Exoplanet Investigations with *Webb*

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Characterizing planets orbiting stars beyond the sun—exoplanets—is one of the scientific frontiers pioneered using *Hubble* observations. When *Webb* becomes operational, the current *Hubble* results will be expanded to an astonishing degree—far more than would be expected based on the increase in aperture. *Webb*'s sensitivity in the infrared, and especially its infrared spectroscopic capability, will be a boon to exoplanetary science. While we await *Webb*, exoplanetary astronomers are using *Hubble* with increasing success and impact.

Spectroscopy of exoplanetary atmospheres

The atmospheres of exoplanets, rather than their interior structure, are usually the aspect most amenable to observations. Understanding the heavy-element content and temperature structure of exoplanetary atmospheres is crucial for testing our ideas concerning the formation and evolution of planetary systems. Heavy elements in massive planets can be diluted by the gravitational attraction of copious molecular hydrogen gas during planet formation. Low-mass planets attract and hold less molecular hydrogen, so their heavy elements will be less diluted by accretion. Moreover, low-mass planets can acquire their atmospheres by outgassing, rather than accretion. The relative amount of ices versus rock that constitute low-mass planets will vary depending on where in the protoplanetary disk they form, and that diversity will affect their atmospheric composition. We therefore expect an overall inverse relation between planet mass and the heavy-element content of exoplanetary atmospheres, with quite varied compositions for outgassed planets such as super-Earths. Because carbon and oxygen are major building blocks of molecules in giant-planet atmospheres, diversity in giant-planet composition can also occur during formation, via a gradient in the carbon-to-oxygen ratio of the disk (Oberg 2011).

The first step on the quest to understand the composition of exoplanetary atmospheres was taken more than a decade ago, with the detection of atomic sodium in the atmosphere of the transiting exoplanet HD 209458b (Charbonneau et al. 2002), using *Hubble*'s Space Telescope Imaging Spectrograph (STIS). Atoms or molecules in the atmospheres of transiting planets absorb starlight as they transit (pass in front of) their star (Figure 1). Subsequent *Hubble* transit spectroscopy used the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) to make detections of both water vapor and methane (Swain et al. 2008). The NICMOS detections have been challenged and debated (Gibson et al. 2011; Waldmann et al. 2013), and NICMOS is no longer operational. However, as far as water vapor is concerned, the reliability of the NICMOS results is moot, given the advent of the spatial scan mode using Wide Field Camera 3 (WFC3).

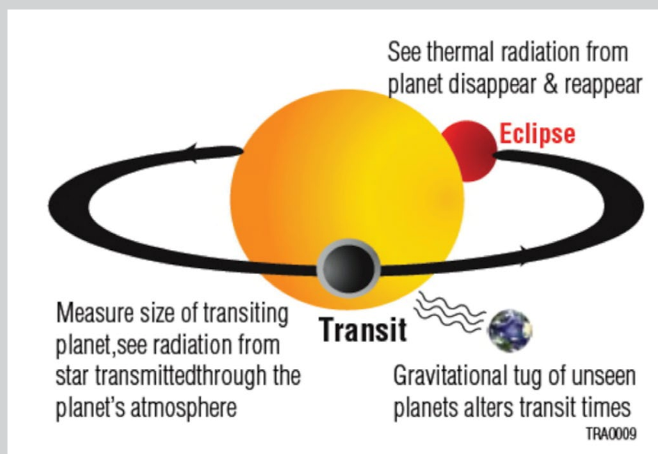

Figure 1: Geometry of exoplanetary transmission spectroscopy. When the planet passes in front of the star as seen from earth, weak absorption features are imposed on the stellar spectrum as star light is transmitted through the annulus of the exoplanetary atmosphere.

In a large Cycle-18 program (PI: Drake Deming), we began to use spatial scans with WFC3 for transmission spectroscopy of giant exoplanets. Because the exoplanets that we probe orbit relatively bright stars (typically, $V = 7$–11), short exposures are required in staring mode. Furthermore, the time required to read the detector and transfer the data makes staring-mode observations inefficient. By contrast, the spatial-scan mode spreads starlight over many pixels in the direction perpendicular to dispersion, and thereby allows much longer exposures without saturating. Spatial scanning has improved the efficiency of exoplanet spectroscopic observations by up to an order of magnitude, depending on the stellar brightness. Moreover, the WFC3 detector has a more uniform response than the NICMOS detector, and detecting water absorption in the WFC3 spectra of transiting planets has proven to be a robust process. Several independent groups have succeeded, with consistent results (Deming et al. 2013; Huitson et al. 2013; Mandell et al. 2013; Wakeford et al. 2013; McCullough et al. 2014; Crouzet et al. 2014).

Current frontiers

There are two current frontiers in transmission spectroscopy of transiting exoplanets using *Hubble*'s WFC3. Both of these frontiers will benefit enormously from *Webb*, because *Webb*'s spectroscopic resolving power and sensitivity will be much greater than *Hubble*'s. Nevertheless, the current *Hubble* capability will allow us to make significant progress prior to the *Webb* launch.

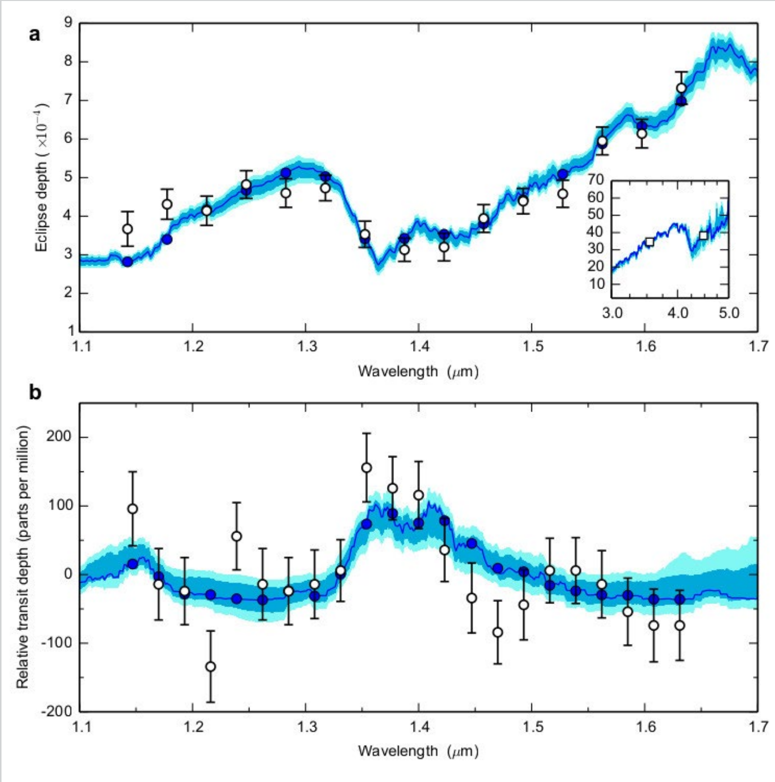

Figure 2: *Hubble* WFC3 spectrum of water vapor absorption in the hot giant transiting planet WASP-43b, from Kreidberg et al. (2014a). The *top panel* shows the spectrum emitted by the star-facing hemisphere of this tidally locked planet (the inset shows *Spitzer* photometry). Prominent water vapor absorption is evident in the WFC3 spectrum, with a bandhead near 1.35 microns. The *lower panel* shows the WFC3 transmission spectrum, i.e., the result of absorption as star light passes through the exoplanetary atmosphere. In the *lower panel*, absorption increases upward—the convention for transmission spectroscopy makes the spectrum appear upside-down. This combination of transmission and emission spectroscopy permits deriving water vapor abundance simultaneously with the temperature structure of the atmosphere.

One frontier is to obtain both transmission and emission spectroscopy on a given planet, and thereby derive a quantitative water abundance with maximum confidence. Emission spectroscopy refers to the capability to measure the emergent spectrum of the planet by exploiting the secondary eclipse, when the planet passes behind the star. In that case, subtraction of the in-eclipse spectrum of the system (planet hidden) from the out-of-eclipse spectrum (planet contributing) yields the spectrum of the planet alone.

Having both transmission and emission spectroscopy makes it possible to derive abundances of the absorbing species, simultaneously with the temperature structure of the planetary atmosphere. Although longitudinal variations in temperature and abundance are possible across the disk of the exoplanet, measuring the phase curve of hot planets like WASP-43b (Stevenson et al. 2014) helps to constrain those variations. Figure 2 shows WFC3 transmission and emission spectroscopy of the hot giant exoplanet WASP-43b, measured in a Cycle-21 program (PI: Jacob Bean). In this case, the combined measurements also include photometry of the secondary eclipse using *Spitzer*. This combination of *Hubble* plus *Spitzer* data allowed Kreidberg et al. (2014a) to deduce a close-to-solar oxygen abundance for this giant planet.

Interestingly, it is easier to make this measurement for hot giant exoplanets than for giant planets in our own solar system. The latter are sufficiently cold that water vapor condenses out of their atmospheres and is sequestered at depths where it is difficult to observe using spectroscopy of the reflected or emitted radiation from the atmosphere.

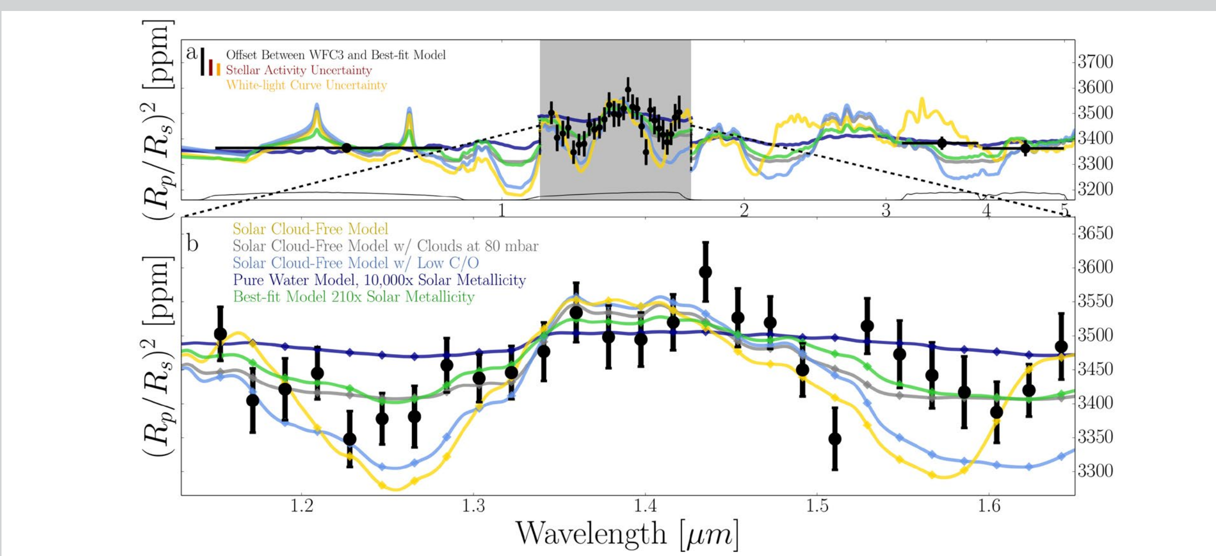

Figure 3: HAT-P-11 transmission spectrum derived by WFC3 observations, reported by Fraine et al. (2014). The *top panel* shows the apparent transit radius of the planet versus wavelength from the optical to the mid-infrared, including the radius measured using *Kepler* (optical) and *Spitzer* (mid-infrared) transits. The points near 1.4 microns are the WFC3 transmission spectrum, expanded on the *lower panel*. The best-fit model (green line) has an overall heavy-element abundance of 190 times the solar value.

A second frontier for WFC3 is to push the water-vapor detections to smaller planets, even to super-Earths. An intense Cycle-21 effort (PI: Jacob Bean) to measure water vapor in the atmosphere of the transiting super-Earth GJ 1214b (2.7 Earth radii) achieved astonishing sensitivity—a precision better than 30 parts per million)—but found a flat spectrum. Similar high-sensitivity observations of the atmospheres of the exo-Neptune GJ 436b (4.0 Earth radii) and the super-Earth HD 97658b (2.2 Earth radii) also showed flat WFC3 spectra (Knutson et al. 2014a, b). The atmospheres of these planets may be sufficiently cloudy to block molecular absorption, or some of them could have hydrogen-poor atmospheres with small scale heights.

While several small planets seem to be cloudy, at least one—the exo-Neptune planet HAT-P-11b (4.3 Earth radii)—has a clear atmosphere above the level of about one millibar of pressure. The spectrum of that planet shows prominent water absorption, shown in Figure 3, from Fraine et al. (2014). From these WFC3 plus *Spitzer* observations, Fraine et al. concluded not only that the atmosphere is relatively clear, but also that its most likely heavy-element content is about 200 times the solar value. Even though the error range is large—from 1 to 700 times solar—the results are broadly consistent with expectations from the core-accretion model of planetary formation.

Although exoplanetary clouds are interesting in their own right, they are also frustrating because they mute the signatures of molecular absorption and make it much harder to determine the hydrogen content and atmospheric chemistries. An important role for *Hubble* is to establish which exoplanets have high cloud decks, so we can focus *Webb* on those with the clearest atmospheres and deepest absorption features in their spectra. One sensitive way to do this is to measure the optical transmission spectrum, and look for increasing absorption in the blue, due to scattering by small haze particles. A Cycle-22 program (PI: Björn Benneke) will probe other Neptune-sized exoplanets such as GJ 3470b (4.1 Earth radii) in both the optical and infrared (STIS and WFC3). That program will extend the water vapor measurements to super-Earths such as 55 Cnc *e* (1.9 Earth radii), and the Earth-mass planet Kepler 138d.

Webb **spectroscopy**

Hubble's WFC3 detects primarily water vapor, with little sensitivity to other molecules. However, *Webb* will be much more panchromatic, and will have much greater spectral resolving power. *Webb* will enable abundance measurements in both oxygen- *and* carbon-containing molecules, such as water, methane and carbon monoxide, with simultaneous constraints on the atmospheric temperature profiles. Recently, powerful methods have been developed (Benneke & Seager 2012; Line et al. 2013; deWit & Seager 2013) to retrieve molecular abundances, cloud properties, and atmospheric temperature structure in an optimal way. Therefore, we are poised to make maximal use of the *Webb* data. *Webb* photometry will not only be more precise than *Spitzer*, but *Webb* will also offer spectroscopy over large swaths of

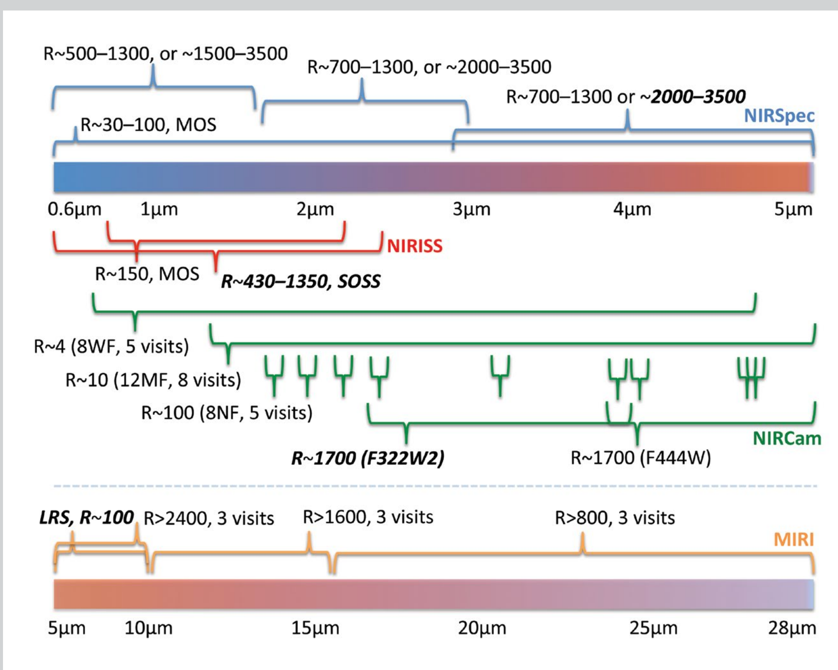

Figure 4: Potential *Webb* observing modes for a hot Jupiter orbiting a bright star, from Beichman et al. (2014). This is the result of a community workshop to plan spectroscopic observing strategies for the brightest and most observable transiting exoplanets. Note that wide spectral coverage that will be possible using *Webb*.

wavelength. Figure 4 (from Beichman et al. 2014) summarizes the many modes whereby *Webb* will be able to observe spectra of transiting exoplanets, and simulation of future exoplanet spectra to be obtained by *Webb* is ongoing.[1]

We expect *Webb* to determine accurate molecular abundances and atmospheric temperature profiles for a large sample of transiting exoplanets, from hot Jupiters to super-Earths. Not only will the *Webb* observations reveal their individual properties, they will also transform our understanding of planetary system formation and evolution.

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[1] **http://www.stsci.edu/jwst/doc-archive/white-papers/JWSTNirspec_BatalhaFinal.pdf**