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A Catalog of Exoplanet Transmission Spectroscopy Data for Use in Atmospheric Studies

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Abstract

The study of exoplanets has produced large amounts of data since the first exoplanet was discovered over two decades ago. Much of these data, specifically transmission spectroscopy (TS) data, are available online to be reused to search for new results. Transmission spectroscopy is a widely used method of determining the composition of exoplanet atmospheres. The goal of this study is to create a catalog of transmission spectroscopy data from many different exoplanets to later be used to search for trends in the composition of their atmospheres. Many atmospheric studies present data from single planets, but few search for trends across multiple planets. This catalog will first focus on hot Jupiter type planets because they transit their parent stars often, their atmospheres absorb a large portion of the stellar flux[19], and thus spectral data on these types of planets is the most abundant. It will later be expanded to include a wider variety of planets. This literature review will produce a compilation of data that will be convenient to researchers who require spectral data for their atmospheric studies.

Keywords: Exoplanet, Transmission spectroscopy, Atmosphere

1. Background

The transit method for detecting exoplanets has been our most successful detection method by far, yielding over 2700 of our nearly 3500 exoplanet discoveries[16]. This method consists of searching for periodic decreases in a star's light, indicating that an orbiting planet has passed between the observer and the star[19]. This method is most sensitive to planets with large radii and short orbital periods[19]. Planets with these characteristics are known as hot Jupiters, which are gas giants orbiting very close to their parent stars[19]. This is a class of planet not found in our solar system. The atmospheres of these planets are enlarged due to their extreme proximity to their stars, making them excellent candidates for transmission spectroscopy because a large amount of starlight can be transmitted through the atmosphere. To perform transmission spectroscopy, spectra of a star are taken during transit, yielding the combined spectrum of the planet and star, and out of transit (either when the star eclipses the planet or just before or after transit to minimize the amount of light reflected by the planet), yielding the pure spectrum of the star. The out-of-transit spectrum is subtracted from the in-transit spectrum, revealing the pure spectrum of the planet[19].

A common practice when studying transits is to set the average unobstructed flux at all wavelengths of an observed star equal to one and express any change in flux as a fraction of the unobstructed flux. Since the fractional change in flux during transit, called the *transit depth*[2], is equal to the ratio of the areas of the observed stellar and planetary disks[19] (A_p and A_s in equation (1)), we can determine the radius of a transiting planet if the radius of the star is known.

$$\frac{\Delta F}{F_s} = \frac{A_p}{A_s} \tag{1}$$

The transit depth varies with the wavelength of light the system is viewed at based on the composition of the planet's atmosphere. This variation is extremely small, so astronomers must find ways to increase the signal-to-noise ratio of their data. One method is to partition light into bins spanning ranges of wavelengths, which lowers the resolution but also lowers the noise[3]. A similar approach is spectrophotometry, or observing a star through wavelength filters without the use of a spectrometer.

In many of the studies compiled for this work[21,9,12], spectra of exoplanet atmospheres are expressed in "differential radius"[9] units, or R_p/R_s, which can be obtained from equation (1).

$$\sqrt{\frac{\Delta F}{F_s}} = \frac{R_p}{R_s} \tag{2}$$

The measurement of the planetary radius R_p will vary with the wavelength of light observed depending on the composition of the atmosphere, hence the name *differential radius* units. A small value for R_p/R_s indicates low absorption by the atmosphere and a large value indicates high absorption.

2. Methods and Results

The Habitable Zone (HZ) Gallery is a website created by Stephen Kane and Dawn Gelino dedicated to tracking the orbits of exoplanets in relation to the habitable zones of their host stars[10]. It gathers orbital and stellar data from the Exoplanet Data Explorer[7] and calculates the amount of time a planet spends in the habitable zone of its star. We used the Habitable Zone Gallery database to select planets for this research based on their radii and orbital period. We wrote a Python script that selected planets with periods less than two Earth days and radii greater than Jupiter's to limit our search to a selection of hot Jupiter type planets (see Figure 1). We then searched for studies where transmission spectroscopy was performed on these planets, finding 10 instances listed in Table 1.

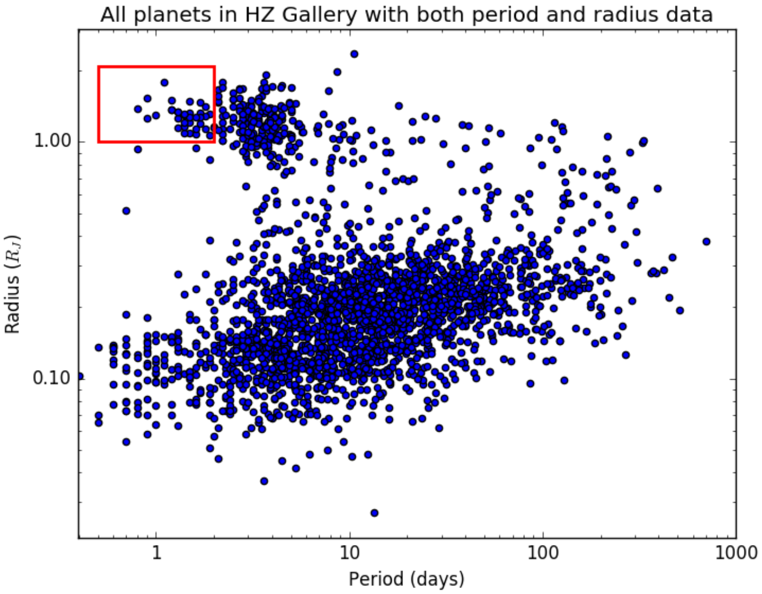

Figure 1. Planets in the HZ gallery plotted by period in days and radius in Jupiter radii. Points in the red box are planets included in our study (see table).

The results of this study reveal the need for transmission spectroscopy studies to be performed on more of the known transiting hot Jupiters. This compilation can be used to improve the parameter space that has not been yet explored.

	Name	Radius (R_J)	Period (Days)	Sources	Wavelength Range (Å)	Instrument	Comments
1	CoRoT-14 b	1.09	1.5				
2	CoRoT-18 b	1.31	1.9				
3	CoRoT-1 b	1.49	1.5	Schlawin, E. 2014[18] Turner, J.D. et al. 2016[23] Ranjan, S. et al. 2014[17]	8000-24000 3030-11750 11000-17000	IRTF SpeX and MORIS Kuiper Telescope, University of AZ HST WFC3	Observed w/ 3030-4170 Å filter, combined w/ archival data
4	CoRoT-2 b	1.466	1.7				
5	HAT-P-23 b	1.368	1.2	Ciceri, S. et al. 2015[5]	4600-9600	CAO 1.23 & 2.2 m telescopes	Observed through *u, g, r,* and *z* photometric filters
6	HAT-P-36 b	1.264	1.3				
7	HATS-2 b	1.168	1.4				
8	HATS-9 b	1.065	1.9				
9	Kepler-17 b	1.33	1.5				
10	Kepler-412 b	1.325	1.7				
11	Kepler-686 b	1.084	1.6				
12	KOI-13 b	1.406	1.8				
13	OGLE-TR-113 b	1.093	1.4				
14	OGLE-TR-132 b	1.2	1.7				
15	OGLE-TR-56 b	1.363	1.2				
16	Qatar-1 b	1.164	1.4				
17	Qatar-2 b	1.144	1.3				
18	TrES-3 b	1.336	1.3				
19	TrES-5 b	1.209	1.5				
20	WASP-103 b	1.528	0.9	Southworth, J et al. 2016[22]	4080-9810	La Silla GROND	Observed with *R, I, g′, r′, i′,* and *z′* filters
21	WASP-104 b	1.137	1.8				
22	WASP-12 b	1.79	1.1	Sing, D.K. et al. 2013[21] Turner, J.D. et al. 2016[23] Kriedberg, L. 2015[11] Mandell, A.M. et al. 2013[15]	2900-10300 2900-10300 8200-16500 11100-16600	HST STIS and WFC3 Kuiper Telescope, University of AZ HST WFC3 HST WFC3	Combined w/ archival data to extend spectral range Observed w/ 5500-9000 and 3030-4170 Å filters, combined w/ archival data
23	WASP-135 b	1.3	1.4				
24	WASP-18 b	1.267	0.9				
25	WASP-19 b	1.386	0.8	Huitson, C.M. et al. 2013[9] Mancini, L. et al. 2013[14] Mandell, A. M. et al. 2013[15] Sedaghati, E. et al. 2015[20]	2900-16870 3700-23500 11100-16600 5500-8300	HST STIS and WFC3 La Silla GROND HST WFC3 VLT FORS2	Combined w/ archival data to extend spectral range Observed w/ *g′, r′, i′, z′, J, H,* and *K* filters
26	WASP-33 b	1.497	1.2	Haynes, K. et al. 2015[8] Turner, J.D. et al. 2016[23]	11350-16290 3030-7750	HST WFC3 Kuiper Telescope, University of AZ	Observed w/ 3300-5500 and 3030-4170 Å filters, combined w/ archival data
27	WASP-36 b	1.269	1.5	Turner, J.D. et al. 2016[23] Mancini, L. et al. 2016[13]	3030-9000 4080-9810	Kuiper Telescope, University of AZ La Silla GROND	Observed w/ 5500-9000 and 3030-4170 Å filters, combined w/ archival data Oserved w/ *g′, r′, i′,* and *z′* filters
28	WASP-3 b	1.29	1.8				
29	WASP-46 b	1.31	1.4	Ciceri, S. et al. 2015[6]	4080-9810	La Silla GROND	Observed w/ *g, R, r, g′, r′, i′,* and *z′* filters
30	WASP-4 b	1.341	1.3				
31	WASP-52 b	1.27	1.7	Louden, T. et al. 2017[12] Chen, G. et al. 2017[4]	4000-8750 5220-9030	William Herschel Telescope GTC OSIRIS	
32	WASP-5 b	1.14	1.6				
33	WASP-64 b	1.271	1.6				
34	WASP-77 A b	1.21	1.4	Turner, J.D. et al. 2016[23]	3030-4170	Kuiper Telescope, University of AZ	Observed w/ 3030-4170 Å filter
35	WTS-2 b	1.3	1				

Table 1. The thirty-five planets selected for this study with sources of transmission spectra included. Instruments referenced: MIT Optical Rapid Imaging System at the Infrared Telescope Facility (IRTF MORIS), Space Telescope Imaging Spectrograph and Wide Field Camera 3 on the Hubble Space Telescope (HST STIS and WFC3), Gamma-Ray Burst Optical/Near-Infrared Detector (GROND) at La Silla Observatory, Calar Alto Observatory (CAO), Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy at Gran Telescopio Canarias (GTC OSIRIS), and Focal Reducer and Low Dispersion Spectrograph 2 on the Very Large Telescope (VLT FORS2).

Most of the studies in this catalog observed planets in the visual and infrared wavelength ranges. This is because many of the compounds we would expect to see in the atmospheres of gas giants such as molecular hydrogen and helium[19] have strong absorption features in these wavelength ranges. Biosignatures, or compounds that hint at the presence of life such as water, methane, and molecular oxygen also have absorption features in the visual and IR ranges[19]. Astrobiologists do not expect to find evidence of life on hot Jupiters, but studying biosignatures on these types of planets where detection is easiest confirms that transmission spectroscopy is effective and could be used in the future to identify biosignatures on terrestrial planets when our telescope technology improves.

3. Future Work

The next step in this research will be to incrementally expand the scope of our literature search until we encompass the entire cluster of hot Jupiter type planets seen in the upper left corner of Figure 1. The intermediate goal of this work is to search for trends in the spectral features of hot Jupiters, but the ultimate goal is to expand our search to other types of planets that may be harder to perform transmission spectroscopy on, such as smaller gas giants, planets with longer orbital periods, and terrestrial planets.

We plan to collaborate with Stephen Kane, one of the creators of the Habitable Zone Gallery, to put the information gathered in this study onto the website. This will give users quick and convenient access to sources of transmission spectroscopy data that can be used to determine the habitability of exoplanets based on their atmospheres.

Of the 35 planets selected for this study, only 10 had transmission spectroscopy data. To increase the size of our data set, we would like to include archival data from studies that used the radial velocity (RV) method to detect exoplanets and studies that measured the Rossiter-McLaughlin (RM) effect.

The RV method is an indirect method for detecting exoplanets. When a planet orbits a star, the star also orbits the center-of-mass of the system. If the plane of the planet's orbit is perpendicular to the sky, then the Doppler shift of the star as it moves towards and away from the observer can be measured[2]. The problem with using RV data for transmission spectroscopy is that peak radial velocity occurs when the planet is at either side of the star as viewed from Earth, not during transit[2]. This means it is unlikely that spectra would be taken during transit, allowing us to extract the pure spectrum of the planet's atmosphere. Another problem that scientists have encountered[1] when performing this type of work is the use of iodine cells in many radial velocity studies. Gaseous iodine is often used to create a reference spectrum against which to compare stellar spectra and increase the accuracy of RV data. This reference spectrum contaminates any transmission spectrum, making it difficult to gather information about the planet's atmosphere. However, it would be worthwhile to search through RV data where reference spectra are not used to find cases where spectra are taken at orbital phases such that transmission spectroscopy would be possible. A more likely source of additional data is archival Rossiter-McLaughlin observations.

The Rossiter-McLaughlin effect is a variation in a star's spectrum due to an orbiting planet or stellar companion[24]. If a star's axis of rotation is not perpendicular to the sky, the portion of the star rotating away from the observer will be redshifted and the portion of the star rotating towards the observer will be blueshifted, causing a broadening of the spectral lines[24]. If the star has a transiting companion orbiting in the same direction as the star's rotation, the companion will first block light from the blueshifted side, causing the star appear more red, and then move to the redshifted side, causing the star to appear more blue[24]. If the companion orbits in the opposite direction of the star's rotation, the observed effect is reversed[24]. This is a better potential source for additional data because unlike the RV method, it requires spectra to be taken during transit. Wyttenbach et al[25] were able to detect sodium in the atmosphere of HD 189733b from HARPS (High-Accuracy Radial-velocity Planet Searcher) data that was originally used to observe the Rossiter-McLaughlin effect of that system.

4. Conclusion

We now know of thousands of transiting exoplanets, many of them hot gas giants with atmospheres perfect for transmission spectroscopy. However, as we have shown, only a low fraction of these perfect candidates have accompanying TS data. We present the first iteration of a catalog compiling sources of TS data to be used later in multiple-planet atmospheric studies. This catalog will be expanded to include a wider range of planetary radii and orbital periods, and a collaboration with the creators of the Habitable Zone Gallery will make this information widely available to the astronomy community.

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