The past two decades have witnessed an explosion in the discovery of exoplanets, and the thousands of planets we now know of reveal a broader diversity of masses, compositions, and orbital configurations than is present in our own Solar System. **My research thus far has focused on detailed observational studies and retrieval modeling of exoplanet atmospheres with space-based and ground-based facilities.** Characterizing exoplanet atmospheres is critical because planetary atmospheres encode the formation and evolutionary histories of their planets as well as control their present-day climate. The gaseous atmospheres of Jupiters to super-Earths are accessible with current instruments on the *Hubble Space Telescope* (HST) and large ground-based telescopes. From transmission spectroscopy observations with these facilities, we can make inferences about the atmospheric structure and chemical composition of transiting exoplanets (e.g., Charbonneau et al. 2002; Vidal-Madjar et al. 2003; Wakeford et al. 2017) – despite the fact that this technique requires painstaking precision to pull out signals ~0.1% in size.

The first comparative atmospheric analyses of exoplanets revealed a continuum of cloudy to clear atmospheres for hot Jupiters (Sing et al. 2016) as well as correlations in atmospheric properties and system parameters of Neptune-sized planets (Crossfield & Kreidberg 2017). Building off of these ground-breaking results, **my dissertation work focused on the atmospheric characterization of giant planets using HST transit observations** that were taken as part of the *Hubble* Panchromatic Comparative Exoplanetology Treasury (PanCET) program (GO 14767). PanCET was awarded 498 HST orbits to observe the atmospheres of 20 giant planets in the ultraviolet, optical, and infrared. The goal of this program was to assemble the first broad wavelength (0.2–1.7 μm) legacy sample of exoplanet transmission spectra for planets that will be well-suited for atmospheric follow-up with the *James Webb Space Telescope* (JWST).

For my thesis, entitled "Characterizing Distant Worlds: Atmospheric Reconnaissance of Giant Planets with *Hubble*", **I led detailed atmospheric studies for the hot Jupiters WASP-52b, HAT-P-32Ab, and WASP-62b,** which were observed in the optical and near-infrared as part of the PanCET program. From the planetary spectra, I analyzed trends in planet radius as a function of wavelength, inferred the size of atmospheric particles, searched for absorption features to understand the chemical composition of the target planets, and modeled their atmospheres using retrievals.

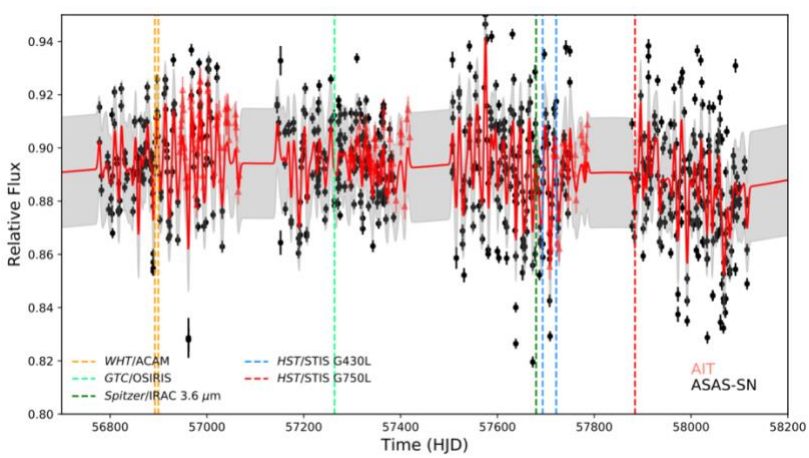

Figure 1. Ground-based photometric observations of WASP-52 from ASAS-SN (black points) and AIT (red triangles), compared to the Gaussian process regression model (red) and 1σ uncertainty (gray) fit to the full dataset.

For WASP-52b, I produced a 0.3–5.0 μm transmission spectrum consistent with clouds and hints of Na I absorption by combining HST/STIS and *Spitzer* transit observations (Alam et al. 2018). Considering the active host star, **I developed a new approach to accurately account for quasi-**

periodic modulations in the changing photosphere of the star using a Gaussian process (GP) regression model fit to ground-based stellar photometry (Figure 1). This technique more accurately corrects for contamination in the planet's spectrum from unocculted star spots than previous methods (e.g., Sing et al. 2011, Huitson et al. 2013), and has now been applied to several planets (e.g., Weaver et al. 2020, Carter et al. 2020, McGruder et al. 2020). This study demonstrated the importance of disentangling stellar and planetary signals to ensure precise atmospheric characterization free from stellar contamination.

I also constructed the first broad wavelength (0.3–5.0 μm) transmission spectrum for HAT-P-32Ab (Alam et al. 2020a) using HST/STIS, HST/WFC3, and *Spitzer* transit observations. My fits to a 1D grid of radiative-convective equilibrium models and retrievals of the planet's atmospheric properties indicate the presence of clouds and hazes in HAT-P-32Ab's atmosphere. In light of theoretical predictions initially suggested for inferring the presence of clouds in gas giant atmospheres (Stevenson 2016, Fu et al. 2017), **I showed that trends in surface gravity – equilibrium temperature space to predict cloudiness do not hold as we expand the number of planets with atmospheric observations** (Figure 2).

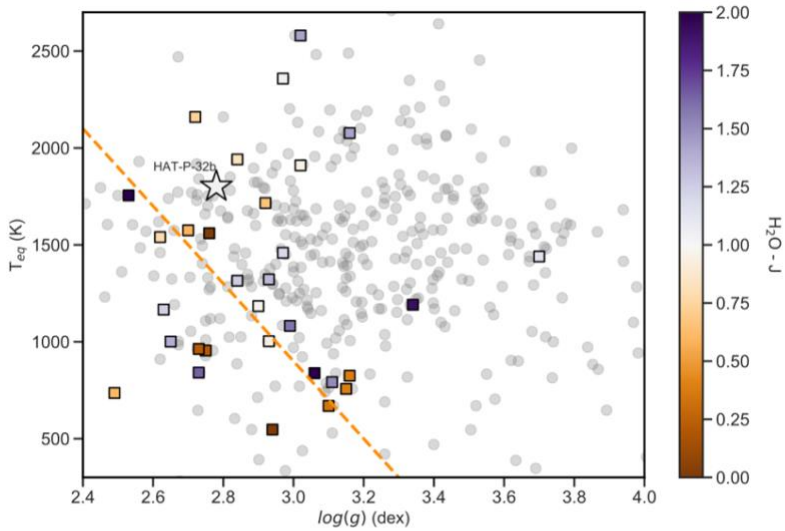

Figure 2. Amplitude of the observed 1.4 μm H_2O bandhead as a function of T_{eq} and log(g) (squares), color coded by the strength of the feature. Exoplanets with mass and radius measurements (gray circles) are shown for reference. The dashed orange line shows the proposed divide (Stevenson 2016) to delineate between cloudy versus clear planets in the T_{eq} – log(g) phase space. HAT-P-32Ab (white star) crosses this proposed divide and falls in the region theorized to be populated by clear atmosphere planets.

Further, **I found a cloud-free, haze-free atmosphere for WASP-62b, the only transiting giant planet in the JWST Continuous Viewing Zone** based on retrievals of the STIS+*Spitzer* transmission spectrum (Alam et al. 2020b). The 0.3–5.0 μm spectrum is characterized by a 5-σ detection of Na I at 0.59 μm in which the pressure-broadened wings of the absorption line are observed from space for the first time, as well as tentative evidence of SiH at 0.4 μm (Figure 3). I simulated JWST observations for a combination of instrument modes and demonstrated that this future facility can conclusively detect Na, H_2O, FeH, SiH, NH_3, CO, CO_2, and CH_4 within the scope of the JWST Early Release Science (ERS) program. WASP-62b could therefore be a potential benchmark planet for detailed atmospheric studies in the JWST era.

My analysis of these three planets led to unique conclusions that directly inform future exoplanet atmospheric observations with JWST. I focused on understanding exoplanet cloud characteristics, a critical piece of the puzzle because JWST will not be able to observe at optical wavelengths where planetary cloud and haze information can be unveiled. My work has expanded

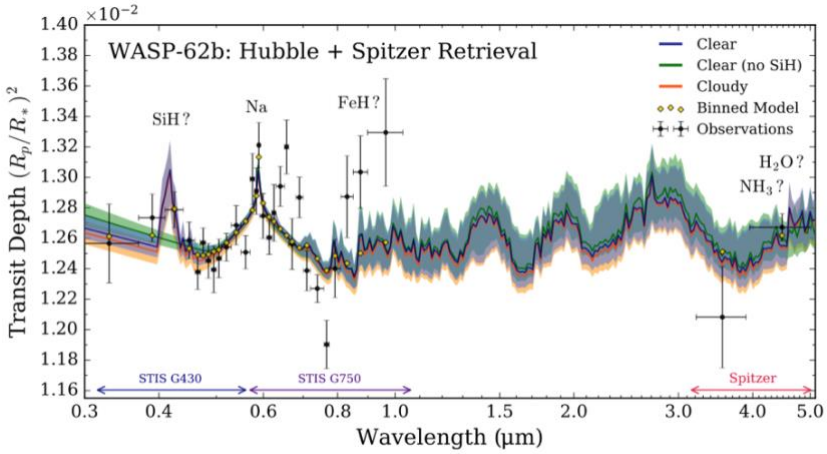

Figure 3. The HST/STIS+Spitzer transmission spectrum of WASP-62b (black points), compared to the best-fitting atmospheric retrieval models for a clear atmosphere with SiH (blue) and without SiH (green) as well as a cloudy model (orange). The cloudy model is consistent with a cloud-free atmosphere for WASP-62b.

efforts for comparative exoplanetology and shed further light on the impact of stellar activity on atmospheric observations and population-level trends in exoplanet cloud properties.

I have also worked on ground-based studies of escaping planet atmospheres via the 1083 nm helium (He) line. I reduced and analyzed the Keck/NIRSPEC He observations of WASP-107b published in Kirk et al. (2020), which demonstrated the capability of NIRSPEC for He studies for the first time. With a single transit observation, we found that our NIRSPEC results were consistent with previously published (Allart et al. 2019) high-resolution (R~80,400) CARMENES observations in terms of signal amplitude and shape of the transmission spectrum. **These results showed that the spectral resolution of the NIRSPEC instrument (R~25,000) is sufficient for high-resolution He searches**, in contrast with the resolution (R>80,000) of typical instruments used for these observations. The results of this work motivated further NIRSPEC He surveys, and I am a co-investigator on a 2020B NIRSPEC program to measure escaping He in the atmospheres of highly irradiated hot Jupiters.

Moreover, **I am leading a Keck/NIRSPEC 2020B program to search for escaping He in young (<100-500 Myr) transiting Neptune-sized planets**. A current open question in our understanding of exoplanets is how well Neptune-sized and smaller planets can survive atmospheric erosion during the first hundreds of million years and retain their primordial atmospheres. The young planets in our sample, discovered in nearby young open clusters and moving groups by the TESS and K2 missions, will provide pioneering cases for probing this poorly explored regime. These observations, scheduled for December 2020 and January 2021, will offer a unique and valuable window into observing atmospheric escape and interpreting the atmospheric evolution of small, irradiated planets.

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