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Searching for Trends in Atmospheric Compositions of Extrasolar Planets

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ABSTRACT—Since the first exoplanet was discovered decades ago, there has been a rapid evolution of the study of planets found beyond our solar system. A considerable amount of data has been collected on the nearly 3,838 confirmed exoplanets found to date. Recent findings regarding transmission spectroscopy, a method that measures a planet's upper atmosphere to determine its composition, have been published on a limited number of exoplanets. The aim of our work was to gather existing data on atmospheric planetary composition and search for potential trends in relation to exoplanets' orbital and physical properties. Due to their short periods and thicker atmospheres, hot Jupiter-type planets wereour first target population. Out of 78 cases with periods shorter than three Earth days and radii larger than 1 R_j (Jupiter radius), we found previously-published data on the atmospheres of 15 hot Jupiters. Only eight cases had an overlapping wavelength range that allowed comparisons: 4,800–9,000 Å. Within that range only one exoplanet shows absorption in their atmospheric data. We report our findings on this set, which will be publicly available on the Habitable Zone Gallery, and our future work plans for expanding the dataset.

KEYWORDS—*exoplanets, atmospheric composition, transmission spectroscopy*

INTRODUCTION—In the past two decades, the search for life on other planets has increased exponentially. Most of the recent developments in this new area of science have revolved around the observations of exoplanets, which are planets that are in orbit around a star outside of our solar system. To date, 3,838 exoplanets have been confirmed; a current list of detected extrasolar planets can be found on NASA's Exoplanet Archive.[1]

Exoplanets are detected using several techniques. One of these techniques is the transit method, which is done by observing the planets as they pass in front of their host star as seen from Earth.[2] This method has been one of the most successful methods to date—2,998 exoplanets have been discovered using the transit method.[3]

The easiest planets to detect are those called hot Jupiters. While we don't have any example of hot Jupiters in our own solar system, many have been detected orbiting other stars. They are easier to detect due to their large mass and close proximity to the parent stars; because of their proximity, they have shorter orbital periods and more frequent transits.

The transit method also provides us with other stellar properties of each exoplanet when used in combination with transmission spectroscopy. Each transit produces two dips in light—once as the planet passes in front of its star as seen from Earth, and again as it passes behind the star (**FIG 1**). While in front of the star, in primary transit, we get a glimpse of the starlight combined with the light shining through the planet's atmosphere. As the planet passes behind its star, in its secondary eclipse, or occultation, only the pure starlight is seen. The difference between the spectral data observed from the secondary eclipse and primary transit reveals the spectral features and emissions of the exoplanet itself. Researchers analyze this using spectroscopy, the study of visible light dispersed according to its wavelength. If the star size is known, this method also informs us of the radius of the exoplanet using the planet to star area ratio (**FIG 1**).

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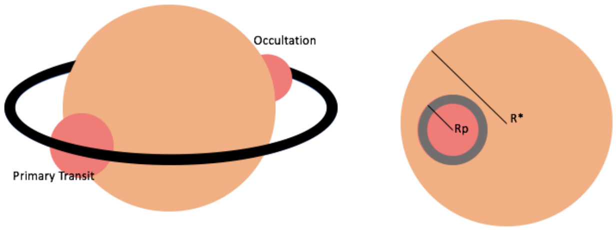

FIGURE 1. A depiction of a planet in transit around its parent star in an arbitrary eccentric orbit, or an orbit that is a deviation of a circle (left). While it passes between the star and the observer, it is in primary transit. When the planet transits behind the star relative to the observer, it is then in occultation, or secondary eclipse. As the planet lies in front of the star relative to us, part of the stellar light passes through the exoplanet's atmosphere (as seen shaded in grey on the right). This light is absorbed by the ions and molecules present, giving us information about the atmospheric composition. The size of the atmosphere and the exoplanet have been exaggerated for clarity.

In this paper we present a study of potential trends between atmospheric composition and physical properties of exoplanets. To do so, we used Habitable Zone Gallery data and published spectroscopic data. The Habitable Zone Gallery, a website by Stephen Kane and Dawn Gelino,[4] was created as a database for exoplanetary systems for which the orbital parameters have been measured. The gallery includes stellar and planetary parameters extracted from the Exoplanet Data Explorer and calculations of the amount of time a planet spends in its habitable zone.[5,6] The Habitable Zone Gallery does not currently provide spectroscopic information of the exoplanets' atmosphere. Our work will help supplement this database so that this information will be available to the astronomy community.

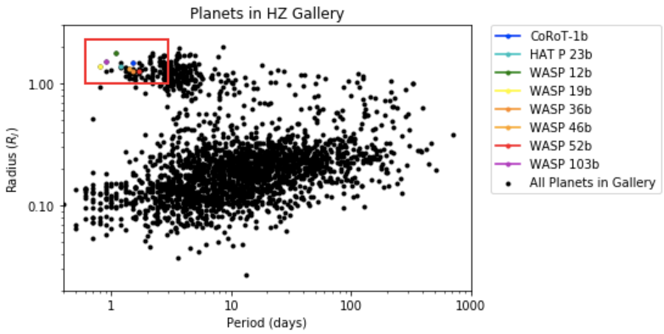

FIGURE 2. This figure shows the orbital periods (in Earth days) versus radius (Jupiter radius, R_J) of all known exoplanets available in the Habitable Zone Gallery. The red box encompasses the planets within the selected parameter space: 1–2 R_J and periods between 1–3 Earth days, and the eight planets we analyzed (see Results section).

METHODS—We began our study by downloading the most current list of exoplanets as of February 2017 from the Habitable Zone Gallery, which included 3,833 exoplanets.

In order to narrow down the amount of planets for our search, we decided to focus on hot Jupiter-type exoplanets, which are physically some of the easiest planets to detect due to their massive size and thick atmosphere, as well as their short orbital periods. In the early stages of our work, we selected exoplanets with radii > 1 R_J (Jupiter radius) and orbital periods of less than two Earth days.[6] As the study progressed, we expanded upon previous work by modifying our cutoff for the orbital period to three Earth days (**FIG 3**). We wrote our own Python script to plot and select our targets. We found 78 exoplanets within this region. We have included data on these exoplanets in **TABLE S1**.

RESULTS—Once we identified the list of exoplanets within the parameter space of interest, we searched the literature for published spectral data on these exoplanets. Out of the 78 exoplanets in our parent sample, only 15 had available data on their atmospheric composition. In addition, the planets in this subset had been observed in various wavelength ranges. To be able to establish comparisons we needed to select an overlapping wavelength region. We found that eight of them had a large overlap within their spectral wavelength range: 480–900 nm.[1,7,8,9,10,11,12,13,14,15]

FIG 3 shows the reproduced spectra of these eight exoplanets. Exoplanets' spectra are shown as R_p/R^* vs wavelength; R_p/R^* is the ratio between the observed radius of the planet and the observed radius of its star. This ratio is proportional to the stellar flux (**EQ 1**), or the energy radiated by the star as measured here on Earth, which is different at different wavelengths.

This is a useful tool in analyzing correlations since it takes into account the difference in starlight per each system.

$$\sqrt{\frac{\Delta F}{F_s}} = \frac{R_p}{R_s} \tag{Eq 1}$$

The spectra of each exoplanet seems to be relatively

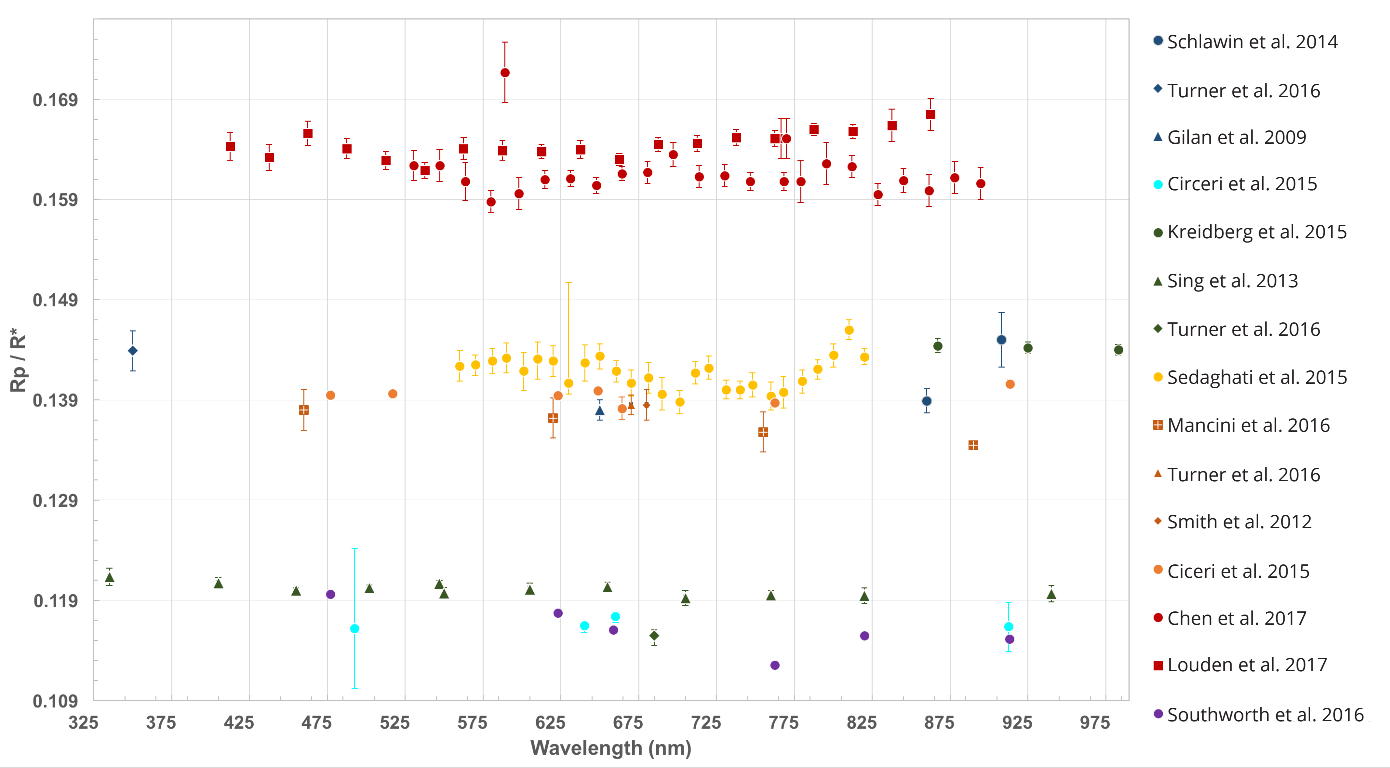

FIGURE 3. Reproduced spectra of the eight exoplanets that had published data on the selected common wavelength range (480–900 nm): CoRoT-1b,[11,15] HAT-P 23b,[8] WASP 103b,[14] WASP 36b,[1,15] WASP 46b,[8] WASP 12b,[13,15] WASP 19b,[1,9,12] and WASP 52b.[7,10] Here we can see a peak in the spectral data of WASP-52b at 589 nm. Once more literature is published and confirmations of peak absorptions are made within each planet's spectral data, we might be able to clearly isolate other peaks amongst the dataset and analyze them accordingly.

flat across all wavelengths, with the exception of the spectral data of WASP-52b, where there is an indication of absorption at approximately 589 nm (FIG 3). Consequently, with only one exoplanet (WASP-52b) that shows absorption in their spectral data, we cannot explore any trends between physical characteristics, orbital properties, and atmospheric composition. Although this is the case, there are multiple exoplanets with radii and orbital periods similar to WASP-52b but without published literature (FIG 4).

WASP-52b physical characteristics are fairly notable compared to the other planets within our set (FIG 5). It has the largest period of 1.7 days and the highest R_p/R^* in our dataset. It has the smallest radius of 1.27 R_J, the smallest mass, and the lowest temperature of all the studied cases. Planets with features similar to those of WASP-52b might produce similar spectral data, but this will require further investigation once more literature becomes available.

CONCLUSION—Though the study of exoplanets is fairly new, in the past two decades it has produced an incredible amount of data, allowing researchers to expand upon

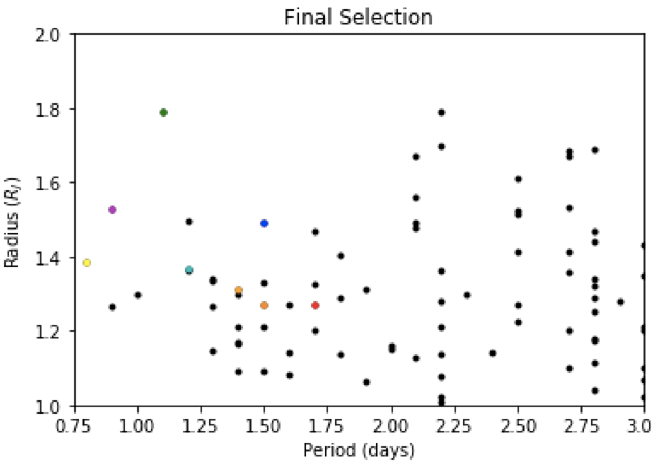

FIGURE 4. This plot includes the 78 planets within our range of parameters. The eight planets with overlapping spectral data are highlighted.

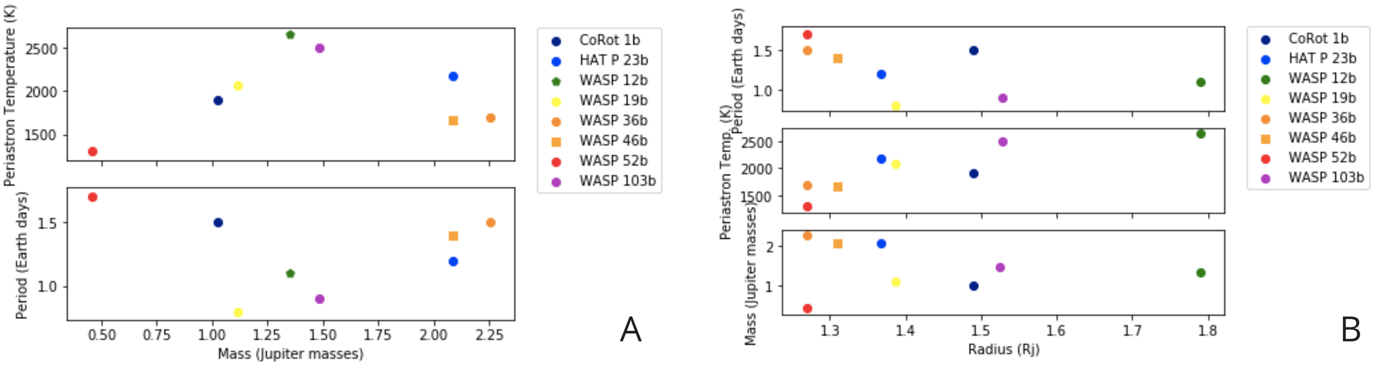

FIGURE 5. (A) The eight exoplanet cases with their Jupiter radii versus Jupiter mass, Periastron surface temperatures, and periods. WASP-52b notably lies on the far left with the smallest mass and surface temperature. (B) The eight exoplanet cases with their Jupiter masses versus periods in Earth days and Periastron surface temperatures. WASP-52b also has the longest period and smallest radius.

our knowledge of these distant worlds. We have initiated a project to search for potential correlations between the physical characteristics of exoplanets and their atmospheric composition. The hot-Jupiter-type planets we targeted had orbital periods of less than three Earth days and large radii ($1 < R_J < 2$). From these 78 planets, our search of available published atmospheric data narrowed down 15 planets, eight of which show spectra within the same wavelength region (480–900 nm) to allow comparisons among the spectra. Out of those, only one spectrum shows absorption, so no trends could be explored.

Our parent sample was largely reduced (from 78 to 8) due to the lack of available spectra and overlapping spectral regions, but we expect that the current growth of atmospheric exoplanet research will result in more cases to add to our study in the near future. The reproduced spectral data will be available soon in the Habitable Zone Gallery website to provide access for the community to carry out these types of studies.

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SUPPLEMENTARY DATA

TABLE S1. List of exoplanets with radii $1 < R_J < 2$ and periods between 1 and 3 Earth days found in the Habitable Zone Gallery. An asterisk "*" indicates the exoplanets that have published literature on their atmospheric data [c18] .

Name	Period (Earth day)	Radius (R_J)	Avg. Temp (K)
CoRoT-12b	2.8	1.44	1445.35
CoRoT-14b	1.5	1.09	1951
CoRoT-18b	1.9	1.31	1526.75
CoRoT-1b	1.5	1.49	1899.4
CoRoT-2b	1.7	1.466	1537
HAT-P-13b	2.9	1.281	1647.65
HAT-P-16b	2.8	1.289	1625.15
HAT-P-23b	1.2	1.368	2058.95
HAT-P-30b	2.8	1.34	1637.35
HAT-P-32b	2.2	1.789	1785
HAT-P-36b	1.3	1.264	1820.95
HAT-P-37b	2.8	1.178	1276.75
HAT-P-41b	2.7	1.685	1937
HAT-P-49b	2.7	1.413	2127.8
HAT-P-56b	2.8	1.466	1839
HAT-P-57b	2.5	1.412	2197.7
HAT-P-5b	2.8	1.254	1537.1
HAT-P-7b	2.2	1.363	2225.2
HATS-14b	2.8	1.039	1274.6
HATS-2b	1.4	1.168	1575.3
HATS-4b	2.2	1.02	1385.7
HATS-9b	1.9	1.065	1816.4
HD 189733b	2.2	1.138	1200.1
KELT-3b	2.7	1.358	1821.3
KELT-7b	2.7	1.533	2049.9
Kepler-17b	1.5	1.33	1744.9
Kepler-412b	1.7	1.325	1828.15
Kepler-423b	2.7	1.2	1412.5
Kepler-670b	2.8	1.176	1388.6
Kepler-686b	1.6	1.084	1614.9
Kepler-718b	2.1	1.477	1862.2
Kepler-785b	2.0	1.162	1146
Kepler-840b	2.5	1.523	1538.5
Kepler-854b	2.1	1.492	1812.9
KOI-13b	1.8	1.406	2607
OGLE2-TR-L9b	2.5	1.61	2033.8
OGLE-TR-113b	1.4	1.093	1342.8
OGLE-TR-132b	1.7	1.2	1974.5
OGLE-TR-56b	1.2	1.363	2206
Qatar-1b	1.4	1.164	1389
Qatar-2b	1.3	1.144	1289.4
TrES-2b	2.5	1.224	1497.6
TrES-3b	1.3	1.336	1628.6
TrES-5b	1.5	1.209	1481.8
WASP-100b	2.8	1.69	2199.9
WASP-103b	0.9	1.528	2504.4
WASP-104b	1.8	1.137	1516.1
WASP-12b	1.1	1.79	2585.75
WASP-135b	1.4	1.3	1712.3
WASP-14b	2.2	1.281	1869.2
WASP-18b	0.9	1.67	2397.75
WASP-19b	0.8	1.386	2065.65
WASP-1b	2.5	1.516	1848.7
WASP-24b	2.3	1.3	1768.3
WASP-26b	2.8	1.32	1412.3
WASP-2b	2.2	1.077	1299.4
WASP-32b	2.7	1.1	1564.4
WASP-33b	1.2	1.497	2673.2
WASP-36b	1.5	1.269	1699.1
WASP-3b	1.8	1.29	1990.1
WASP-44b	2.4	1.14	1347.4
WASP-46b	1.4	1.31	1658
WASP-48b	2.1	1.67	2033.2
WASP-49b	2.8	1.115	1370.2
WASP-4b	1.3	1.341	1670.2
WASP-50b	2.0	1.153	1392.5
WASP-52b	1.7	1.27	1300.8
WASP-5b	1.6	1.14	1741.4
WASP-64b	1.6	1.271	1690.1
WASP-72b	2.2	1.01	2060.4
WASP-74b	2.1	1.56	1922.3
WASP-75b	2.5	1.27	1704.5
WASP-77Ab	1.4	1.21	1670.9
WASP-78b	2.2	1.7	2294.7
WASP-82b	2.7	1.67	2178.8
WASP-95b	2.2	1.21	1617.4
WASP-97b	2.1	1.13	1539.9
WTS-2b	1	1.3	1543.9