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**CLEANING OUR HAZY LENS: STATISTICAL TRENDS IN
TRANSMISSION SPECTRA OF WARM EXOPLANETS**

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Abstract

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Relatively little is understood about the atmospheric composition of temperate to warm exoplanets (equilibrium temperature $T_{\text{eq}} < 1000$ K), as many of them are found to have uncharacteristically flat transmission spectra. Their flattened spectra are likely due to atmospheric opacity sources such as planet-wide photochemical hazes and condensation clouds. We compile the transmission spectra of 23 warm exoplanets previously observed by the *Hubble Space Telescope* and quantify the haziness of each exoplanet using a normalized amplitude of the water absorption feature (A_{H}). By examining the relationships between A_{H} and various planetary and stellar forcing parameters, we endeavor to find correlations of haziness associated with planetary properties. Our analysis shows that the previously identified linear trends between A_{H} and T_{eq} or hydrogen-helium envelope mass fraction (f_{HHe}) break down with the addition of new exoplanet data. Among all the parameters we investigated, atmospheric scale height (H), planet gravity (g_{p}), and planet density (ρ_{p}) hold the most statistically significant linear or linear logarithmic correlations with A_{H} ($p \leq 0.02$). We also tentatively identified positive correlations for eccentricity (e) and stellar age (t_{age}) with A_{H} . Specifically, lower H , higher g_{p} , ρ_{p} , e , or t_{age} lead to clearer atmospheres. However, none of the parameters show very strong linear correlations with A_{H} , suggesting that haziness in warm exoplanets is not simply controlled by any single planetary/stellar parameter. Additional observations and laboratory experiments are needed to fully understand the complex physical and chemical processes that lead to the hazy/cloudy atmospheres in warm exoplanets.

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To
my dog,
Roxi

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1 Introduction

1.1 Exoplanets and Transmission Spectra

In the past few decades, astronomical advances have resulted in various new techniques for exoplanet detection and thousands of exoplanet discoveries (e.g., Mayor et al., 2011; Fressin et al., 2013; Howell et al., 2014; Ricker et al., 2015; Thompson et al., 2018; Kunimoto & Matthews, 2020). These exoplanets vary drastically in size, mass, and composition, which give us a large sample size to understand trends of exoplanetary properties (e.g., Johnson et al., 2017; Fulton et al., 2017; Fulton & Petigura, 2018). The most common types of exoplanets are with radius (R_p) between Earth-sized and Neptune-sized planets ($1R_\oplus < R_p < 4R_\oplus$); henceforth, referred to as “sub-Neptunes”¹ (Howard et al., 2012a; Fressin et al., 2013; Petigura et al., 2013a,b). Sub-Neptunes, and larger in radius exoplanets, typically are gaseous planets with large hydrogen-helium dominated atmospheres, with trace amounts of other molecules.

One detection method for these exoplanets is transit detection. This detection method is the observation of the host-star and exoplanet’s partial-eclipse. As the exoplanet passes in front of the host-star from the observers perspective, there is a small, but detectable dip in the overall brightness of the host-star. By observing this brightness dip at a wavelength of light over the full eclipse, one can construct a time-series curve called a light curve. This curve is normalized to the mean brightness at the same wavelength. Its width is proportional to the time taken for the planet

¹This definition of sub-Neptunes also includes the so-called “super-Earth” exoplanets, whose sizes are smaller than $2R_\oplus$ (Fressin et al., 2013).

to cross the width of the star over its transit path, $2R_* \cos(\theta)$, where R_* is the star's radius and θ is the orbital inclination. Its a max depth is proportional to the ratio of planet to star cross-sectional area, i.e., the transit depth ($D = R_p^2/R_*^2$). This technique determines the "transit radius" of the exoplanet which varies with wavelength and is affected by stellar and planetary properties.

One important and useful effect is the exoplanet's atmospheric absorption and scattering that occludes a significant amount of stellar light. Thus, there will be a change in the transit depth depending on the atmospheric composition of the exoplanet. The observed light curve is the resulting transmitted light curve reduced primarily by absorption. Fortunately, absorption and scattering are both wavelength dependent and the atom/molecule dependent creating a predictable spectrum that can be analyzed. By taking transit measurements over many different wavelength, we can construct a profile of the transit-light curves over the observed spectrum, i.e., the transmission spectrum. Transmission spectroscopy is the resulting observation method to characterize the atmospheric composition of exoplanets.

1.2 Anomalous Water Absorption Features

Recently, there have been extensive observational studies on characterizing the atmospheric compositions of sub-Neptunes large exoplanets using transmission spectroscopy. In particular, H₂O absorption features were discovered in the transmission spectra taken from the Wide Field Camera Three (WFC3) of the *Hubble Space Telescope (HST)* for several sub-Neptunes (e.g, Fraine et al., 2014; Wakeford et al., 2017; Kreidberg et al., 2018; Benneke et al., 2019a; Tsiaras et al., 2019; Benneke et al., 2019b; Kreidberg et al., 2020; Guo et al., 2020; Edwards et al., 2021; Mikal-Evans et al., 2021). Meanwhile, many transmission spectra were found to be flat and featureless (e.g, Kreidberg et al., 2014; Knutson et al., 2014a,b; Libby-Roberts et al., 2020; Chachan et al., 2020; Mugnai et al., 2021). Most notably, GJ 1214 b, with 15 transits, was observed to have an almost completely flat spectrum over the WFC3 range of $\sim 1.1\text{--}1.7 \mu\text{m}$ (Kreidberg et al., 2014). Several reasons could lead to such observed flat spectra: 1) an absence of H₂O and/or CH₄ in these atmospheres; 2)

the atmospheres having high mean molecular weight compositions; 3) and opacity sources such as high-altitude condensation clouds or photochemical hazes obscuring the $\text{H}_2\text{O}/\text{CH}_4$ spectral features.

It is believed that fine solid/liquid particles suspended in the atmosphere, called aerosols, likely act as the opacity sources that flatten the transmission spectra (e.g., Brown, 2001; Fortney, 2005; Howe & Burrows, 2012; Morley et al., 2013; Fortney et al., 2013; Charnay et al., 2015; Sing et al., 2016; Lavvas & Koskinen, 2017; Kawashima & Ikoma, 2018; Gao & Benneke, 2018; Adams et al., 2019; Powell et al., 2019; Ohno et al., 2020). Condensation clouds and photochemical hazes are two common types of aerosols that can mute spectral features (for recent review, see Gao et al., 2021). Laboratory experiments suggest a likely ubiquity of photochemical hazes in warm exoplanet atmospheres with equilibrium temperature $T_{\text{eq}} \leq 800$ K (Hörst, 2017; Hörst et al., 2018; He et al., 2018a,b, 2019, 2020a,b; Moran et al., 2020; Vuitton et al., 2021; Yu et al., 2021). In addition, photochemical models suggest haze formation is likely promoted in temperate to warm exoplanet atmospheres with $T_{\text{eq}} \leq 1000$ K (Fortney et al., 2013; Morley et al., 2015; Kawashima & Ikoma, 2019). Aerosols are also suggested to impact the thermal structure of exoplanet atmospheres (e.g., Heng et al., 2012; Morley et al., 2015; Lavvas & Arfaux, 2021), which potentially affects atmospheric chemical compositions (Molaverdikhani et al., 2020) and dynamics (Roman & Rauscher, 2017). Aerosols can also significantly inflate the observable transit radius from that expected for clear atmospheres, complicating the interpretation of the observed radius (Lammer et al., 2016; Wang & Dai, 2019; Kawashima et al., 2019; Gao & Zhang, 2020; Ohno & Tanaka, 2021). Understanding the effect of these opacity sources are vital to unveil the atmospheric properties, such as composition and dynamics, of sub-Neptunes.

To unveil the nature of cloudy/hazy exoplanetary atmospheres, it is vital to understand how the atmospheric cloudiness/haziness depends on planetary properties. Sing et al. (2016) and Stevenson (2016) (henceforth S16) first developed a metric to cross-compare the observed H_2O absorption feature’s amplitude between different exoplanet atmospheres, the so-called “water amplitude” (A_{H}), using transmission spectroscopy data. The “water” amplitude measures the flatness of the spectra

observed by *HST*/WFC3 based on the difference of transit depth between the H₂O absorption band (wavelength $\lambda \sim 1.4 \mu\text{m}$) and the baseline J-band ($\lambda \sim 1.25 \mu\text{m}$). The water amplitude is an estimated predictor for cloudiness/haziness for a given exoplanet, given that clouds and hazes are the main cause of the featureless spectra. S16 and Fu et al. (2017) (henceforth F17) set out to discover empirical trends for hot-Jupiters and some sub-Neptunes, and established a linear trend between the cloudiness/haziness versus T_{eq} (S16; F17). Crossfield & Kreidberg (2017) (henceforth CK17) found a similar linear trend between A_{H} vs T_{eq} and the predicted hydrogen-helium mass fraction (f_{HHe}) for warm sub-Neptunes, though their sample size is considerably smaller ($N = 6$ for CK17; $N = 14$ for S16; and $N = 34$ for F17). Based on the aforementioned trend, Gao et al. (2020) suggested that condensed silicate clouds are likely the dominant opacity sources in hot exoplanets ($T_{\text{eq}} > 950 \text{ K}$) while photochemical hazes likely dominate atmospheric opacity at lower temperature exoplanets ($T_{\text{eq}} < 950 \text{ K}$). Recently, there has also been some efforts looking into trends of haziness/cloudiness for hot, jupiter size exoplanets using the thermal emission (“heat”) spectra data (Mansfield et al., 2021).

In this study, we aim to expand upon previous works on characterizing the cloudiness/haziness of exoplanets, focusing on temperate to warm exoplanets with T_{eq} less than 1000 K, where photochemical hazes are likely the dominant opacity source (Gao et al., 2020). Compared to the previous work of CK17, we include new observations, especially for colder exoplanets. We also investigate trends for more planetary/stellar parameters. With the increased sample size, we investigate whether previously established trends hold true, and whether we can establish new trends between haziness and planetary/stellar parameters. These trends, if any exist, will help us better understand the physics of haze formation and removal on exoplanets and assess under which circumstances we are more likely to see clear versus hazy exoplanets for future observations.

1.3 System Parameters of Exoplanet

We select exoplanet targets mainly based on their equilibrium temperature ($T_{\text{eq}} < 1000$ K), where we assumed a planetary Bond albedo (A_b) of 0.3, regardless of their masses or sizes. Our targets are mostly sub-Neptunes ($R_p < 4R_{\oplus}$), but it also includes a few super-puffs (large radii $R_p > 4R_{\oplus}$ but similar masses $M_p < 10M_{\oplus}$ as sub-Neptunes), Neptune to super-Neptune sized ($4R_{\oplus} < R_p < 13R_{\oplus}$), and terrestrial-sized exoplanets ($R_p < 2R_{\oplus}$). The targets are summarized in Table 1.1. Overall, our exoplanet targets have radii ranging from ~ 1 to $13 R_{\oplus}$, masses range from ~ 1 to $185 M_{\oplus}$ (or $\sim 0.6 M_J$), and T_{eq} range from ~ 200 to 1000 K. Even though all the TRAPPIST-1 system planets (Gillon et al., 2017) fit in our T_{eq} criterion, we do not include those with transmission spectra data in our present analysis due to large uncertainties in their transmission spectra (de Wit et al., 2016, 2018; Zhang et al., 2018).

1.3.1 Stellar Forcing Parameters

In this section, we detail the calculations for most of the system parameters related to the star and/or orbit of the exoplanets.

For the properties related to stellar forcing, we collected from the literature the spectral type, age (t_{age} [Gyr]), mass ($M_* [M_{\odot}]$), radius ($R_* [R_{\odot}]$), effective temperature ($T_{\text{eff}}^* [\text{K}]$), orbital semi-major axis (a [AU]), metallicity ($Z_{[\text{Fe}/\text{H}]} [\text{dex}]$), eccentricity (e), and stellar rotation period (P_{rot} [day]). We also calculated the density ($\rho_* [\rho_{\odot}]$), surface gravity ($g_* [\text{m s}^{-2}]$), and bolometric luminosity ($L_{\text{bol}} [\text{erg s}^{-1}]$) for the stars. For the near-UV (NUV, 170–320 nm) flux density ($F_{\text{NUV}} [\text{erg cm}^{-2} \text{ s}^{-1}]$), far-UV (FUV, 91.2–170 nm) flux density ($F_{\text{FUV}} [\text{erg cm}^{-2} \text{ s}^{-1}]$), and X-rays plus extreme-UV (or the so-called XUV, 0.5–91.1 nm) flux density ($F_{\text{XUV}} [\text{erg cm}^{-2} \text{ s}^{-1}]$), we use a combination of literature and estimated values. All the stellar forcing parameters are summarized at https://exoplanethaziness.shinyapps.io/Exoplanet_Haziness

For HD 97658b, GJ 436b, GJ 1214b, we used their measured and reconstructed FUV, NUV, and XUV flux luminosities from the MUSCLES TREASURY Survey reported by France

Planet Name	t_{age} [Gyr]	M_p [M_{\oplus}]	R_p [R_{\oplus}]	T_{eq} [K]	g_p [m^2/s]	H [km]	A_H [H]	WFC3 Ref(s).
GJ 436 b	6^{+4}_{-5} [1]	25.4 ± 2.1 [2]	4.10 ± 0.16 [2]	586 ± 10	14.81 ± 1.68	143 ± 16.45	0.43 ± 0.34	[a]
GJ 1132 b	9 ± 4 [3]	1.66 ± 0.23 [4]	1.13 ± 0.056 [5]	535 ± 23	12.74 ± 2.17	152 ± 26.67	-0.31 ± 0.19	[b,c,d]
GJ 1214 b	6.5 ± 3.5 [6]	6.26 ± 0.91 [7]	2.80 ± 0.24 [7]	544 ± 3	7.82 ± 1.76	252 ± 56.56	0.02 ± 0.05	[e]
GJ 3470 b	1.8 ± 1.2 [8]	12.58 ± 1.31 [9]	3.88 ± 0.32 [10]	670 ± 10	8.19 ± 1.60	296 ± 57.89	0.42 ± 0.19	[f]
HAT-P-11 b	$6.5^{+5.9}_{-4.1}$ [11]	23.4 ± 1.5 [12]	4.36 ± 0.06 [12]	740 ± 8	12.06 ± 0.84	222 ± 15.64	2.46 ± 0.56	[g]
HAT-P-12 b	2.5 ± 2 [13]	67.1 ± 3.8 [13]	10.7 ± 0.3 [13]	877 ± 11	5.69 ± 0.47	557 ± 46.82	0.13 ± 0.44	[h]
HAT-P-17 b	7.8 ± 3.3 [14]	184 ± 19.0 [15]	11.8 ± 0.4 [15]	724 ± 16	13.04 ± 1.67	201 ± 26.17	0.76 ± 0.87	[h]
HAT-P-18 b	$12.4^{+4.4}_{-6.4}$ [16]	62.6 ± 4.1 [16]	11.2 ± 0.6 [16]	776 ± 13	4.93 ± 0.61	569 ± 70.93	0.88 ± 0.31	[h]
HAT-P-26 b	$9^{+3}_{-4.9}$ [17]	18.75 ± 2.23 [17]	6.03 ± 0.75 [18]	946 ± 16	5.06 ± 1.39	677 ± 186.8	1.84 ± 0.62	[i]
HAT-P-38 b	$10.1^{+3.9}_{-4.8}$ [14]	84.9 ± 6.4 [19]	9.247 ± 1.031 [19]	988 ± 19	9.72 ± 2.29	367 ± 86.69	1.06 ± 0.82	[h]
HD 3167 c	7.8 ± 4.3 [20]	9.8 ± 1.3 [20]	3.01 ± 0.42 [20]	512 ± 6	10.60 ± 3.27	174 ± 53.95	1.82 ± 0.65	[j]
HD 97658 b	6.1 ± 0.7 [21]	7.81 ± 0.55 [22]	2.303 ± 0.110 [22]	650 ± 15	14.43 ± 1.71	163 ± 19.7	1.32 ± 0.47	[k,l]
HD 106315 c	4.48 ± 0.96 [23]	15.2 ± 3.7 [23]	4.35 ± 0.23 [23]	810 ± 6	7.87 ± 2.09	372 ± 98.82	1.65 ± 0.67	[m]
Kepler-51 b	0.5 ± 0.25 [24]	3.69 ± 1.86 [24]	6.89 ± 0.14 [24]	477 ± 5	0.76 ± 0.39	2270 ± 1146	0.00 ± 0.34	[n]
Kepler-51 d	0.5 ± 0.25 [24]	5.70 ± 1.12 [24]	9.46 ± 0.16 [24]	328 ± 4	0.62 ± 0.12	1900 ± 379.7	0.16 ± 0.21	[n]
Kepler-79 d	$1.3^{+1}_{-0.4}$ [25]	5.3 ± 0.9 [25]	7.2 ± 0.2 [25]	597 ± 6	1.02 ± 0.18	2120 ± 380.1	-0.93 ± 0.41	[o]
K2-18 b	2.4 ± 0.6 [26]	8.63 ± 1.35 [27]	2.610 ± 0.087 [28]	255 ± 3	12.41 ± 2.11	74.2 ± 12.65	2.36 ± 0.74	[p,q]
LHS 1140 b	9 ± 4 [29]	6.98 ± 0.89 [30]	1.727 ± 0.032 [30]	214 ± 3	22.93 ± 3.04	33.8 ± 4.508	3.07 ± 1.38	[r]
WASP-29 b	10.5 ± 3.5 [14]	73 ± 16 [15]	8.6 ± 0.8 [15]	890 ± 28	9.61 ± 2.73	334 ± 95.38	-0.17 ± 0.47	[h]
WASP-67 b	$12.6^{+1}_{-4.2}$ [14]	137 ± 29 [15]	12.9 ± 1.2 [15]	939 ± 18	8.06 ± 2.29	421 ± 119.7	2.33 ± 1.16	[h]
WASP-69 b	1 ± 1 [14]	92 ± 10 [15]	12.4 ± 0.4 [15]	878 ± 9	5.83 ± 0.74	544 ± 68.78	0.35 ± 0.17	[h]
WASP-80 b	7 ± 7 [14]	171 ± 11 [15]	11.2 ± 0.3 [15]	754 ± 17	13.36 ± 1.18	204 ± 18.62	0.61 ± 0.29	[h]
WASP-107 b	8.3 ± 4.3 [31]	30.5 ± 1.7 [32]	10.39 ± 0.33 [33]	676 ± 11	2.77 ± 0.23	884 ± 75.81	0.59 ± 0.08	[s]

Table 1.1 Summary of Parameters. For all parameter values and references, see https://exoplanethaziness.shinyapps.io/Exoplanet_Haziness/. We use the first reference listed in our calculation of A_H . We select the reference based upon it being the most up-to-date published result and consistent/similar method of data reduction.

References. — [1] Torres (2007); [2] Lanotte et al. (2014) [3] Berta-Thompson et al. (2015); [4] Bonfils et al. (2018); [5] Dittmann et al. (2017a); [6] Charbonneau et al. (2009); [7] Anglada-Escudé et al. (2013); [8] Pale et al. (2020); [9] Kosiarek et al. (2019); [10] Biddle et al. (2014); [11] Bakos et al. (2010); [12] Yee et al. (2018); [13] Hartman et al. (2009); [14] Bonomo et al. (2017); [15] Stassun et al. (2017); [16] Hartman et al. (2011a); [17] Hartman et al. (2011b); [18] von Essen et al. (2019); [19] Sato et al. (2012); [20] Christiansen et al. (2017); [21] Henry et al. (2011); [22] Guo et al. (2020) [23] Barros et al. (2017); [24] Libby-Roberts et al. (2020); [25] Chachan et al. (2020); [26] Guinan & Engle (2019); [27] Cloutier et al. (2019); [28] Benneke et al. (2019b); [29] Dittmann et al. (2017b); [30] Ment et al. (2019); [31] Močnik et al. (2017); [32] Piaulet et al. (2021); [33] Dai & Winn (2017)

WFC3 Observations/Data — [a] Knutson et al. (2014a); [b] Mugnai et al. (2021); [c] Libby-Roberts et al. (2021); [d] Swain et al. (2021); [e] Kreidberg et al. (2014); [f] Benneke et al. (2019b); [g] Fraine et al. (2014); [h] Tsiaras et al. (2018); [i] Wakeford et al. (2017) [j] Mikal-Evans et al. (2021); [k] Guo et al. (2020); [l] Knutson et al. (2014b); [m] Kreidberg et al. (2020); [n] Libby-Roberts et al. (2020); [o] Chachan et al. (2020); [p] Benneke et al. (2019a); [q] Tsiaras et al. (2019); [r] Edwards et al. (2021); [s] Kreidberg et al. (2018);

et al. (2016), and converted them into a flux density at their orbital semi-major axis, a . We are also able to estimate the FUV, NUV, XUV flux densities for three additional planets given their measured flux spectra taken with *HST*-COS G130M mode: HAT-P-11b, GJ 3470b, and WASP-69b. For these three targets, we scaled their UV fluxes using a combination of the reconstructed MUSCLES UV flux data and the *HST*-COS data (France et al., 2018). We first calculate the ratios for the integrated fluxes at Si IV ($\sim 1400 \text{ \AA}$) and N V ($\sim 1240 \text{ \AA}$) emission lines between the target star and a MUSCLES star using the *HST*-COS data. We then scaled the NUV, FUV, XUV fluxes of our target stars at their corresponding wavelengths by multiplying the ratio of integrated fluxes to the reconstructed MUSCLES star data. Finally, we calculate the converted stellar UV fluxes into flux densities at the planets orbital semi-major axis. We scaled HAT-P-11 (stellar type K4) and WASP-69 (K5) using the MUSCLES star HD 85512 (K6) as a proxy, and GJ-3470 (M1.5) using the MUSCLES star GJ-832 (M1.5) as a proxy (K. France, private communications). We find the emission line flux ratio to be $\sim 0.9 - 2.0$ between HD-85512 and Hat-P-11, $\sim 3.3 - 4.6$ between HD-85512 and WASP-69, and $\sim 1.1 - 1.8$ between GJ 832 and GJ 3470.

For the rest of the planets without directly measured UV fluxes, we estimated their F_{NUV} and F_{FUV} using the following relationships, which are fitted using the reported flux values of 13 FGK stars from France et al. (2013, 2016):

$$\begin{aligned} \log_{10}(F_{\text{NUV}}) &= 9.63 \times 10^{-4} T_{\text{eff}*} - 7.16 + \log_{10} \left(\frac{L_{\text{bol}}}{4\pi a^2} \right), \\ \log_{10}(F_{\text{FUV}}) &= -9.85 \times 10^{-4} T_{\text{eff}*} + 2.8 + \log_{10}(F_{\text{NUV}}). \end{aligned} \tag{1.1}$$

We estimated the XUV flux densities (F_{XUV}) for these planets using a combination of published relationships in the literature. We can use the age of their parent stars (t_{age}) to estimate the X-ray flux densities (F_X , $\sim 0.5\text{--}10 \text{ nm}$) of the star. In particular, we use the relationship in Guinan et al. (2016) for M-type stars, the relationship in Ribas et al. (2005) for G-type stars, and Sanz-Forcada et al. (2010) for F- and K-type stars. To estimate the EUV flux densities (F_{EUV} , $\sim 10\text{--}91.2 \text{ nm}$) for G-type stars, we use the relationship in Ribas et al. (2005) between t_{age} and

Star Type	F_X (1 AU)	Ref.	$F_{Ly\alpha}$ (1 AU)	Ref.	F_{EUV} (1 AU)	Ref.
M-	$1.3 \times 10^{0.411-1.424(\log(t_{age}))}$	[1]	Table 5	[2]	Table 5	[3]
G-	Table 5	[4]	Table 5	[4]
F- and K-	$6.72t_{age}^{-1.55}$	[5]	Table 5	[2]	Table 5	[3]

Table 1.2 XUV Flux Estimation Summary. All fluxes are normalized fluxes at 1 AU and have units of $\text{erg s}^{-1} \text{cm}^{-2}$, t_{age} has a unit of Gyr. For plotting and reference proposes, we normalize from 1 AU to each planets a by $F(a) = F(1 \text{ AU})/a^2$

References. — [1] Guinan et al. (2016); [2] Linsky et al. (2013); [3] Linsky et al. (2014); [4] Ribas et al. (2005); [5] Sanz-Forcada et al. (2010)

F_{EUV} . To estimate F_{EUV} for M-, F- and K- stars, we can use Lyman alpha flux densities ($F_{Ly\alpha}$) to estimate their F_{EUV} using relationships given in Linsky et al. (2014). We estimate $F_{Ly\alpha}$ using the fifth method described in Linsky et al. (2013). Combining the estimated F_X ($\sim 0.5\text{--}10 \text{ nm}$) and F_{EUV} fluxes ($\sim 10\text{--}91.2 \text{ nm}$), we get the XUV flux densities ($\sim 0.5\text{--}91.2 \text{ nm}$) for these planets.

1.3.2 Planetary Parameters

For each exoplanet, we collected from the literature the mass (M_p [M_\oplus]) and radius (R_p [R_\oplus]). We calculated the equilibrium temperature (T_{eq} [K], see 2), density (ρ_p [ρ_\oplus]), surface gravity (g_p [m s^{-2}]), atmospheric scale height (H [m]), and bulk hydrogen-helium ($\text{H}_2\text{-He}$, see 2) mass fraction (f_{HHe} [%]) of the planets. All the intrinsic planetary parameters are summarized at https://exoplanethaziness.shinyapps.io/Exoplanet_Haziness

For most of our planets that are of about a Neptune mass or smaller ($M_p < 20M_\oplus$), we estimated f_{HHe} from Lopez & Fortney (2014), either using the calculated values from their Table 7 or interpolation from their Table 1-6. For planets above $20M_\oplus$, we calculated f_{HHe} following the method described in Thorngren & Fortney (2019).

1.4 Statistics

In this section, we explain the test statistics we will use to determine the linear or linear on logarithmic-scale trends of A_H versus each parameter. We choose these statistics for their simplicity, and so we may compare our results easier with previous works.

We use the Pearson correlation coefficient (r) which determines the correlated linear behavior between a parameter and A_H calculated as (Bevington & Robinson, 2003, Eq. 11.17),

$$r = \frac{N \sum x_i A_{H,i} - \sum x_i \sum A_{H,i}}{[N \sum x_i^2 - (\sum x_i)^2]^{1/2} [N \sum A_{H,i}^2 - (\sum A_{H,i})^2]^{1/2}}, \quad (1.2)$$

where x_i is the independent variable and is an individual planet or star's parameter (plotted on the horizontal axis in our figures), and $A_{H,i}$ is the corresponding exoplanet's water amplitude. We determine the probability, "p-value" (p), of an uncorrelated data set also having the same r value as Bevington & Robinson (2003) do in their Equations 11.18, 11.19, which we do not show explicitly for brevity. As r approaches ± 1 , the parameter and A_H are more linearly correlated. While lower p -values reduce concerns of accidental/false correlation between uncorrelated data. We show an unweighted least-square fit and plot it as a qualitative visual for the linear correlation statistics.

We additionally perform a weighted least-square linear fit ($A_{H,\text{fitted}} = ax + b$) on all parameters vs A_H and perform a goodness of fit test by calculating the weighted linear fit's χ^2 which we normalize by the degrees of freedom ($\nu \equiv N - \text{number of fitted parameters}$, where typically for our fits $N = 23, \nu = 2$) giving us the reduced χ^2 (χ_ν^2) as,

$$\chi_\nu^2 = \frac{1}{\nu} \sum_i^N \frac{(A_{H,\text{fitted}}(x_i) - A_{H,i})^2}{\sigma_{A_{H,i}}^2}. \quad (1.3)$$

Generally, lower χ_ν^2 indicates a better fit up to $\chi_\nu^2 \approx 1$. If χ_ν^2 is too low (typically $\chi_\nu^2 \ll 1$), this indicates a possible fallacy of the test statistic. We do not see this occur in our results.

We may extend these linear statistics to the log-scale by performing the same statistics on log-scaled values (i.e., $x_i = \log_{10}(y_i)$). This is done for parameters where log-scaled values produced better statistics than the linear statistics, and thus are plotted in log-scale.

2 H₂O Absorption Amplitude Metric

2.1 Definition of Water Amplitude

In previous works (S16; CK17), the common idea in the definition of the water amplitude metric involves calculating the difference of transit depths at two wavelengths where a spectral feature is expected and not. The transit depth (D) measured from transmission spectroscopy is a function of wavelength (λ):

$$D(\lambda) = \frac{R_p(\lambda)^2}{R_*^2}, \quad (2.1)$$

where $R_p(\lambda)$ is the transit planetary radius as a function of wavelength and R_* is the stellar radius.

Specifically, here we estimate the haziness of the transmission spectrum by normalizing the amplitude difference between the H₂O absorption feature around 1.4 μm and the J-band baseline around 1.25 μm . The normalized transit radius difference between these two wavelengths establishes our water amplitude metric.

To calculate the water amplitude from transmission spectra, we first compute the inverse-variance weighted average of the transit depths around 1.25 μm from ~ 1.22 -1.3 μm , and around 1.4 μm from ~ 1.36 -1.44 μm , depending on the spectral binning conventions used between various sources (adapted from S16). Next, we compute $R_p(\lambda)$ from Equation (2.1), where we substitute in the averaged transit depth (D_{avg}) (adapted from CK17). Taking the difference of transit radii at 1.4 and 1.25 μm , we define the water amplitude metric as

$$A_H = \frac{R_*}{H} \left(\sqrt{D_{\text{avg}}(1.4 \mu\text{m})} - \sqrt{D_{\text{avg}}(1.25 \mu\text{m})} \right), \quad (2.2)$$

where $H = k_B T_{\text{eq}} / \mu g_p$ is the atmospheric scale height, k_B is the Boltzmann constant, μ is the atmospheric mean molecular mass, g_p is the surface gravity of the planet. To compute H , we assume solar composition atmospheres with mean molecular weight of 2.3 amu following CK17, since most of the planets are large enough to have H₂-He dominated atmospheres. We calculated T_{eq} from the stellar effective temperature ($T_{\text{eff}*}$), radius (R_*), planet orbital semi-major axis (a), and Bond albedo (A_B) by the relationship of $T_{\text{eq}} = T_{\text{eff}*} (1 - A_b)^{1/4} \sqrt{R_*/2a}$. We choose a Bond albedo of 0.3 because Earth, Mars, Titan, and the giant planets in the Solar System all have Bond albedos around 0.2-0.4 (de Pater & Lissauer, 2001), as well as some hot-Jupiters (Charbonneau et al., 2005; Heng et al., 2021). We will discuss the caveats regarding these assumptions in Section 5. Our method takes a very similar approach compared to S16 and CK17 and is a simple way of estimating the water amplitude of exoplanets from available observational data. We will discuss the consistency of the results obtained from our method with previous studies in Section 5.

In Figure 2.1, we present our adopted transmission spectra for the 23 targets observed with *HST*/WFC3 ordered by T_{eq} (from warm to cool). We select existing reduced transmission spectra data from the literature. For some exoplanets with multiple published reduced data, we adopt the ones that have the most transits or use more up-to-date stellar parameters. We summarize the calculated water amplitudes and our adopted transmission spectra data references for all our exoplanet targets in Table 1.1.

Before we search for trends between our water amplitude metric and the various stellar/planetary parameters, we clarify that our definition of water amplitude depends only on atmospheric properties and does not have an explicit dependence on the planetary/stellar parameters. To this end, we analyse our definition of A_H using an analytical model of the transmission spectrum. Heng & Kitzmann (2017) provided an approximate solution for $R_p(\lambda)$ as,

$$R_p(\lambda) \approx R_0 + H \left[\gamma + \ln \left(\frac{P_0 \kappa(\lambda)}{g} \sqrt{\frac{2\pi R_0}{H}} \right) \right], \quad (2.3)$$

where $\gamma \approx 0.57721$ is the Euler-Mascheroni constant, R_0 is the reference planetary transit radius, $\kappa(\lambda)$ is the atmospheric opacity—extinction cross sections per mass—as a function of wavelength,

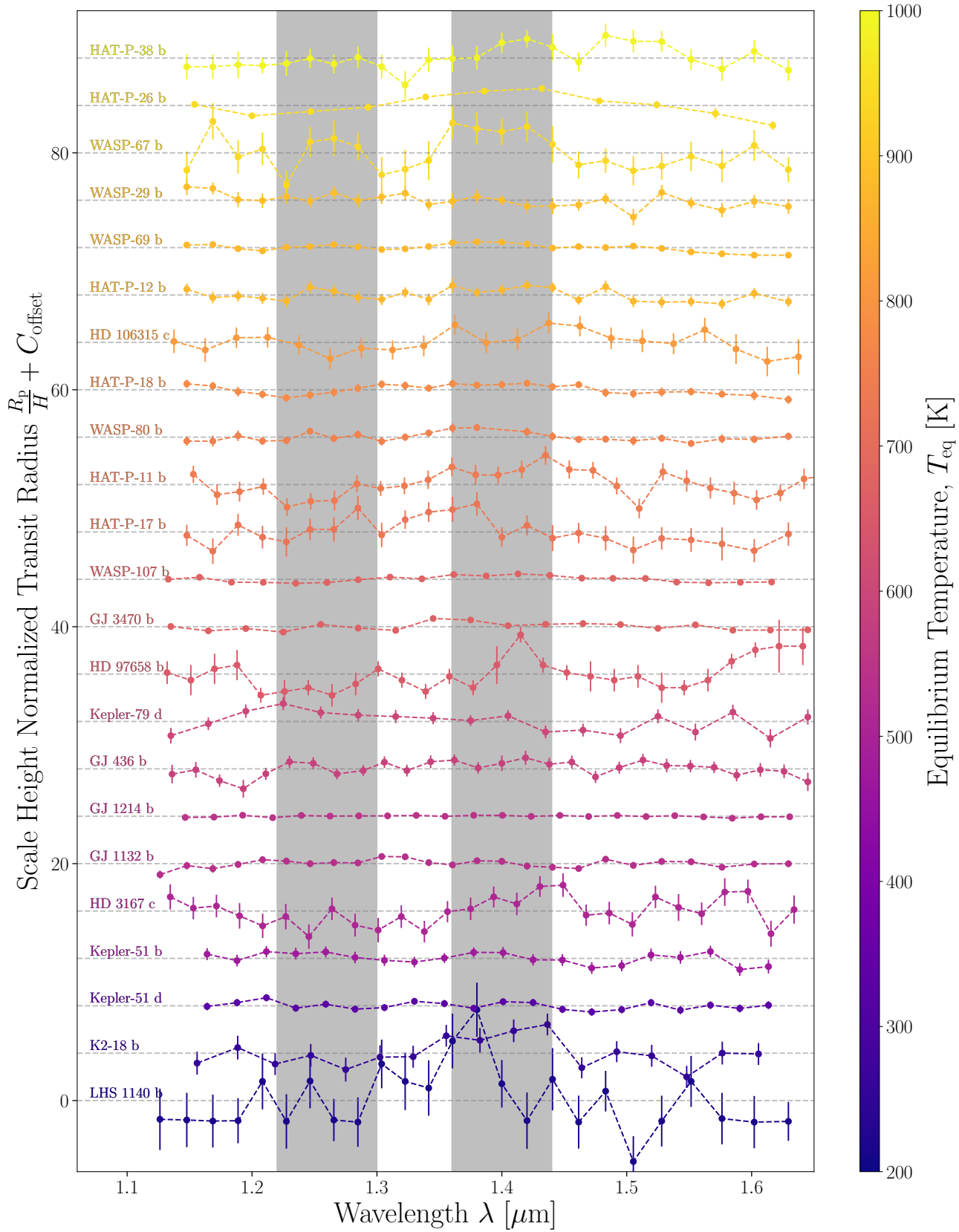


Figure 2.1 Transmission spectra data (points) connected linearly between each point for clarity (dashes) for our 23 exoplanet targets. We normalize the observed transit radius of each target by the atmospheric scale height (H) and offset for clarity. The color of the data points shows the equilibrium temperature (T_{eq}) for each target.

and P_0 is the pressure at radius R_0 . Equation (2.3) is valid for isothermal atmospheres with vertically constant gravity and opacity (for vertically varying opacity, see Ohno & Kawashima, 2020). Inserting Equation (2.3) into Equation (2.2), we can express the water amplitude as:

$$\begin{aligned} A_{\text{H}} &\approx \frac{R_*}{H} \frac{H}{R_*} \left[\ln \left(\frac{P_0 \kappa(1.4 \mu\text{m})}{g} \sqrt{\frac{2\pi R_0}{H}} \right) - \ln \left(\frac{P_0 \kappa(1.25 \mu\text{m})}{g} \sqrt{\frac{2\pi R_0}{H}} \right) \right] \\ &= \ln \left(\frac{\kappa(1.4 \mu\text{m})}{\kappa(1.25 \mu\text{m})} \right). \end{aligned} \quad (2.4)$$

Equation (2.4) demonstrates that our water amplitude metric does not have any explicit dependence on any specific planetary/stellar parameters. The water amplitude is a measure of the ratio of atmospheric opacity between the two wavelengths. For a cloud/haze free atmosphere with water vapor, A_{H} should be around 7 (CK17). If the water amplitude depends on planetary/stellar parameters, this indicates that atmospheric opacities have implicit dependencies on stellar/planetary parameters. We will explore the possible implicit dependencies of the opacities for hazy atmospheres using a simple but physically motivated haze model in Section 4.

2.2 Previous Water Amplitudes

In this section, we summarize the previous water amplitude definitions from S16; CK17. CK17 started by applying a weighted least square fit of a normalized template spectra derived from a model carbon-free GJ 1214b spectra (S_t) to the observed spectra (S_O) as a function of wavelength (λ) and S_t to get $S_O = a_1 + a_2\lambda + a_3S_t$, where $a_{1,2,3}$ are the fitting parameters. This results in a close fit between the original transit depth spectra data and their model for each of their planets. To calculate the water amplitude, CK17 converted their model's transit depth to the transit R_p using Eq. (2.1) as a function of wavelength which is normalized by the atmospheric scale height. Then, they took the difference at the wavelengths 1.4 and 1.25 μm .

The water amplitude is defined by S16 as the transit depth difference between the H_2O absorption feature around 1.4 μm and the J-band baseline around 1.25 μm , normalized by the change in transit depth $\Delta D = 2HR_p/R_s^2$, with H being the atmospheric scale height. While we see

no obvious flaws with this method, we explored how other methods mentioned and in literature affect the results of this analysis, such as the method described by S16. Instead of fitting a model, S16 took the weighted average of transit depths around 1.25 and 1.4 μm . This in general included three or four closest wavelength bins – depending on bin divisions. The main purpose of this weighted average is to flatten any jagged spectra due to random observational noise at the expected feature and baseline at 1.4 and 1.25 μm . Additionally, this improves the error for the average transit depths compared to the error of each bin separately, and decreases the effect of different authors reporting different division of bins. The biggest difference comes from the normalization factor which for S16’s method is defined to be $\Delta D \sim 2HR_p/R_*^2$. This achieves essentially the same metric as CK17. However, due to the approximate relation for the normalization factor, and a difference in the way at which the transit depth is converted to the transit radius, it does not match exactly to the method developed by CK17. As such, we adopted the initial averaging as a part of our method in place of CK17’s weighted fitting, but maintained CK17’s method of conversion to transit radius and normalization.

3 Statistical Trends of Water Amplitude verses System Parameters

Table 3.1 details the linear test statistics of every stellar forcing and planetary parameter we investigated against water amplitude, A_H . The majority of the linear trends held no statistical significance. However, the log of atmospheric scale height ($\log(H)$), planetary surface gravity (g_p), and the log of planet density ($\log(\rho_p)$) hold the best linear trends among all the tested parameters ($p \leq 0.02$). We also find tentative positive correlations between A_H versus orbital eccentricity (e) and stellar age (t_{age}) ($p \leq 0.10$). With the increased amount of water amplitude data (23 in this study versus 6 in CK17), previously observed linear trends in CK17 with equilibrium temperature (T_{eq}) and bulk hydrogen-helium fraction (f_{HHe}) no longer hold. We describe in the following sections in detail the observed trends for the major stellar forcing and planetary parameters. In addition, we would like to note that, for all the exoplanet targets we investigated, their computed water amplitudes A_H are much lower ($A_H \sim 4$) than expected for cloud/haze free atmosphere ($A_H \sim 7$, CK17). This demonstrates that clouds and hazes are indeed ubiquitous in temperate to warm exoplanet atmospheres with $T_{\text{eq}} < 1000$ K.

3.1 Stellar Forcing Parameters

Among all the stellar forcing parameters, orbital eccentricity (e) and age of the star (t_{age}) hold better linear trends against A_H . The orbital semi-major axis (a) holds a good linear trends

parameter	r	p	χ^2_ν	parameter	r	p	χ^2_ν
$\log(H)$	-0.57	< 0.01	4.8	R_*	-0.15	0.49	3.7
$\log(\sqrt{T_{\text{eq}}}/g)$	-0.55	0.01	4.9	a	-0.15	0.50	5.1
g_p	+0.53	0.01	5.0	$Z_{[\text{Fe}/\text{H}]}$	-0.13	0.55	5.2
$\log(\rho_p)$	+0.47	0.02	4.4	M_*	-0.11	0.61	3.7
e	+0.39	0.07	2.4	T_{eff}	-0.11	0.62	4.0
t_{age}	+0.35	0.10	5.0	T_{eq}	-0.10	0.64	4.1
R_p	-0.23	0.28	3.7	$\log(L_{\text{bol}})$	-0.09	0.69	3.5
f_{HHe}	-0.21	0.35	3.6	P_{rot}	+0.08	0.72	3.3
$\log(F_{XUV})$	-0.21	0.35	4.7	g_*	+0.07	0.74	3.1
$\log(F_{NUV})$	-0.18	0.42	3.6	ρ_*	+0.03	0.89	3.0
$\log(F_{FUV})$	-0.17	0.45	4.5	M_p	<0.00	0.99	4.4

Table 3.1 Linear Test Statistics.

against A_{H} without the super-puff exoplanets. We do not see any noticeable linear trends for all the other stellar forcing parameters, including mass (M_*), radius (R_*), density (ρ_*), surface gravity (g_*), effective temperature ($T_{\text{eff}*}$), bolometric luminosity (L_{bol}), metallicity ($Z_{[\text{Fe}/\text{H}]}$), stellar rotation period (P_{rot}), and various stellar UV fluxes (F_{NUV} , F_{FUV} , F_{XUV}), as shown in Table 3.1. In Figure 3.1a-c, we show the observed trends between A_{H} and e , t_{age} , and a . In Figure 3.1d-f, we show the relationships between A_{H} and the UV fluxes of different wavelengths. Plots for the rest of the stellar forcing parameters can be found at https://exoplanethaziness.shinyapps.io/Exoplanet_Haziness

We find a relatively strong linear correlation ($r = 0.39$; $p = 0.07$; $\chi^2_\nu = 2.4$) between orbital eccentricity (e) and A_{H} (see Figure 3.1a). This tentative positive correlation suggests exoplanets with circular orbits tend to be hazier than exoplanets with more elliptical orbits. However, the orbital eccentricity for each planet has large uncertainties, and better constrains on e are needed to determine if this tentative linear trend holds true.

We also find a relatively strong linear correlation ($r = 0.35$; $p = 0.10$; $\chi^2_\nu = 5.0$) between stellar age (t_{age}) and A_{H} (Figure 3.1b). Due to the sparseness of reliable age data from literature, the values we collected vary drastically in accuracy. In general, there appears to be a positive correlation

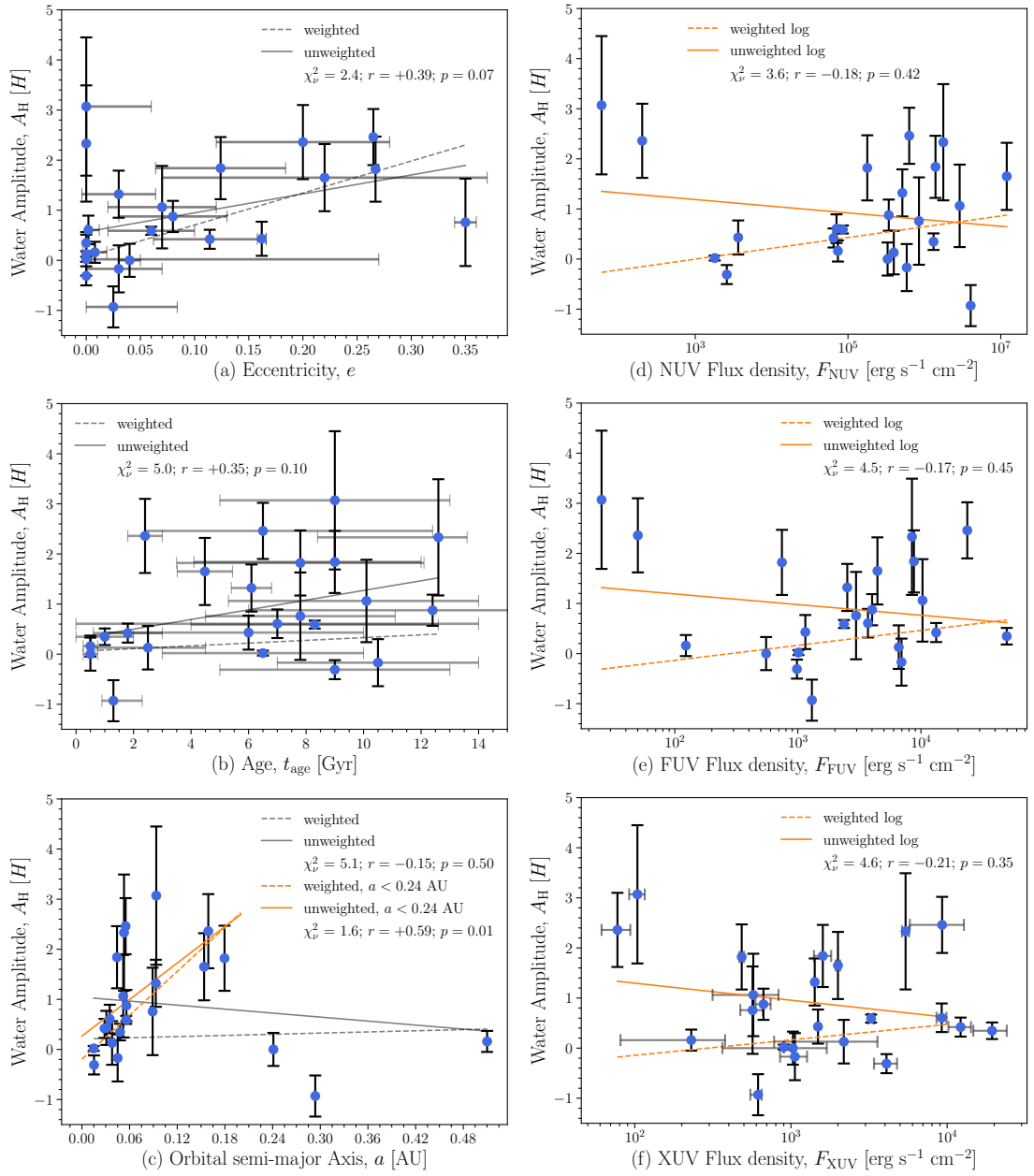


Figure 3.1 (a)-(c): Stronger linear correlations between A_H and orbital eccentricity (e), age of the star (t_{age}), and orbital semi-major axis (a). The solid black and dashed black lines respectively represent the unweighted and weight linear fits. The orange lines show the unweighted (solid) and weighted (dashed) linear fit, excluding Kepler 51b,d & Kepler 79. (d)-(f): Weaker linear correlations between A_H and the received stellar UV fluxes of the exoplanets. The solid orange and dashed orange lines respectively represent the unweighted and weight fits for the linear logarithmic correlation. We included 1σ uncertainty of A_H , e , t_{age} , and F_{XUV} as error bars in the plots.

where younger systems have hazier planets while older systems have clearer planets. But we also note that our sample did not show strong correlation between the A_H and the stellar metallicity.

The orbital semi-major axis of the exoplanet (a) holds a poor linear correlation ($r = -0.15$; $p = 0.50$; $\chi^2_\nu = 5.1$) with A_H (Figure 3.1c). However, if we exclude the super-puff targets (Kepler-51 b,d & Kepler-79 d), we find a relatively strong correlation ($r = 0.59$; $p = 0.01$; $\chi^2_\nu = 1.6$). This trend excluding the super-puffs indicates exoplanets closer to their host star are hazier than those further away. This agrees with physical intuition as closer exoplanets receive more relative stellar flux from this host star, which would help the haze formation processes. However, it is difficult to determine if the super-puff targets are outliers due to their extraordinary nature (Lee & Chiang, 2016) or if they actually belong to an overall nonlinear trend.

Stellar UV fluxes are believed to play a significant role in haze formation (Trainer et al., 2006) and are parameterized in models to scale for haze production (Kawashima & Ikoma, 2018; Lavvas et al., 2019). However, we found no linear trends between NUV, FUV, XUV fluxes and A_H (see Figure 3.1d-f). The $\log(F_{NUV})$ and $\log(F_{FUV})$ trends share a similar parabolic shape, as seen in Figure 3.1d and 3.1e. This shape is close to the trend found with T_{eq} (see Figure 3.2b). This is not unexpected as we estimated the FUV/NUV fluxes of many of the targets' host stars (due to the lack of observed FUV/NUV data) using relationships that depend upon T_{eff*} and a (see Equation (1.1)), which is also how T_{eq} is calculated. Specifically, $\log(F_{NUV})$ and $\log(F_{FUV})$ both have a strong positive correlation with T_{eq} ($r = 0.75$ and $r = 0.97$, respectively). For $\log(F_{XUV})$, we find a poor linear logarithmic correlation (see Figure 3.1f), in agreement with CK17. We still need more UV flux observations or better estimations for these exoplanet host stars (mostly M- type stars) to better assess these correlations.

3.2 Planetary Parameters

Among all the planetary parameters, the log of atmospheric scale height ($\log(H)$), planet surface gravity (g_p), and the log of planet density ($\log(\rho_p)$) hold better linear trends against A_H . We

do not see any noticeable linear trends for all the other planetary parameters, including planetary mass (M_p), radius (R_p), equilibrium temperature (T_{eq}), and bulk hydrogen-helium (H/He) mass fraction (f_{HHe}), as summarized in Table 3.1. In Figure 3.2a-c, we show the trends between A_{H} and H , g_p , and ρ_p . In Figure 3.2d-f, we show the relationships for R_p , T_{eq} , and f_{HHe} , which are found to be linear correlated with A_{H} in CK17. Plots for the rests of the planetary parameters can be found at https://exoplanethaziness.shinyapps.io/Exoplanet_Haziness.

We find a relatively strong linear correlation ($r = -0.57$; $p < 0.01$; $\chi^2_{\nu} = 4.8$) between A_{H} and $\log(H)$ (see Figure 3.2a). As demonstrated in Section 2.1, in our definition of the water amplitude metric, the transit depth difference between $1.25 \mu\text{m}$ and $1.4 \mu\text{m}$ was divided by scale height to remove the H dependence (see Equation (2.2) and (2.4)). However, A_{H} is still linearly correlated with $\log(H)$. This suggests that an exoplanet atmosphere is likely hazier if its atmosphere is more extended. In Section 4, we further explore whether A_{H} has any implicit dependence on H using a simplified haze model. However, if we remove K2-18 b and LHS 1140 b and the super-puffs, which have the lowest and highest H among all the targets, this trend becomes insignificant. We still need more atmospheric characterization data for exoplanets with intermediate H (larger than the super-Earths and smaller than the super-puffs) to determine if this trend holds true.

We find a relatively strong linear correlation ($r = -0.53$; $p = 0.01$; $\chi^2_{\nu} = 5.3$) between A_{H} and planet gravity, g_p (see Figure 3.2b). S16 found a weakly positive correlation for A_{H} with $\log(g_p)$. However, F17 reported that they did not find any significant correlation between A_{H} and $\log(g_p)$ with their larger hot-Jupiter data set. CK17 also did not find significant correlation between A_{H} and $\log(g_p)$ for the sub-Neptunes. This linear correlation suggests that planets with higher gravity would have less hazy atmospheres, which could link to the removal of aerosol particles in planetary atmospheres. Larger gravity would lead to higher settling velocities of the aerosol particles, and could make the atmospheres clearer. We also identified a similar but slightly worse linear correlation between A_{H} and $\log(\rho_p)$ ($r = +0.47$; $p = 0.02$; $\chi^2_{\nu} = 4.4$, see Figure 3.2c).

The previously identified linear correlations no longer hold in our extended planet sample.

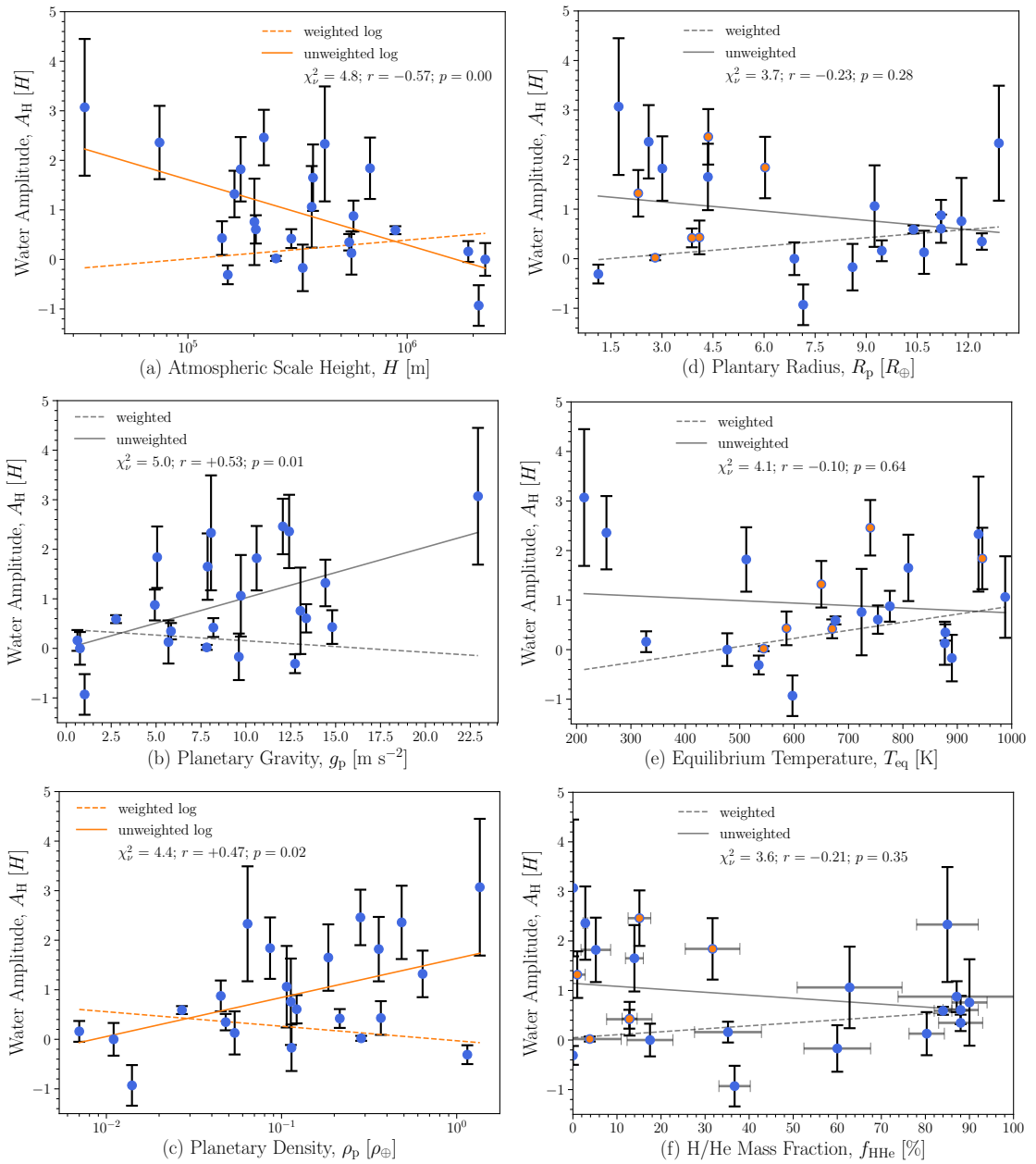


Figure 3.2 (a)-(c): Stronger linear correlations between A_H and planetary scale height ($\log(H)$), planet gravity (g_p), and planet density (ρ_p). The vertical error bars (black) represent the estimated 1σ uncertainty of A_H . (d)-(f): Weaker linear correlations between A_H and planet radius (R_p), planet equilibrium temperature (T_{eq}), and planet atmospheric hydrogen-helium mass fraction (f_{HHe}). The solid and dashed lines respectively represent the unweighted and weight fits for the linear logarithmic correlation (orange) and linear correlation (gray). The data points that are marked in orange are the targets in CK17.

While CK17 identified positive linear correlation between A_H and planet radius (R_p), the addition of new planets breaks down this linear trend, as shown in Figure 3.2d ($r = -0.23$; $p = 0.28$; $\chi_\nu^2 = 3.7$). CK17 found a significant linear correlation ($r = 0.81$, $p = 0.05$; $\chi_\nu^2 = 1.4$) between A_H and the estimated planet atmospheric hydrogen-helium mass fraction, f_{HHe} , whereas we find no significant linear correlation ($r = -0.21$, $p = 0.35$; $\chi_\nu^2 = 3.6$) between A_H and f_{HHe} with the addition of new planets (see Figure 3.2f). The linear correlation identified for T_{eq} in CK17 also does not hold with the addition of new planets (Figure 3.2e).

Recently, Yu et al. (2021) pointed a possibly quadratic trend between T_{eq} and A_H . They suggested that the exoplanets are likely haziest around 400–500 K because of the low removal rates of photochemical hazes. The low removal rate is due to a combination of the low surface energy of experimental haze analogs at 400–500 K (Yu et al., 2021) and scarcity of condensable species in atmospheres with T_{eq} between 300–600 K (Zhang, 2020). Meanwhile, hazes can be removed more easily for planets with higher and lower T_{eq} , leading to clearer atmospheres. Thus, the previously identified positive linear correlation between A_H and T_{eq} in CK17 could just be part of the quadratic trend for planets with $T_{\text{eq}} > 500$ K. F17 also found a positive correlation of T_{eq} with A_H for planets with T_{eq} between 500 and 2500 K. Since currently we only have two data points for the colder part of the quadratic trend (K2-18 b and LHS 1140 b), more transmission spectra data for colder planets are needed to solidify this proposed quadratic trend.

4 Analyzing Asymptotic Dependencies

Motivated by Haze Micro-physics

In Section 2.1, we have demonstrated that A_H does not have any explicit linear dependence on any particular planetary/stellar forcing parameters. However, in Section 3, we clearly see the water amplitude is correlated with a few planetary/stellar forcing parameters. Interestingly, the log of atmospheric scale height ($\log(H)$) has the strongest linear correlation with A_H . From Equation (2.4) we can see that the A_H should not depend on the planetary scale height if the opacity is independent of the scale height. This strong correlation for $\log(H)$ potentially suggests that the haze opacity is dependent of the scale height. In what follows, we further explore this possibility using a simple yet physically motivated haze model.

For a clear atmosphere with water vapor, $A_H \approx 7$ (CK17) due to the molecular opacity difference of water at $1.25 \mu\text{m}$ and $1.4 \mu\text{m}$. In Section 3, we found none of our exoplanet targets have A_H values close to 7, indicating the ubiquity of clouds and hazes in their atmospheres. Photochemical hazes are more likely the predominant opacity sources according to previous modeling studies (Gao et al., 2020). Thus, we here examine what planetary/stellar parameter dependence the haze absorption causes in the water amplitude. Co-dependency on haze absorption and molecular water absorption makes a general analytical solution for A_H like Equation (2.4) impossible. For simplicity, we assume the water absorption dominates the opacity at $1.4 \mu\text{m}$ and the haze absorption dominate

the opacity at 1.25 μm . Then, Equation (2.4) can be written as:

$$A_{\text{H}} = \ln \left(\frac{\kappa_{\text{H}_2\text{O}}(1.4 \mu\text{m})}{\kappa_{\text{haze}}(1.25 \mu\text{m})} \right), \quad (4.1)$$

where the opacity of molecular water ($\kappa_{\text{H}_2\text{O}}$) is a constant at 1.4 μm , and the haze opacity (κ_{haze}) can be analytically approximated as (Ohno & Kawashima, 2020):

$$\kappa_{\text{haze}} = \frac{36\pi g_{\text{p}} H F_{\text{haze}}}{\rho_{\text{haze}} P v_{\text{t}}} \left[1 - \exp \left(-\frac{v_{\text{t}} H}{K_{zz}} \right) \right] \frac{nk\lambda^{-1}}{(n^2 - k^2 + 2)^2 + (2nk)^2}, \quad (4.2)$$

where F_{haze} is the downward haze mass flux from its chemical source in the upper atmosphere, which corresponds to the column-integrated haze production rate, K_{zz} is the eddy diffusion coefficient, P is the atmospheric pressure, ρ_{haze} is the density of the haze particles, n and k are wavelength-dependent real and imaginary parts of the refractive indices of the hazes, and v_{t} is the terminal velocity of haze particles. For tiny haze particles, we can approximate v_{t} as (Woitke & Helling, 2003):

$$v_{\text{t}} \approx \frac{\rho_{\text{haze}} g_{\text{p}}^2 H}{P \sqrt{8k_{\text{B}} T / \pi \mu}} a_{\text{haze}}, \quad (4.3)$$

where a_{haze} is the radius of haze particles. Equation (4.2) is valid when the haze particles have low single scattering albedos and are much smaller than the gas mean free path and the relevant wavelengths. Additionally, K_{zz} and $a_{\text{haze}} \rho_{\text{haze}}$ were assumed to be constant when deriving Equation (4.2) (Ohno & Kawashima, 2020).

Since the eddy diffusion coefficient is still highly uncertain for exoplanets, here we assume that the eddy diffusion timescale is much slower than the gravitational settling timescales, i.e., $v_{\text{t}} H / K_{zz} \gg 1$. By assuming constant haze density, particle size, planetary gravity, and temperature, we can now further reduce the haze opacity of Equation (4.1) into:

$$\kappa_{\text{haze}} = \frac{36\sqrt{8\pi k_{\text{b}}} F_{\text{top}} f \lambda^{-1} \sqrt{T}}{\sqrt{\mu} a_{\text{haze}} \rho_{\text{haze}}^2 g_{\text{p}}}, \quad v_{\text{t}} H / K_{zz} \gg 1, \quad (4.4)$$

where $f = nk / [(n^2 - k^2 + 2)^2 + (2nk)^2]$ is a dimensionless constant depending on haze refractive indices. Plugging Equation (4.4) into Equation (4.1), A_{H} can be expressed as:

$$A_{\text{H}} = -\ln \left(\frac{36\sqrt{8\pi k_{\text{b}}} F_{\text{top}} f \lambda_{1.25}^{-1} \sqrt{T}}{\sqrt{\mu} a_{\text{haze}} \rho_{\text{haze}}^2 \kappa_{\text{H}_2\text{O}} g_{\text{p}}} \right), \quad (4.5)$$

where $\lambda_{1.25} = 1.25 \mu\text{m}$. Equation (4.5) indicates that the water amplitude becomes smaller as the temperature increases and/or the gravity decreases. This is because high T and low g lead to a large atmospheric scale height, which hinders the removal of haze particles through eddy diffusion and gravitational settling. Because the atmospheric scale height is proportional to T/g , Equation (4.5) suggests that the water amplitude roughly has a logarithmic dependence on the scale height rather than a linear dependence, in agreement with our best correlation found in the log of atmospheric scale height (Section 3.2).

Motivated by haze microphysics, we can use this theoretical metric using combinations of a few planetary parameters and examined its correlation with A_{H} . Equation (4.5) shows that A_{H} may have an implicit dependence on both planet gravity and temperature. Our previous assumptions for Equation (2.4) allow us to set T as T_{eq} and g_p as our vertically constant planet gravity. If F_{top} and a_{haze} are insensitive to planetary parameters, the water amplitude would have implicit dependence $\sqrt{T_{\text{eq}}/g_p}$. Thus, we further explored whether A_{H} has any correlation with this asymptotic solution ($\sqrt{T_{\text{eq}}/g_p}$, see Figure 4.1). A strong correlation $\sqrt{T_{\text{eq}}/g_p}$ would indicate a preference for the settling regime for our planet set.

For $\sqrt{T_{\text{eq}}/g_p}$, we find a relatively strong linear logarithmic correlation ($r = -0.55$; $p = 0.01$; $\chi^2_{\nu} = 4.9$). This correlations is one of the strongest trend we find among the blind search for all the stellar forcing and planetary parameters. However, none of these parameters can be considered to have very strong correlations with A_{H} . The weak correlation of $\sqrt{T_{\text{eq}}/g_p}$ could be caused by several reasons listed below: 1) our exoplanet targets do not fall into the settling regime only; 2) we have fixed a number of uncertain parameters, such as downward haze mass flux F_{top} , but they may also have dependence on planetary parameters; 3) we assume the atmospheric opacity at $1.4 \mu\text{m}$ is dominated by water and at $1.25 \mu\text{m}$ is dominated by hazes, while in reality, the opacity at both wavelengths should be the combination of both haze and gas opacity; 4) the calculated A_{H} for the exoplanet targets may have some intrinsic spread due to assumption we make in the calculations, such as assuming a constant mean molecular weight of the atmosphere ($\mu = 2.3 \text{ amu}$);

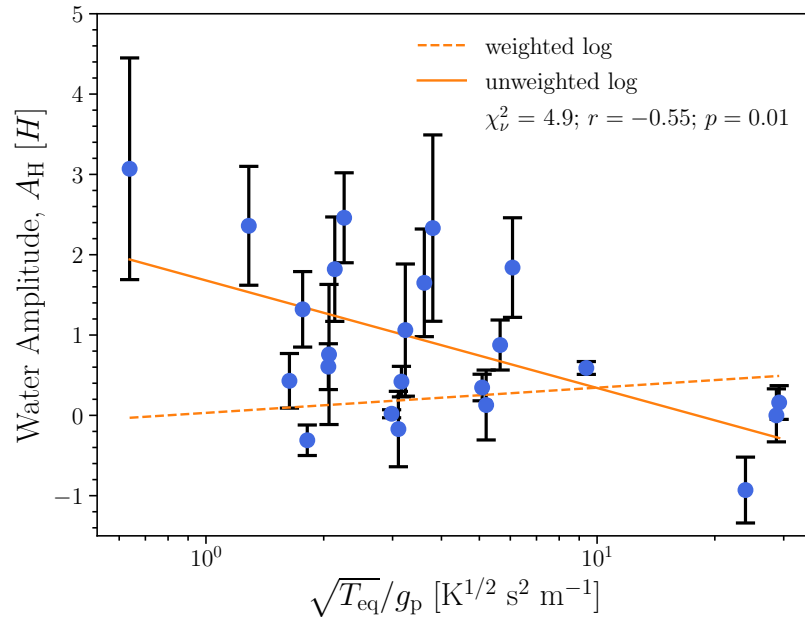


Figure 4.1 Linear correlations between A_H and $\log(\sqrt{T_{\text{eq}}}/g_p)$. The vertical error bars (black) represent the estimated 1σ uncertainty of A_H . The solid and dashed orange lines are the unweighted and weighted fit.

5) condensation clouds may also contribute to the atmospheric opacity in addition to photochemical haze for our exoplanet targets (e.g., Morley et al., 2013).

Overall, our analysis led to an asymptotic solution that also does not correlate strongly with the derived A_H for our exoplanet targets. This supports that A_H , or haziness of exoplanets, may not be solely determined by a single or a simple combination of planetary/stellar forcing parameters. We note that our haze model presented here is highly simplified. Further studies with detailed microphysical models (e.g., Lavvas & Koskinen, 2017; Kawashima & Ikoma, 2018; Gao & Zhang, 2020; Ohno & Tanaka, 2021) will be warranted to examine the haze trends that may appear in observed trends.

5 Discussion

5.1 Consistency with Previous Studies

Even though we have adopted a more simplified method than CK17 to compute the water amplitude, we confirmed that most of our A_{H} values are in close agreement with those derived by CK17 if we use their planetary parameters. We also confirmed that our A_{H} values are in agreement with those derived by S16; F17 using the planetary values we collected. The only exception is HD 97658 b, which we calculated its A_{H} to be 1.32 ± 0.47 , using the updated transmission spectra data from Guo et al. (2020) (4 transits). While CK17 gives $A_{\text{H}} = -0.09 \pm 0.55$ using data from Knutson et al. (2014b) (2 transits).

5.2 Caveats

We have adopted several assumptions in our analysis. In the following sections, we discuss the validity of our assumptions along with potential caveats for our sample and data analysis.

5.2.1 Statistical Uncertainties

In Section 3, we do not consider the effects of our relatively small sample size on the test statistics. Even though we increased our exoplanet sample size from 6 to 23 compared to CK17, our sample size is still tiny compared to the confirmed planet population size ($\sim 0.5\%$ of the over 4000 confirmed exoplanets). Our small sample size makes outliers difficult to catch and more

difficult to statistically rule out. For example, our super-puff targets present the most outlier-like behavior and are physically the most different (see Figure 3.1c). However, it is difficult to conclude whether they represent end-member behaviors of a continuous trend or whether they are outliers. In Section 5.2.3, we discuss the inclusion of the super-earth targets (LHS 1140 b & GJ 1132 b) and their effects on the trends. Thus, the test statistics we reported in Table 3.1 and Section 3 are mere indicators of potential correlations between stellar forcing/planetary parameters and exoplanet haziness. We do not intend to use these statistics as benchmarks that pass or do not pass arbitrary levels of significance (e.g., $p \leq 0.05$). More observations from the *HST* and future missions such as the *James Webb Space Telescope (JWST)* and the *Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL)* will alleviate some of this uncertainty by increasing the number of exoplanets measured through transmission spectroscopy.

5.2.2 Selection of Atmospheric Metallicity and Albedo

When calculating A_H (see Equation (2.2)), we divide the transit radii difference at $1.4 \mu\text{m}$ and $1.25 \mu\text{m}$ by the atmospheric scale height to remove the explicit planetary parameter dependence. However, when determining the atmospheric scale height for each of our exoplanet targets, we make two key assumptions: 1) all exoplanets have a $\text{H}_2\text{-He}$ dominated atmospheres with atmospheric mean molecular weight $\mu = 2.3 \text{ amu}$, and 2) they all have a planetary Bond albedo $A_B = 0.3$. While some sub-Neptunes are suggested to have atmospheric metallicity close to solar values (e.g., GJ 3470 b, Benneke et al., 2019b), some sub-Neptunes likely have much higher metallicity (> 100 times solar metallicity), such as GJ 1214 b (Morley et al., 2013, 2015; Ohno & Okuzumi, 2018; Gao & Benneke, 2018; Lavvas et al., 2019; Ohno et al., 2020) and GJ 436 b (Morley et al., 2017a). Planet formation models also predicted that sub-Neptunes tend to have high-metallicity atmospheres (Fortney et al., 2013; Venturini et al., 2016; Cridland et al., 2019). Thus the first assumption may not hold true for all exoplanets. Previous trend studies have used μ values from 2.3 amu for all planets (Sing et al., 2016; Crossfield & Kreidberg, 2017), or 2.3 amu for Jupiter-sized exoplanets and 3.8 amu for

Neptune-sized exoplanets and below (S16; F17). Similarly, there is no typical expected values of A_B for most of our exoplanet targets. Previous trend studies have used $A_B = 0$ (S16; F17) or $A_B = 0.2$ (CK17). However, since H is used for normalization, a change in μ or A_B only acts as a scale factor to increase or decrease the features (slopes/curves) of the trends. Fine grain choices of either for each exoplanet would be baseless as we have no precise data. Thus, we assume that μ and A_B are constant for all targets in this study.

The errors of these systematic effects can be determined. For μ , the percent error goes as $1 - \mu_{2.3}/\mu_{\text{True}}$. That gives for $\mu = 3.8$ amu and $\mu = 12$ amu a $\sim 40\%$ and $\sim 80\%$ error, respectively. Higher μ for some exoplanets may start to affect our analysis, and would mainly affect exoplanets with larger water amplitudes ($A_H \gtrsim 1.5$). For A_B , the percent error goes as $1 - (1 - A_{B,\text{True}})^{1/4}/(0.915)$. That gives for $A_B = 0$ a $\sim 9.3\%$ error against $A_B = 0.3$. Thus, the choice of A_B has little affect on our analysis unless these exoplanets are highly reflective ($A_B \sim 1$).

5.2.3 Terrestrial Atmospheres

While we expect most of our targets to hold H₂-He-rich atmospheres, some of our smaller targets could have atmospheres that are more terrestrial-like (e.g., outgassed secondary atmospheres or super-high metallicity primordial atmospheres). We first examined whether our targets are below or above the proposed radius valley by using the relationship proposed by Mordasini (2020). For planets below the radius valley, they are proposed to be close to stripped rocky cores due to the high stellar irradiation they receive (Lopez & Fortney, 2013; Owen & Wu, 2013, 2017) and are more likely to have thin terrestrial-like atmospheres. As shown in Figure 5.1a, only GJ 1132 b is below the radius valley. Thus, GJ 1132 b exists in a parameter space in which most of its atmosphere tends to be lost by photoevaporation.

We also examined the bulk densities of our targets to verify our assumption of H₂-He atmosphere. As shown in Figure 5.1b, most of our sample planets have radii fairly larger than those expected for pure H₂O planets, implying the presence of H₂-He atmospheres that puff up

the observable radius. However, the bulk densities of HD 97658 b and K2-18 b are consistent with those of 100% H₂O planets. Thus, it is unclear whether these planets are rocky planets with H₂-He atmospheres or icy planets with steam-like (i.e., high metallicity) atmospheres. The impacts of the possible high-metallicity atmospheres are discussed in Section 5.2.2. In addition, both LHS 1140 b and GJ 1132 b have Earth-like bulk densities. This presumably indicates that there are little-to-no H₂-He atmospheres in LHS 1140 b and GJ 1132 b. These targets may contribute two effects in our analysis: 1) terrestrial atmospheres likely have much higher μ than H₂-He atmospheres and their true atmospheric water amplitudes could greatly deviate from the ones calculated with $\mu = 2.3$ amu (see discussion in Section 5.2.2), 2) these terrestrial exoplanets could be the outliers of our samples, since their atmospheric chemistry could be very different from sub-Neptunes due to the differences in bulk atmospheric composition. Thus, we removed these two targets from our samples and reanalysed all the trends in Section 3. We found that our results remained unchanged with the statistics varying only slightly for most stellar forcing/planetary parameters. Thus, we leave the both of them in our analysis.

5.2.4 Spectral Signatures: Water vs Methane

We note that while we call our metric the “water” amplitude, any other molecules with spectral features present at around 1.4 μm may also be attributed to increase the “water” amplitude. For example, Bézard et al. (2020) suggests that methane absorption (which also has a spectral feature of 1.4 μm) could dominate over water absorption for exoplanets with $T_{\text{eq}} < 600$ K. In this study, the “water” amplitude is a mere measurement of the atmospheric haziness of exoplanets. The main absorber species at 1.4 μm does not affect our calculation A_{H} or assessment of the haziness of the exoplanet. Unless if the main absorber is substantially changing the mean molecular weight of the atmosphere, see the discussion in Section 5.2.2.

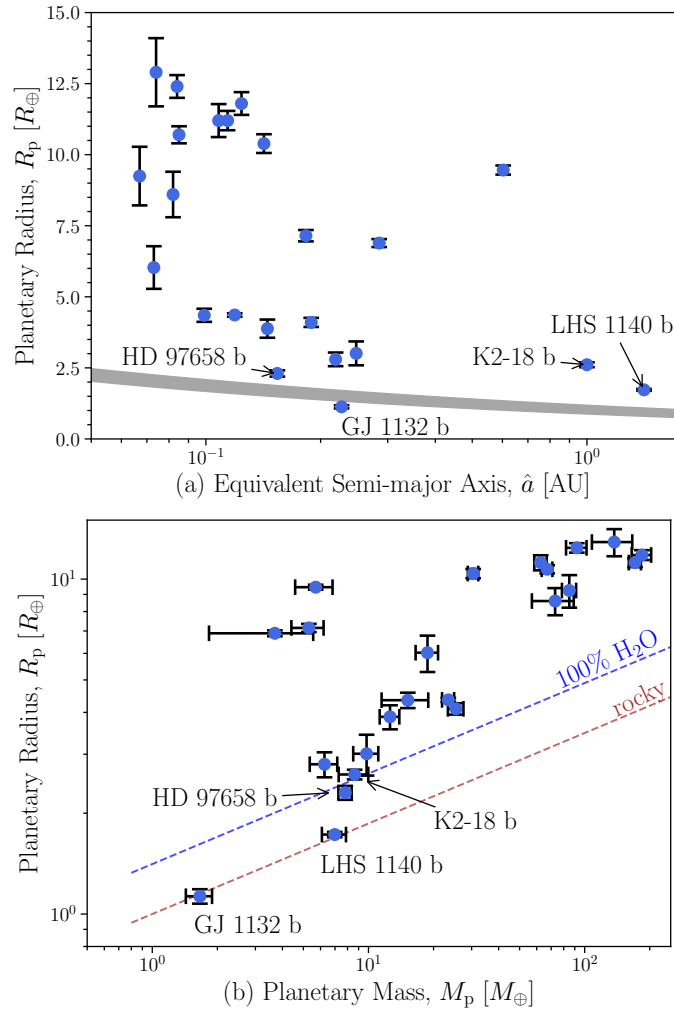


Figure 5.1 (a) Determining whether our exoplanets targets are within the radius valley. The shaded region represents a fit to the radius valley where the atmosphere is completely lost due to evaporation (adapted from Mordasini, 2020). The orbital distances of the targets are scaled to an equivalent semi-major axis, assuming they are orbiting the same Sun-like star ($T_{\text{eff}*} = 5778$ K and $R_* = R_{\text{sun}}$). (b) Mass-Radius distribution of our exoplanets targets compared to 100% H₂O (blue dashed line) atmosphere and Earth-like rocky (brown dashed line). Both lines are calculated from $R_p[R_\oplus] = (1 + 0.55x - 0.14x^2)(M_p[M_\oplus])^{1/3.7}$, where x is the ice mass fraction ($x = 1$ for 100% H₂O, $x = 0$ for rocky) (adapted from Zeng et al., 2019).

5.2.5 Transmission Data Reduction

In this study, we collected transit data from the literature in which the data reduction methods vary for each study. Such inhomogeneous data reduction may affect the results of our analysis. For example, the choice of the number of channels averaged in each wavelength bin can disrupt small features and the differences of intermediate data reduction steps could completely change the resulting data product (e.g., Alexoudi et al., 2018). As an example, the transit data of GJ 1132 b was reduced independently by three groups: Swain et al. (2021); Mikal-Evans et al. (2021); Libby-Roberts et al. (2021). Swain et al. (2021) analysis produced a sloped spectral feature around $1.3 \mu\text{m}$, and a larger negative $A_H \approx -0.9$. The analysis of Mugnai et al. (2021) and Libby-Roberts et al. (2021) found instead a visibly flat spectra, and with A_H close to zero. Since the last two groups return similar results, we choose to calculate A_H using reduced data from Mugnai et al. (2021), which is also close to the A_H calculated from Libby-Roberts et al. (2021). A trend study using uniform data reduction methods would be preferred, allowing for more rigorous comparison between exoplanets intrinsic properties (e.g., Sing et al., 2016; Tsiaras et al., 2018; Roudier et al., 2021). At present, we choose reduced data from the more recently published works, which either incorporate data from more recent transit observations (e.g., HD 97658 b we use Guo et al., 2020 instead of Knutson et al., 2014a) or use more up-to-date stellar parameters (e.g., K2-18b we use Benneke et al., 2019a instead of Tsiaras et al., 2019). Future studies with a consistent data reduction pipeline for all targets would provide more rigorous correlations between A_H and planetary/stellar parameters.

5.2.6 Negative Water Amplitudes

For three of our targets, we find a negative water amplitude: GJ 1132 b, WASP-29 b, and Kepler 79 d. For GJ 1132 b and WASP-29 b, their A_H are close to zero ($A_H = -0.31 \pm 0.19$ and -0.17 ± 0.47 , respectively) and in agreement with a flat spectra. Kepler 79 d is our only negative A_H of concern ($A_H = -0.93 \pm 0.41$). This could be partly due to the uncertainty of transit depth from Kepler 79 d's limited number of transits, which could be improved with more transit

observations. For TRAPPIST-1 planets, the observed negative A_{H} are suggested to originate from the heterogeneity on the photosphere of their host star (Rackham et al., 2018; Zhang et al., 2018). However, the negative amplitude of Kepler 79 d is unlikely due to heterogeneity on the photosphere of its host star (Chachan et al., 2020).

It is worth noting that the negative water amplitude can also originate from the atmospheric spectrum if the atmosphere is extremely hazy. For a very hazy exoplanet, a haze opacity dominates over gas opacity at both 1.25 and 1.4 μm . Inserting Equation (4.2) into Equation (2.4), the water amplitude can be written by ¹

$$A_{\text{H}} = \ln \left(\frac{1.25}{1.4} \frac{f(1.4 \mu\text{m})}{f(1.25 \mu\text{m})} \right). \quad (5.1)$$

Assuming that the optical constants (i.e., f in Equation 4.4) are nearly invariant with wavelength from $\lambda = 1.25\text{--}1.4 \mu\text{m}$, which is true for the refractive indices of soot and Titan tholin (see e.g., Figure 2 of Lavvas & Arfaux, 2021), Equation (5.1) yields a negative amplitude of $A_{\text{H}} \approx \ln(1.25/1.4) < 0$. In other words, the water amplitude becomes negative because the transit depth monotonically decreases with wavelength in the haze-induced spectral slope, i.e., $D(1.25 \mu\text{m}) > D(1.4 \mu\text{m})$. The actual amplitude of the slope-induced A_{H} is heavily dependent on the optical properties of the haze particles (i.e., f in Equation (5.1)), which are still largely unconstrained for the exotic conditions in exoplanet atmospheres.

¹Strictly speaking, Equation (2.4) is valid only for vertically constant opacity. We note that the vertical variation of haze opacity alters the gradient of the spectral slope but does not change its sign (Ohno & Kawashima, 2020)

6 Conclusion

In this study, we compiled and compared the haziness of 23 temperate to warm exoplanets using their transmission spectra data observed by *HST*/WFC3. By examining the relationship between the water amplitude A_{H} and various planetary and stellar forcing parameters, we found some notable correlations among all the parameters we investigated. Our analysis shows that:

1. Previously established linear trends between A_{H} vs. T_{eq} and f_{HHe} in CK17 break down with the addition of new exoplanet data.
2. Among all the stellar forcing parameters, orbital eccentricity and age of the star hold better linear correlations with A_{H} ($p \leq 0.10$). Specifically, planets with more eccentric orbits with older parent stars tend to have clearer atmospheres.
3. Among all the planetary parameters, log of atmospheric scale height, planet gravity, and log of planet density hold the most statistically significant linear correlations with A_{H} ($p \leq 0.02$). Specifically, planets with smaller scale heights (less puffy atmospheres), larger surface gravity, and larger bulk densities tend to be clearer. This potentially supports the idea that the water amplitudes are correlated with the planetary properties controlling the efficiency of haze removal, namely the scale height and gravity.
4. Our simple analytical haze model showed that A_{H} may be dependent on a combination of planetary parameters (equilibrium temperature and planet gravity): $\log(T^{1/2}/g)$. This parameter holds a decent trend with A_{H} compared to the other parameters tested (other than

scale height). However, its correlation with A_{H} is still not very good. This may indicate that our fixed parameters, such as haze mass flux and eddy diffusion coefficient, have implicit dependence on planetary parameters.

In this study, we tentatively suggest that less hazy atmospheres exist for exoplanets with smaller atmospheric scale heights, higher surface gravity, bulk densities, orbital eccentricities, and with older stars. However, none of the parameters have very strong linear correlations with A_{H} . This suggests that haziness in warm exoplanets may not be simply controlled by a single or a simple combination of planetary/stellar parameters. We still need more observations, laboratory experiments, and modeling work to fully understand the complex physical and chemical processes that lead to hazy exoplanet atmospheres. Note that as the field evolves with more upcoming transit observations, our interpretation might also change. Thus, we make a public-available website archiving all the data presented in this study: https://exoplanethaziness.shinyapps.io/Exoplanet_Haziness/. This would allow us to add any new observations and to keep track of the updated trends.

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