that was even larger than the predicted value (2017). Delrez et al. also observed the atmosphere of WASP-103b and found some evidence for sodium absorption, but not enough to make a conclusion; they indicated that data of a higher resolution would be necessary to confirm the presence of sodium (2018).

Potassium: Along with the sodium detection, Lendl et al. detected definite potassium absorption in the atmosphere of WASP-103b, again with a larger signal than that which had been predicted (2017). For Delrez et al., some evidence of potassium absorption was present in the data, but further observations would be necessary to make a conclusive potassium detection (2018).

3.1.9 WASP-121b

The exoplanet WASP-121b has potential sodium absorption.

Sodium: Sodium is weakly favored in data obtained by Evans et al. (2018). Observations of a higher resolution would be needed to confirm this feature, but an increased value for R_p/R_* can be seen at the wavelength expected for sodium absorption.

3.2 Analysis & Results

To begin with, we conducted a Kolmogorov-Smirnov test (K-S test) for each of the individual parameters, to test if there is a connection between planets which show absorption and any of the individual physical and orbital parameters. To conduct this test, we create two lists; a list of the masses of the 9 planets with absorption, and a list of the masses of all 24 planets. The K-S test determines the probability that these two lists came from the same population. Testing for a significance level of 0.03, we would conclude a trend if the probability that the two lists came from the same population was less than 3%.

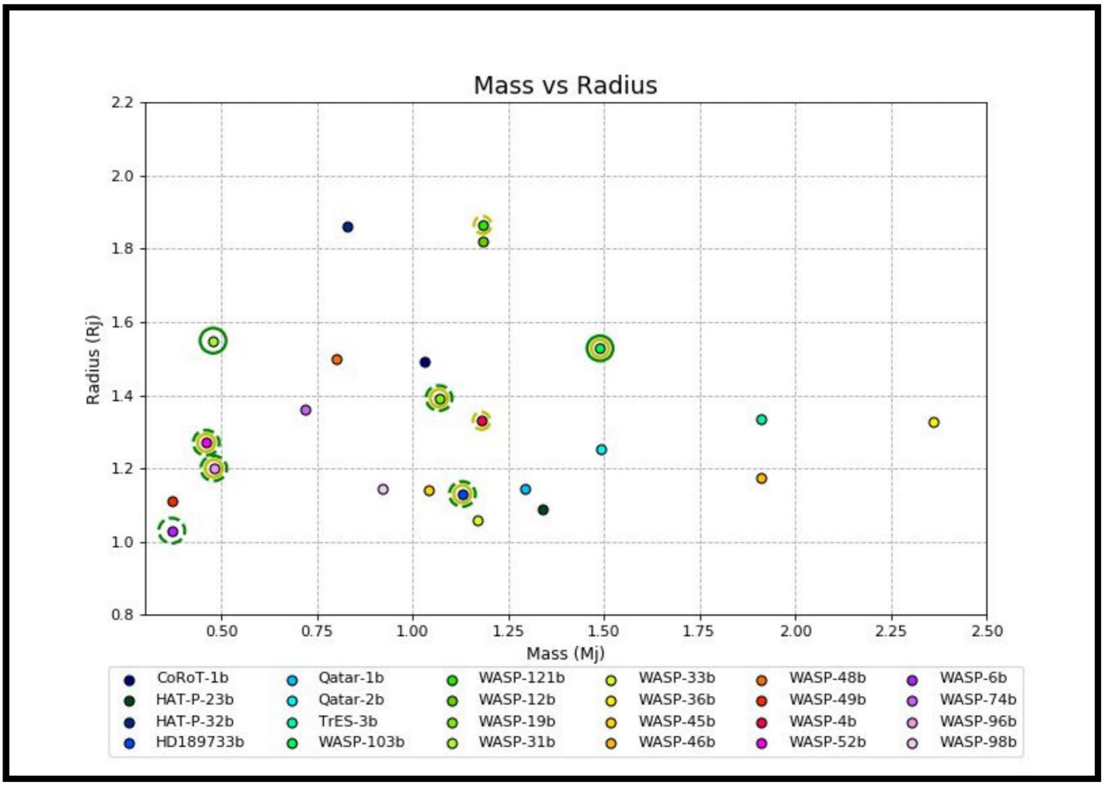
By conducting this test, we found no trends relating the presence of sodium and/or potassium in an exoplanet's atmosphere to their mass, radius, average density, period, or equilibrium temperature. For most of the physical properties, there is more than an 89% probability that the 9 planets with absorption are a random sample, drawn from the same population of all planets in the HZG with both period and radius data. In other words, any of the planets in our search could have been found to have potassium/ sodium absorption; there is nothing significant about the individual physical properties of the 9 planets which showed absorption.

Beyond trends relating potassium/sodium absorption to a single parameter, we wanted to see if we could find a trend relating absorption to a combination of parameters. Figures 2 - 11 show plots comparing the different parameter combinations. Only planets with definite or potential absorption are circled: planets which show definite sodium/potassium absorption have a solid yellow/green circle, respectively; planets which show potential sodium/potassium absorption have a dashed yellow/green circle.

We are looking for trends which relate the planets which show potential and/or definite absorption to a certain part of the parameter space. For instance, do planets which show absorption all have the smallest radii and the largest periods? Does any planet with an average density of less than one times the density of Jupiter, and a radius of between 1.5 R_j and 1.7 R_j show potential potassium absorption?

Looking at the plot of mass vs. radius (figure 2), we see no trends relating these two parameters to the presence of sodium and/or potassium. 18 of the 24 planets have masses of less than 1.5 M_j and radii of less than 1.6 R_j.

Figure 2. Plot of mass vs. radius of the 24 planets.

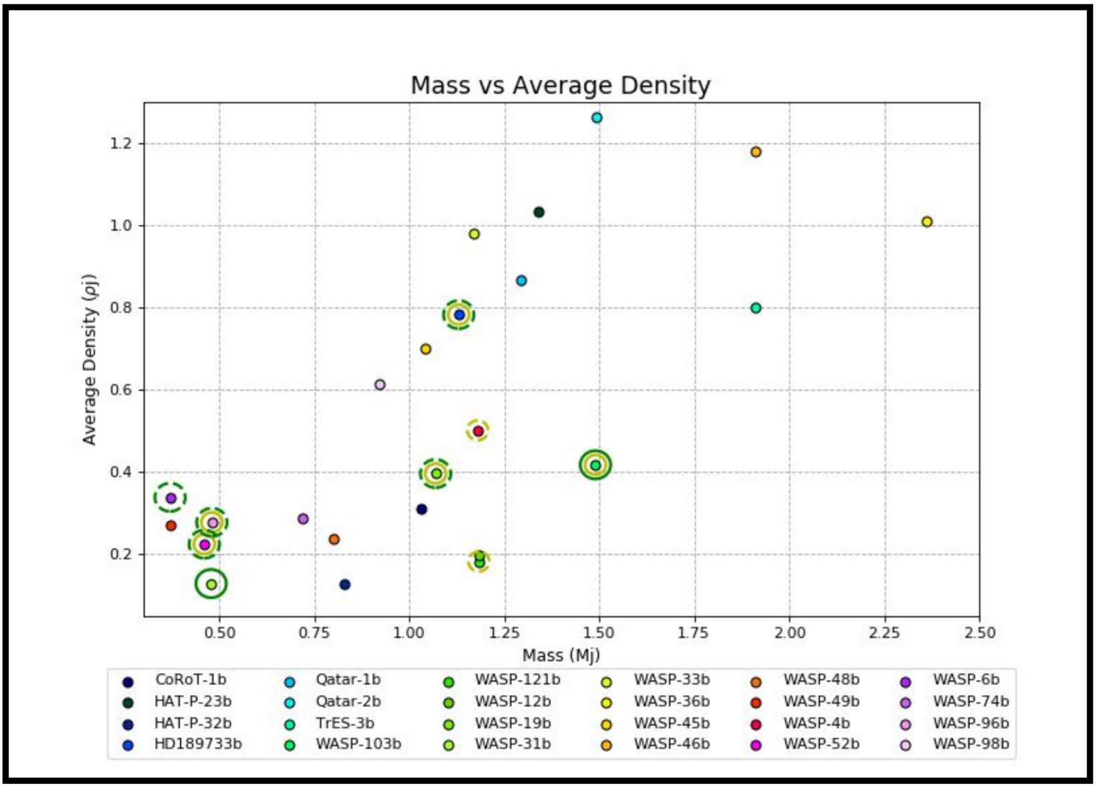


From the 6 planets that have a mass greater than 1.5 M_j or a radius greater than 1.6 R_j, only one (WASP-121b) shows absorption. In the space containing planets with masses of less than 1.5 M_j and radii of less than 1.6 R_j there are 8 planets with absorption, and they occupy every corner of this subspace. From figure 2, there is no evidence that planets with absorption are related by a combination of mass and radius.

Figure 3 shows a plot of mass vs. average density. We see that all 9 planets with absorption have average densities of less than 0.8 ρ_j and masses of less than 1.5 M_j. This might be interesting, were it not for the fact that 19 of the 24 planets also exist in this part of the parameter space. If we were seeing a trend relating planets with absorption to low average densities and low masses, we would expect this to be a less populated part of the parameters space. Because most of the 24 planets share these same characteristics, we do not see any trends in figure 3.

Even more so than the previous plots, the plot of mass vs. temperature (figure 4) shows that the planets with absorption exhibit a wide range of temperature and mass values. It is becoming even more apparent that the 9 planets we found to have absorption do not share a unique combination of parameters; only 3 planets exist outside the main group in this plot, none showing absorption. From the 21 planets that are spread randomly in the temperature range of 1100 - 2700 K with masses of less than 1.5 M_j, 9 show absorption. WASP-103b has the highest temperature and largest mass of all the planets with absorption, the fourth highest mass and third highest temperature of all 24 planets; WASP-6b, which also shows absorption, has the second lowest temperature and is tied for lowest mass of all 24 planets. In between WASP-103b and WASP-6b, the other 7 planets with absorption are distributed randomly throughout the space, and we cannot conclude any trends by analysing this plot.

Figure 3. Plot of mass vs. average density of the 24 planets.



We are again unable to see any clear trends in the plot of period vs. mass (figure 5). The 9 planets which show absorption share the same general spread of period and mass combinations as the planets which do not show absorption. It is interesting that the three planets with the longest periods (WASP-6b, WASP-31b, and WASP-96b) and mass values of less than 0.5 M_j all show absorption. However, this is not enough to determine a trend.

Figure 6 shows the plot of period vs. radius. In this plot, the 24 planets are divided almost evenly into four quadrants. If we were seeing a trend, we would expect most of the planets with absorption to be relegated to a single quadrant, and we would expect very few of the planets which don't show absorption to be present in this quadrant. Instead, figure 6 shows us the planets with absorption are divided almost equally, just the same as the planets which do not show absorption. We see that the two planets which have the shortest periods (WASP-103b and WASP-19b) and the three planets which have the longest periods share the same range of radius values from 1 R_j to 1.6 R_j, and planets in between these two endpoints are not grouped by whether or not they show absorption.

There is an interesting feature in figure 7, which shows the plot of period vs. average density. This plot shows that all 7 planets with densities greater than 0.8 ρ_j also have periods between 1 and 1.5 days; none of the 7 planets in this subspace show absorption, so we cannot conclude any trends from this, but it is interesting nonetheless. The 17 remaining planets which have densities less than 0.8 ρ_j show a broad spread of period values; among them, the 9 planets with absorption mirror that spread. Thus, we cannot conclude any trends relating a combination of period and average density to the presence of sodium and/or potassium in an exoplanet's atmosphere.

Figure 4. Plot of mass vs. temperature of the planets

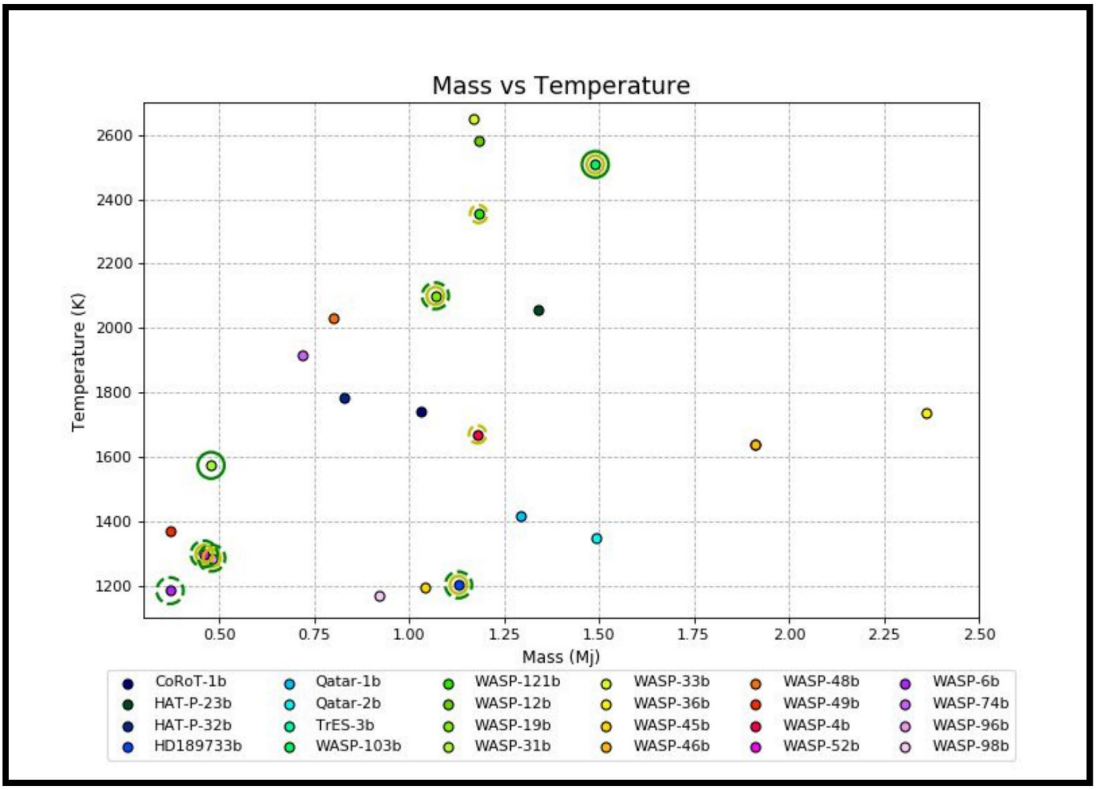


Figure 5. Plot of period vs. mass of the 24 planets.

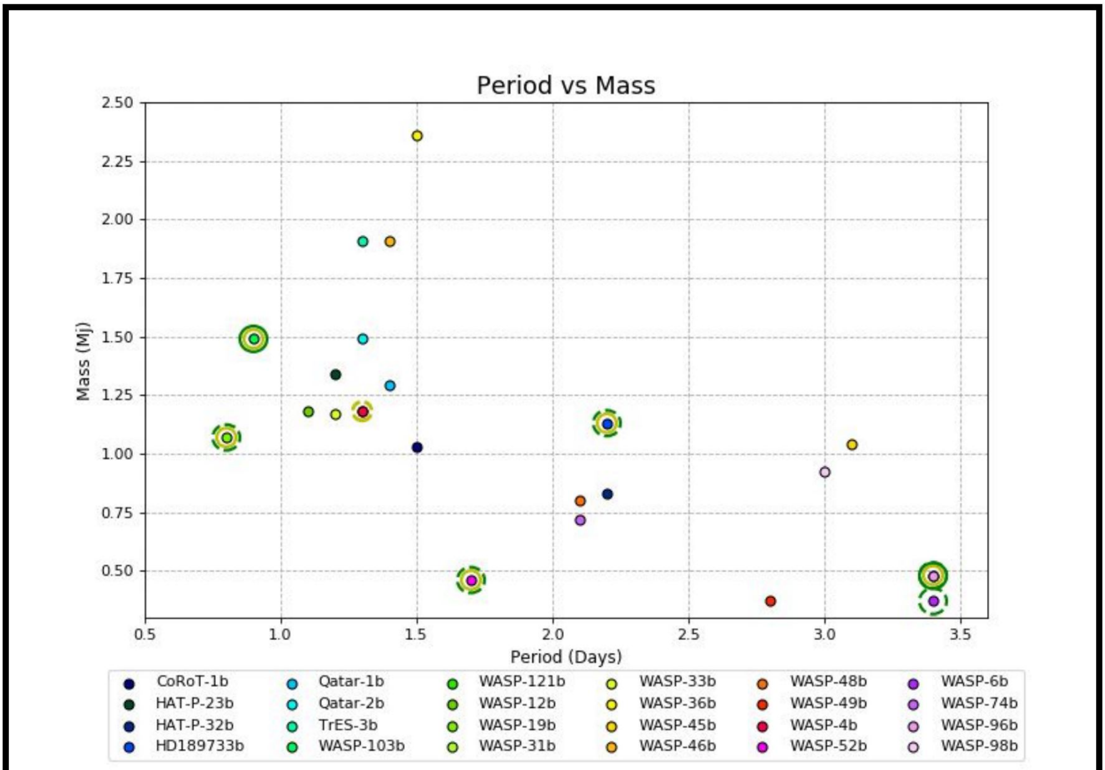


Figure 6. Plot of period vs. radius of the 24 planets.

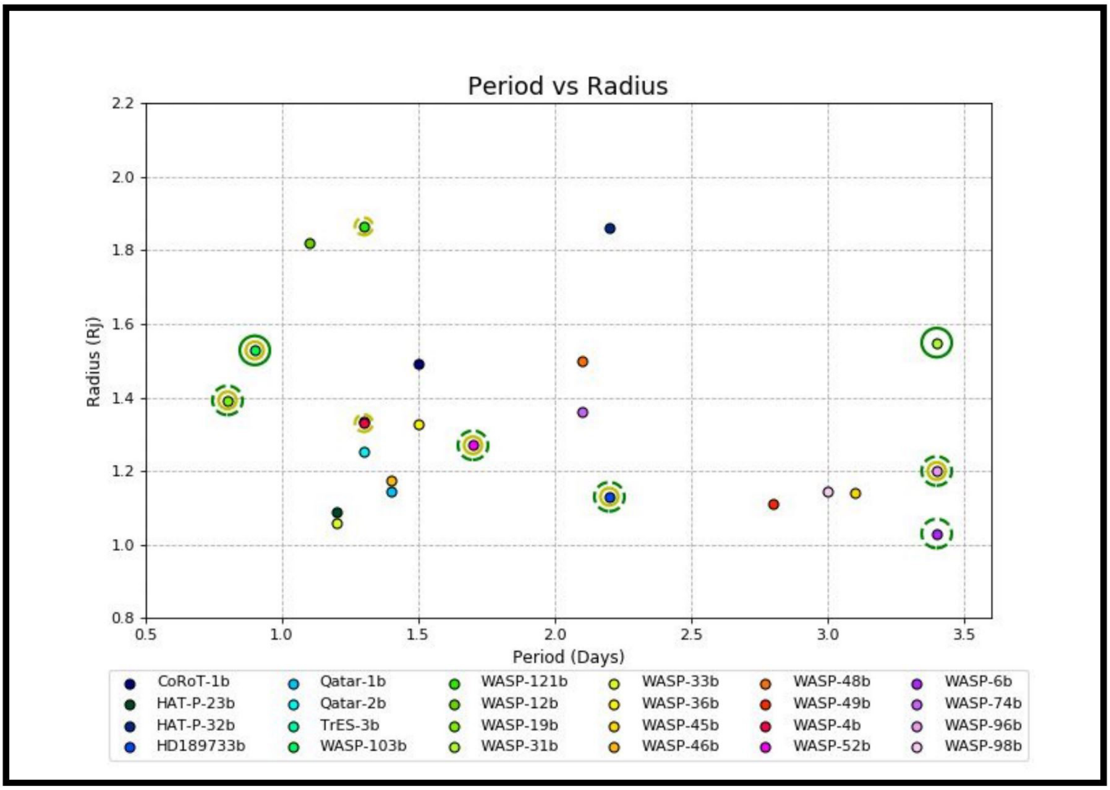


Figure 7. Plot of period vs. average density of the 24 planets.

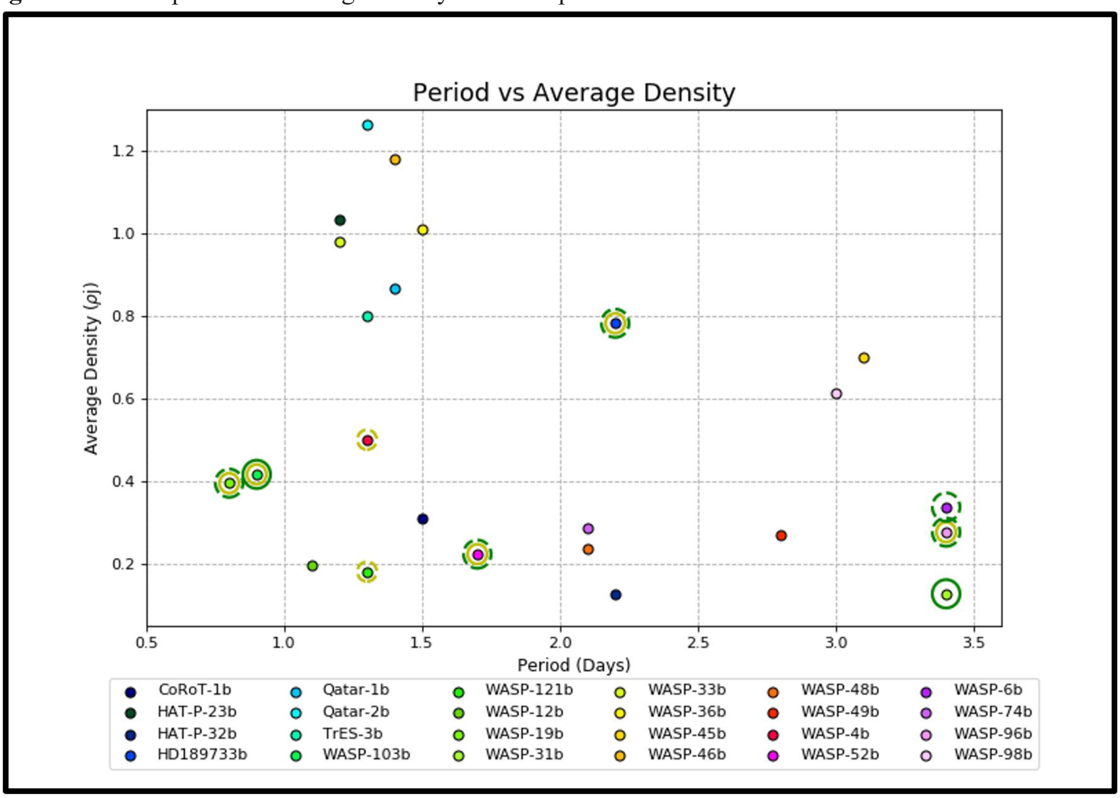


Figure 8. Plot of period vs. temperature of the 24 planets.

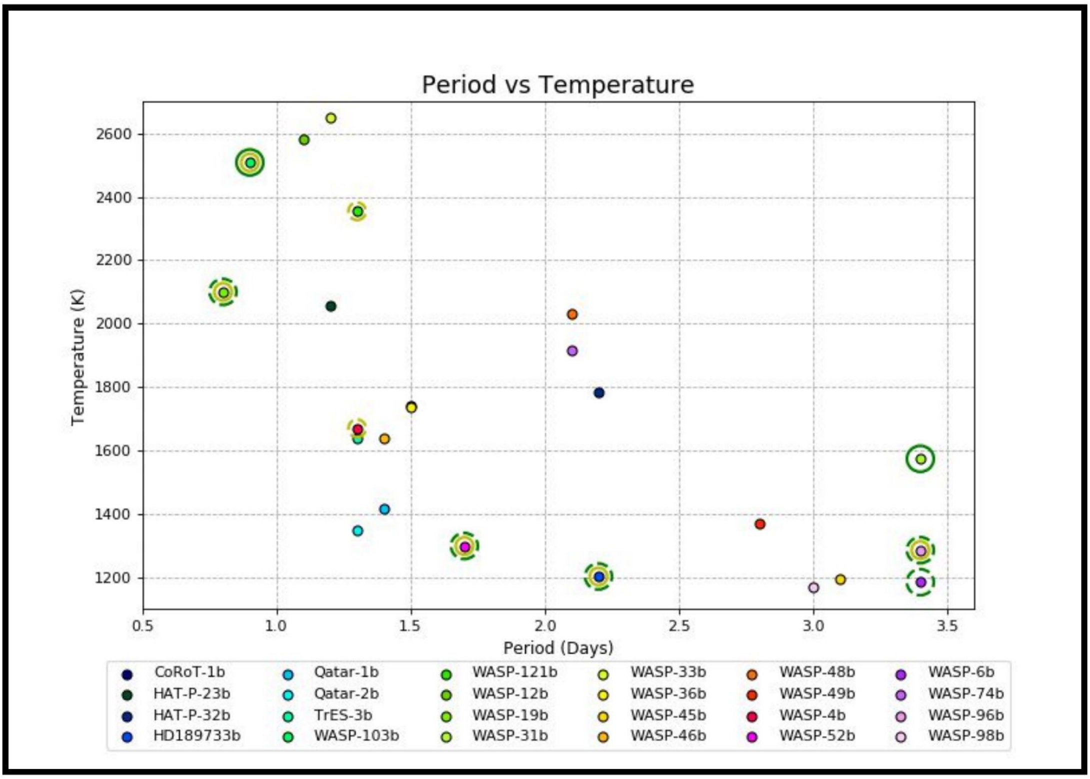
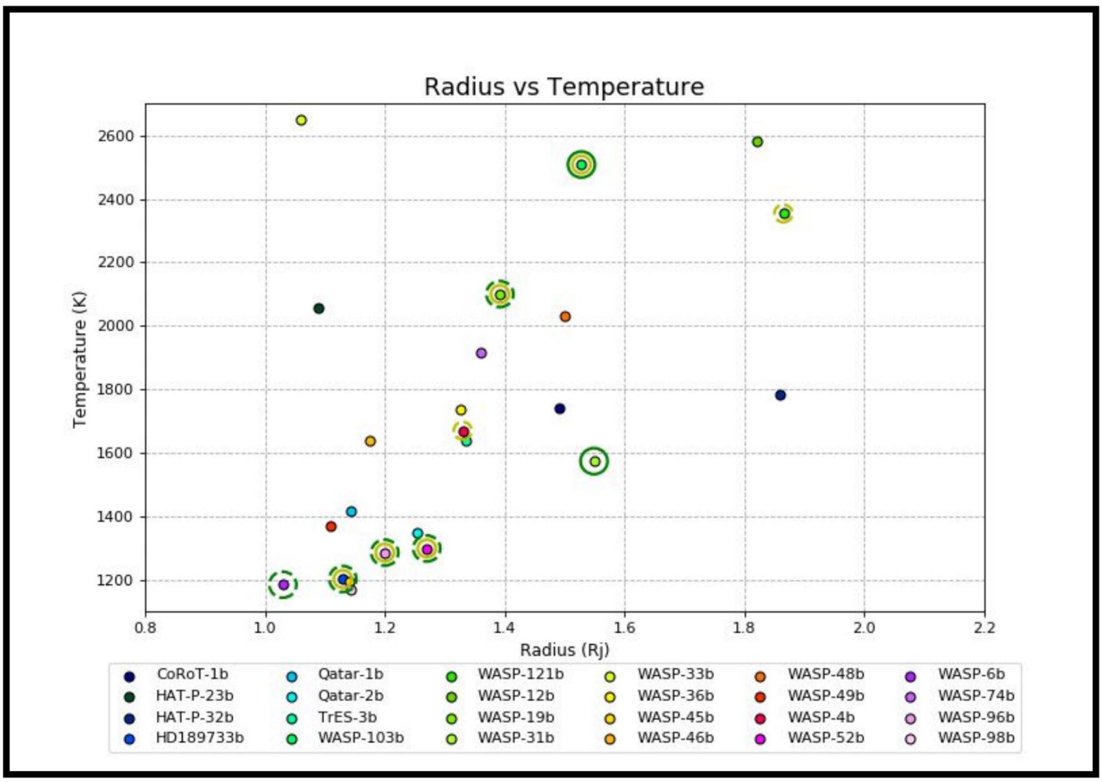


Figure 9. Plot of radius vs. temperature of the 24 planets.



We find no trends in the plot of period vs. equilibrium temperature (figure 8). We see that planets with high temperatures and short periods appear just as likely to show absorption as planets with low temperatures and long periods. Exemplifying this observation, WASP-19b, WASP-103b, and WASP-121b, all showing absorption, are three planets out of six with temperatures greater than 2000 K and periods shorter than 1.5 days. On the other end of the spectrum, WASP-6b, WASP-31b, and WASP-96b are three planets out of six with periods longer than 2.5 days and temperatures less than 1600 K. The other three planets which show absorption are evenly spread between these, mixed among the remaining 9 planets which do not show absorption.

Figures 9 and 10, which respectively show plots of radius vs. equilibrium temperature and average density vs. radius, are interesting because they seem to be showing general relationships between the combined parameters of the planets.

Figure 9 shows that an increase in radius generally coincides with an increase in planetary equilibrium temperature. There are a couple of outliers; WASP-33b and HAT-P-23b, neither of which show absorption, have small radii and high temperatures. Other than those two, 22 planets seem to share the same relationship of increasing radii with temperature. There is no clear reason for this general trend; in relation to our research, this trend is not indicative of a trend relating the presence of sodium and/or potassium to a unique combination of radius and temperature. Quite the opposite; the 9 planets which show absorption follow the general spread of the planets very well, and it is clear from figure 9 that there are no trends relating absorption to radius and temperature.

The general relationship which can be seen in figure 10 appears to have more of a clear justification; planets with larger radii tend to have smaller densities. This makes physical sense. The 24 planets in our search have similar values for mass and radius, thus it makes sense that planets with large radii generally have smaller average densities. Though once more, this relationship between physical parameters is not an indication of a relationship between physical parameters and absorption. As with figure 9, the 9 planets which show absorption follow the general shape of the plot along with the 15 planets which do not show absorption. We have concluded that there are no trends relating sodium/potassium absorption to a combination of radius and average density.

Finally, in the plot of average density vs. equilibrium temperature shown in figure 11, we again find no trends. There is no greater probability of a planet showing absorption in one part of this plot than the next.

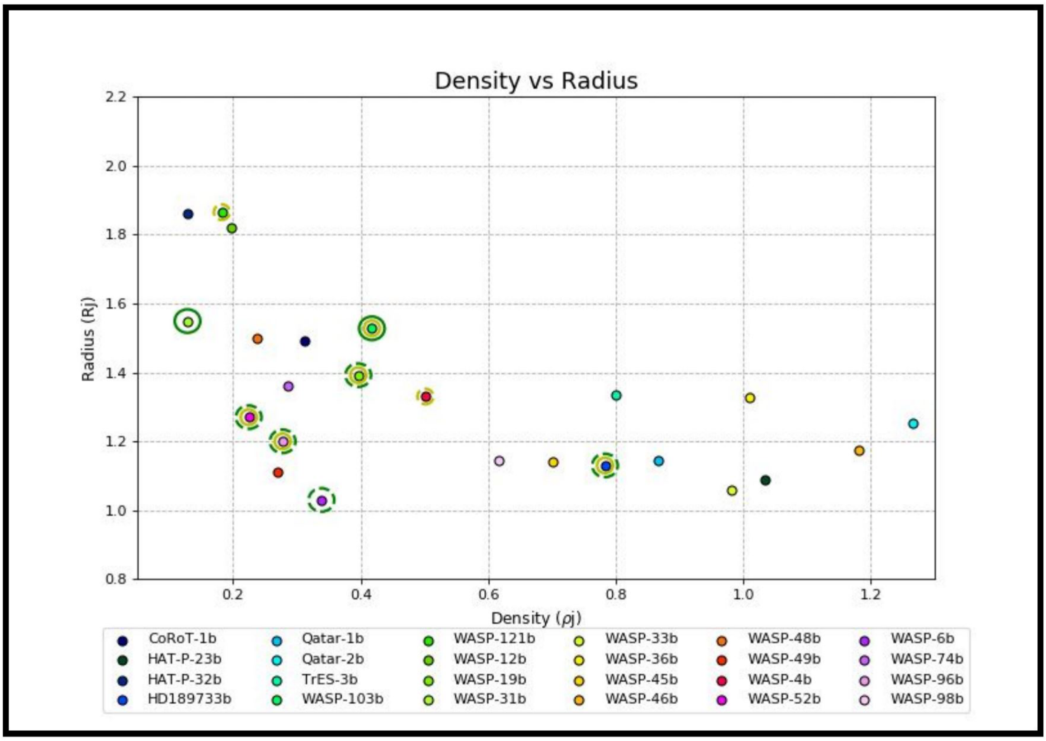
4. Discussion

Having explored the relationship between the individual physical parameters of the exoplanets in our search and atmospheric absorption, and the relationship between combinations of physical parameters and atmospheric absorption, we have found no trends. With only 9 of the 24 planets in our search showing potential and/or definite absorption, we may still be limited in our ability to recognize trends by small sample size.

Two previous studies which have been conducted searching for trends include a comparative study by Sing et al., which compared water absorptions in the spectra of 10 hot Jupiters, and the analysis conducted by Wellbanks et al., which compared the relative abundances of water, potassium, and sodium in 19 hot Jupiters (2016; 2019).

Sing et al. compared the spectra of 10 hot Jupiters, and found that water is not depleted in hot Jupiters: when the spectral strength of absorption by water is weak, it is due to clouds and hazes in the exoplanet's atmosphere (2016). The exoplanets in their study have similar radii

Figure 10. Plot of average density vs. radius of the 24 planets.



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 planets between our study and the study conducted by Sing et al. (2016). 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).

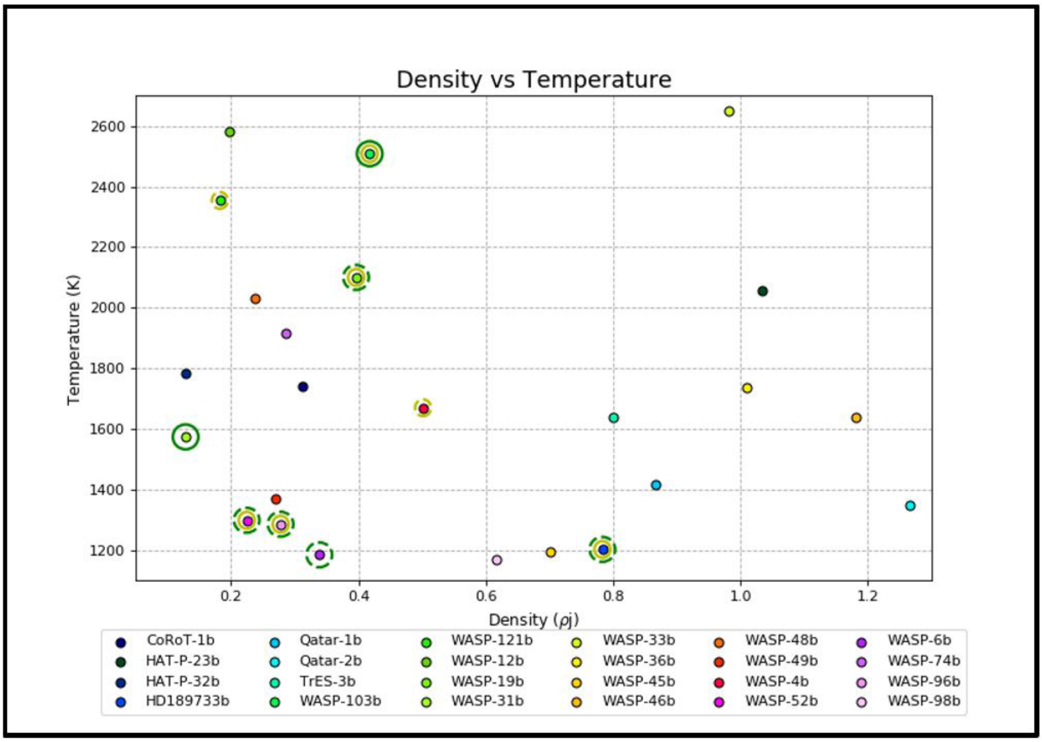
However, Wellbanks et al., analyzed the absorption features of water, sodium, and potassium in their study of 19 hot Jupiters, including the 10 studied in (Sing et al., 2016; 2019). Where they included the study of the metallicity of the host star, they found that there was a one-to-one correlation between the relative abundances of sodium and potassium, but this was not the case for water/potassium relative abundances (Wellbanks et al., 2019). 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.

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. (2016; 2019). In particular, Sing et al. stated that future studies will benefit from atmospheric surveys which are able to differentiate planets with cloudy atmospheres from those with clear atmospheres; then, planets with clear atmospheres could be targeted for further study, which would allow us to determine valuable constraints on hot Jupiter formation models (2016).

5. Conclusions & Future Work

We have explored hot Jupiters with periods of up to 3.5 Earth days and with radii between one and two times the radius of Jupiter. We have searched for trends relating individual physical properties with absorption, and relating combinations of physical properties with absorption. In both cases, our results are the same; we have found no clear trends relating the physical properties of the planets in our search to the presence of sodium and/or

Figure 11. Plot of average density vs. temperature of the 24 planets.



potassium in their atmospheres. The number of planets with transmission spectral data is still small; of the original 191 in our search, only 24 had published spectral data. Of those, only 9 showed potential or definite potassium and/or sodium absorption. We have increased our numbers from the previous search, but still may be limited in our ability to recognize trends by our numbers.

Future work includes working directly with Prof. Stephen Kane and the Habitable Zone Gallery. The Habitable Zone Gallery will host the results of our research, and we will be working on introducing improvements with the goal of making the HZG a better resource for exoplanetary scientists. As previously mentioned, we will also be expanding our wavelength range of interest to include wavelengths from 3000 - 17000 Å; in this wavelength range, atmospheric features from potassium, sodium, and water can be seen.

6. Acknowledgements

I would like to acknowledge the scholarship support provided by the Mary Gates Endowment for this research.

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