New Insights on Exoplanet Atmospheres

Jacob Bean, *jbean@oddjob.uchicago.edu*, **and Jean-Michel Désert,** *desert@colorado.edu*

The importance of exoplanet atmosphere observations

The multitude of recently discovered exoplanets presents both challenges and opportunities. The challenge is to understand these objects as part of a complete theory of planetary system cosmogony, which is one of the forefront topics of modern astrophysics and planetary science. The opportunity is the chance to study a large and diverse sample of planets, including solar system analogues in different physical regimes (e.g., hot Jupiters) and classes of planets with no solar system counterparts (e.g., super-Earths).

Now that we are getting tight constraints on the rate of planet occurrence from exoplanet surveys, a key next frontier for the field is atmospheric characterization. The fundamental themes of exoplanet atmosphere characterization are the measurements of compositions, thermal structures, energy budgets, and dynamics to understand planetary origins and physics. *Hubble* has been making groundbreaking contributions in this area for 15 years using transit observations. Furthermore, *Hubble* has maintained its forefront position with the installation of the WFC3 instrument during SM4, which enables accurate near-infrared spectroscopy, and the implementation of spatial scanning, which enables observations of bright stars so that the required high signal-to-noise levels can be reached efficiently.

A new method to probe exoplanet atmospheres: phase-resolved spectroscopy

In this article we highlight two new results based on *Hubble* WFC3 transit spectroscopy observations that were carried out as part of a Large Treasury program in Cycle 21 (GO-13467). One of the exciting new developments is the demonstration of phase-resolved emission spectroscopy of exoplanets. The idea behind emission spectroscopy is that the effect of molecular absorption on the planet's thermal emission can be used to scan the temperature-pressure profile of the planet's atmosphere. For example, within a molecular band, where opacity is high, we probe the temperature structure higher in the atmosphere, while outside molecular bands where opacity is low, we probe deeper layers. This technique reveals the hemispheric average of the planet's dayside thermal structure when applied to secondary eclipse observations. Observations of an exoplanet as a function of its rotational phase enable necessary measurements of the thermal structure of the planet's atmosphere as a function of longitude.

Using *Hubble*, we performed the first phase-resolved emission spectroscopy of an exoplanet during our Cycle 21 program (Stevenson et al. 2014). We targeted the hot Jupiter WASP-43b for this demonstration. The observations spanned three complete orbits of the planet (P = 19.5 hr) using 14 continuous *Hubble* orbits for each planetary orbit. Our emission spectroscopy data set also included two observations centered just on the secondary eclipse. WASP-43b is likely tidally locked due to its close proximity to its host star. Therefore, there is a 1:1 correspondence between orbital phase and rotational phase for this planet.

Figure 1 is a screenshot of a movie that summarizes our phase-resolved measurements for WASP-43b. Previous exoplanet phase-curve observations were limited to broadband photometry (e.g., Knutson et al. 2007), and the interpretation of such data has an inherent degeneracy between the atmospheric composition and thermal structure. Our spectroscopic observations enabled us to break this degeneracy and uniquely determine the composition and thermal structure of an exoplanet atmosphere as a function of longitude for the first time.

We have used the data for WASP-43b to confront 3D atmospheric circulation models (Kataria et al. 2015). We find that the models correctly predict the dayside spectrum

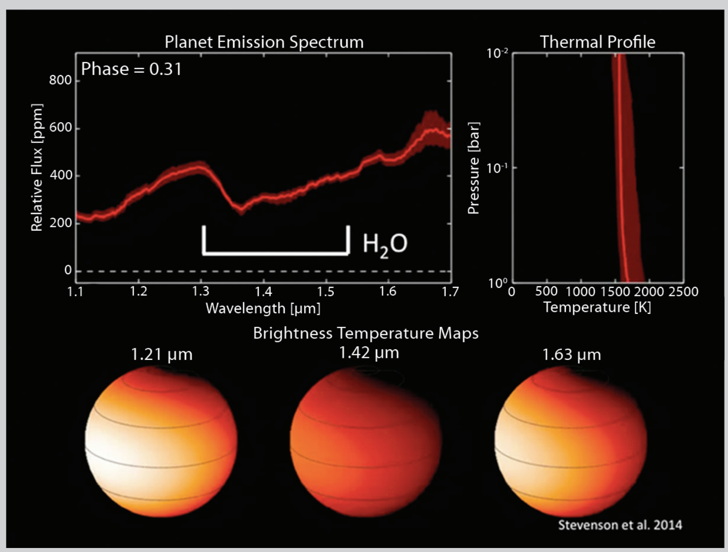

Figure 1: Screenshot of a movie constructed from observations of the first phase-resolved spectroscopy of an exoplanet. The data are from our Cycle 21 program on the hot Jupiter WASP-43b. The *top left panel* shows the measured emission spectrum of the planet at phase 0.31. A water absorption band that is spanned by the data is labeled. The *top right panel* shows the retrieved temperature-pressure profile of the planet's atmosphere. The shaded regions correspond to 1σ error bars. The *bottom panel* shows brightness temperature maps for the planet at three representative wavelengths inferred from the observations. The movie can be viewed here: **http://astro.uchicago.edu/~kbs/wasp43b.html**.

of the planet, which is a major success. However, the models over-predict the flux measured from the night side, which suggests less efficient energy transport from the day-to-night side or the existence of thick clouds blocking our view to the deeper and hotter parts of the atmosphere.

The demonstration of phase-resolved spectroscopy with WFC3 opens the door to unique comparisons of the thermal structures, energy budgets, and dynamics of more exoplanet atmospheres. We anticipate that the application of this new technique will break new ground in understanding many exoplanet characteristics.

New constraints on exoplanet atmosphere compositions

A second recent development in *Hubble* transit spectroscopy studies is the demonstration of constraints on the carbon-to-oxygen ratios in exoplanet atmospheres. Oxygen and carbon are critically linked to the formation of planets because they are the third and fourth most abundant elements in the universe. Because of their dominance, the relative abundance of these elements sets the chemistry in planet-forming disks. There are roughly two oxygen atoms for every carbon atom in the Sun's photosphere, which is often used as the template abundance pattern in protoplanetary disks. The final carbon-to-oxygen ratio (C/O) in a planetary atmosphere is a result of the complex interplay between nebular gas and planetesimal accretion at the location in the disk where the planet formed. The carbon-to-oxygen ratio in the atmosphere of solar system giant planets is poorly known because the oxygen is locked up in water that has condensed out and is difficult to measure. However, close-in exoplanets are hot enough that volatile condensation does not deplete their atmospheres, and thus remote observations should yield an unbiased measurement of their carbon and oxygen abundances.

Nikku Madhusudhan and collaborators made a big splash in the field of exoplanet atmospheres in 2011 by showing that the hot Jupiter WASP-12b could have a non-solar C/O value (Madhusudhan et al. 2011). They suggested that the planet had a C/O > 1 based on observations and modeling of its dayside emission. This was important because it suggested a very different chemistry and formation pathway than was commonly assumed for giant planets. However, the WASP-12b result was based on just broadband photometry rather than the robust spectroscopic identification of molecules that would only be present in a high C/O atmosphere. Therefore, the high C/O result remained a hypothesis rather than a definitive conclusion.

We have measured a precise transmission spectrum for the planet WASP-12b using during our Cycle 21 program to test the high C/O hypothesis for this planet (Kreidberg et al. 2015). In addition to using the now-standard G141 grism ($\lambda = 1.1$ to 1.7 µm), which is mainly sensitive to water vapor, we also observed transits for the first time using the G102 grism ($\lambda = 0.8$ to 1.1 µm) to gain sensitivity to a wider variety of molecules. The resulting spectrum is shown in Figure 2.

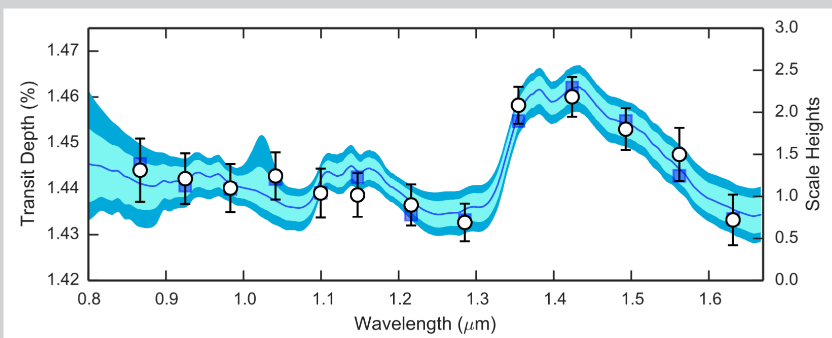

Figure 2: Transmission spectrum of WASP-12b measured with the G141 ($\lambda > 1.1$ µm) and G102 ($\lambda < 1.1$ µm) WFC3 grisms. The shaded regions indicate 1-and-2σ credible intervals in the retrieved spectrum (medium and light blue, respectively), relative to the median fit (dark blue line). The secondary *y*-axis labels indicate the atmospheric scale height. One scale height corresponds to 470 km (for a temperature of 1400 K). The increase in transit depth near 1.4 µm corresponds to a water band. Figure from Kreidberg et al. (2015).

We detect water absorption in the WASP-12b transmission spectrum at 7σ confidence. Our detection is the first spectroscopic identification of a molecule in this benchmark planet's atmosphere. However, our goal for these measurements was not simply to detect molecules, but rather to measure their abundances precisely enough to constrain the composition. This was the motivation for our intensive observing campaign, which utilized 30 *Hubble* orbits to measure three transits of the planet with each of the two grisms.

The strength of the water absorption in our measured spectrum implies a water-rich composition for WASP-12b's atmosphere. This is surprising given that water would not be abundant in a C/O > 1 atmosphere. The reason for this is that all of the oxygen atoms would be locked up in CO due to the overabundance of carbon for the region of the atmosphere being probed. Figure 3 illustrates how the measured water abundance is inconsistent with this prediction. Detailed modeling of the transmission spectrum by collaborator Michael Line constrains the C/O of the atmosphere to be less than 1.0 at more than 3σ confidence assuming chemical equilibrium. For this inference, the lack of detection of the other molecules that would be expected in a high C/O atmosphere is just as important as the detection of water.

There has also been an independent effort to model our WASP-12b data together with WFC3 transmission spectra of seven other hot Jupiters that show evidence of water absorption (Benneke 2015). The main conclusion of this work is similar to our findings: the data for all eight planets are consistent with solar C/O values and there is no evidence of unusual abundances. Thus the high C/O hypothesis for WASP-12b and other planets may need revision. Speaking more generally, the agreement between two independent modeling efforts for the WASP-12b spectrum demonstrates that unambiguous results can be obtained for exoplanet atmospheres if enough observing time is invested to make high precision measurements.

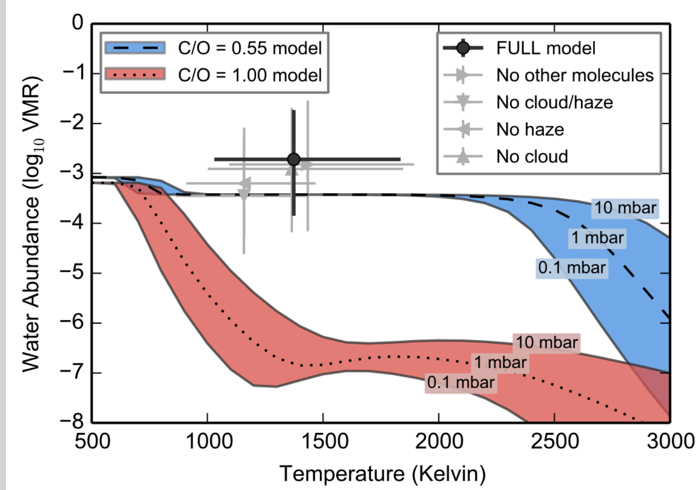

Figure 3: Measurement of the water abundance and scale height temperature for WASP-12b (points) compared to equilibrium chemistry predictions of the water content for different atmospheric compositions (lines and shading). The black point indicates the water abundance and temperature measurements from the main model fit to the WFC3 spectrum. Results from other nested models are shown in gray. The black dashed line and blue shading correspond to water abundance predictions for a solar C/O composition (0.55), and the black dotted line and red shading correspond to C/O = 1. Both models have solar metallicity. For each model composition, the shading shows the span of predicted water abundances over pressures ranging from 0.1–10 mbar. The black lines correspond to 1 mbar, which is the typical pressure level probed by our observations. Figure from Kreidberg et al. (2015).

Looking to the future with *Webb*

The *James Webb Space Telescope* is expected to revolutionize the field of exoplanet atmospheres (Beichman et al. 2014). The results discussed here suggest that given its design capability, *Webb* will be instrumental in complete planet characterization studies. Transiting planets offer multiple atmospheric diagnostics: transmission, dayside emission, and phase-resolved emission spectroscopy. These multiple diagnostics are needed to break modeling degeneracies and untangle the complexity of exoplanet atmospheres. A special handful of planets are within reach for the full complement of transit spectroscopy measurements with *Hubble*, and these measurements will be feasible for many more planets with the increased power of *Webb*.

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