Comparative Planetology: Transiting Exoplanet Science with JWST

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1. Introduction

The study of transiting exoplanets has provided most of the key data to date on the properties of exoplanets, such as direct estimates of their mass and radius (e.g. Charbonneau 2007), and spectral diagnostics of their atmospheres (e.g. Swain et al. 2008). The Hubble Space Telescope (HST) and Spitzer Space Telescope (SST) have both played lead roles in making the demanding, high S/N observations of light curves, and spectra of transiting exoplanets. Ground-based surveys have so far provided the candidate targets for space-based characterization studies. The study of transiting exoplanets requires the extraction of a differential signal from high S/N observations so the James Webb Space Telescope (JWST), by virtue of its 25 m^2 collecting area (~50x SST), will open up a new discovery space for transiting exoplanet science. Specifically, it will enable the characterization of intermediate and low mass exoplanets. The goal of this white paper is to provide an informational briefing for the panel on the expected capabilities of JWST for observations of exoplanet transits, in particular the characterization of transiting lower mass planets ($\leq M_{Nep}$).

2. Future surveys

Currently, there are numerous ground-based surveys focused exclusively on the detection of transiting exoplanets including the Trans-Atlantic Exoplanet Survey (O'Donavan et al 2007), Hungarian Automated Telescope (Bakos et al. 2007), XO survey (McCullough et al. 2006), and the SuperWASP Consortium (Pollacco et al. 2008). In addition, the ongoing radial velocity searches for exoplanets continue to find transit candidates (Butler et al. 2004; Fischer et al. 2006). The success of these surveys can be measured by the rapid growth of known transiting exoplanet systems in the last decade to ~60 known systems. More recent ground-based surveys have started to target late spectral type stars, such as the MEarth survey (Charbonneau et al. 2008a) that is specifically dedicated to a search for superearths ($R \leq 2R_{\otimes}$) and hot Neptunes around M stars.

Several current and future space-based surveys will significantly increase the number of known transiting exoplanet systems. Corot is a European mission that surveys two 2.8^o x 2.8^o fields on the sky. It is expected to find many tens of transiting gas giant planets, and could discover between 10 – 40 superearths. Recently, CoRoT announced the first transiting superearth, CoRoT-Exo-7 b, a hot, 1.7$R_{\otimes}$ exoplanet (Rouan et al. 2009). The Kepler mission (Borucki et al. 2007) will be launched in March 2009 and will monitor a field of ~10^5 main sequence stars over a period four years. It expects to find between ~50–600 earths and super-earths. In addition, it will find ~900 gas giants with Periods ≤ 1 week from reflected light modulation, and up to another ~165 transiting gas giants. Finally, the TESS mission (Ricker et al. 2008), an all-sky survey specifically focused on finding transiting exoplanets around the brightest stars, expects to catalog ~1000 new transiting systems including hot-Neptunes and superearths. The TESS mission is currently in phase-A, and if selected for flight, may launch as early as 2012. In contrast to the narrow-deep surveys of CoRoT and Kepler, TESS will deliver transiting systems with brighter parent stars, especially suited to detailed spectroscopic characterization.

In summary, an increasingly rich diversity of transiting exoplanet systems will be discovered by ground and space-based surveys in the next decade. JWST occupies a unique niche as the successor to HST and Spitzer. It is the laboratory that will have to do the majority of the follow-up characterization of these systems, and is the only facility available that will be capable of undertaking spectral characterization of hot-Neptune and super-earth exoplanets.

3. JWST

The expectation that JWST will be the primary facility for characterization of exoplanet systems raises the question, what is JWST capable of doing? JWST offers some impressive capabilities for observations of transiting exoplanets (Clampin 2009, Gardner

Table 1: Key Transit Observing Modes for JWST Science Instruments

Instrument Mode	λ (μm)	R ($\lambda/\delta\lambda$)	FOV	Application
NIRCam Imaging	0.6 - 2.3 2.4 - 5.0	4, 10, 100 4, 10, 100	2 x (2.2' x 2.2') 2 x (2.2' x 2.2')	High precision light curves of primary and secondary eclipses.
NIRCam Phase Diversity Imaging	0.6 – 2.3	4, 10, 100	Image diam. - 57 pixels - 114 pixels	High precision light curves of transits for bright targets that need to be defocused to avoid saturation within the minimum t_{int}
MIRI Imaging	5 – 29	4-6	1.9' x 1.4'	High precision light curves of secondary eclipses.
TFI Imaging		100		High precision light curves
NIRCam Spectroscopy	2.4 – 5.0	1700	2 x (2.2' x 2.2')	High precision transmission and emission spectroscopy
NIRSpec Spectroscopy	1.0 – 5.0	100, 1000, 2700	1.6" x 1.6" slit	Transmission and emission spectroscopy of transiting planets.
MIRI Spectroscopy	5 - 11	100	Slitless	High precision emission spectroscopy
MIRI Spectroscopy	5.9 – 7.7 7.4 – 11.8 11.4 – 18.2	3000 3000 3000	3.7" x 3.7" 4.7" x 4.5" 6.2" x 6.1"	High precision emission spectroscopy

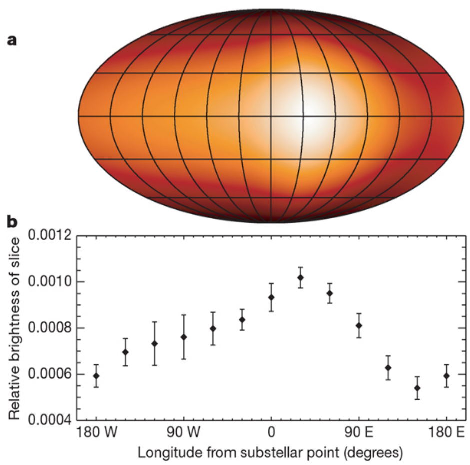
2009). The most important instrument operating modes that address transit photometry and spectroscopy requirements are summarized in Table 1, with descriptions of their application. In addition to the standard imaging and spectroscopic modes, several instrument modes designed for phasing the primary mirror can also be exploited. In these modes, weak lenses are inserted producing defocused images that are used to determine the wavefront characteristics of the optical train by phase retrieval. Such defocused images can also be used to advantage for transiting exoplanets: they permit averaging any detector pixel-to-pixel variations and allow brighter targets to be imaged within the full well capabilities of the detectors. These can be used for high precision light curves of very bright sources allowing JWST to obtain sufficient S/N for high precision light curves of terrestrial planets. NIRCam also employs a 2.5 μm – 5 μm grism to support coarse phasing of the telescope and this slitless grism offers a complementary spectroscopic capability to NIRSpec

3. JWST Transiting Exoplanet Science

Photometry

Both NIRCam and MIRI offer the opportunity to obtain high precision light curves, a capability that has served as the mainstay of Spitzer transit science. JWST will be able to obtain light curves of primary and secondary eclipses of $1R_{\otimes}$ terrestrial planets around main sequence stars. High precision light curves offer both basic characterization of the transiting exoplanet, and the opportunity to search for unseen planets by means of transit timing (Steffen et al. 2007).

Figure 1: A map of day to night temperature difference for HD189733b (Knutson, Charbonneau, et al. Nature 2007), shows efficient heat re-distribution. Courtesy D. Charbonneau.



MIRI and NIRCam offer sub-array capabilities for observing brighter target stars, and NIRCam has defocus optics that will allow it to obtain high precision light curves for stars as bright as K = 3.4. NIRCam obtains short and long wavelength light curves simultaneously. In the case of terrestrial planets/superearths that cannot be characterized spectroscopically, simple filter-based observations can be used to diagnose the 15 μm CO_2 absorption feature using MIRI filter observations (Deming 2009). The Tunable Filter imager (TFI), with its selectable, R=100 bandpass imaging, permits a similar filter-based characterization of spectral features in the near-IR.

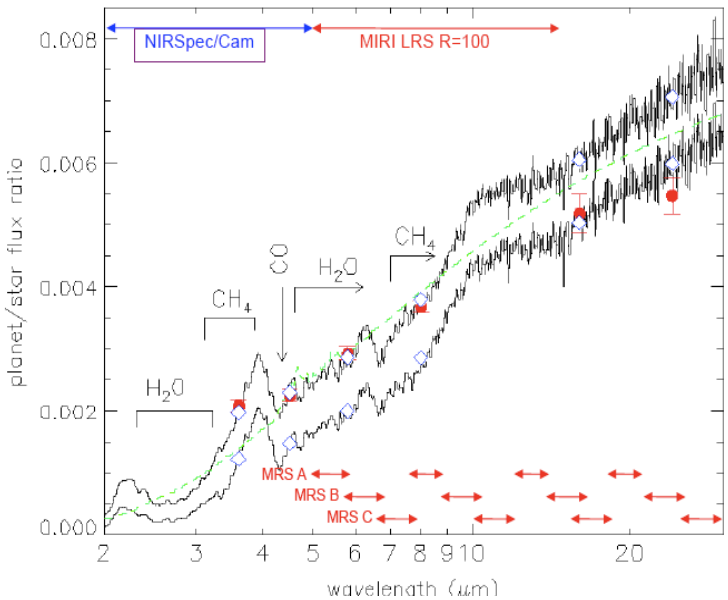
Spitzer has also been successful mapping the surface emission of exoplanets by means of phase light curves, as shown in Figure 1. MIRI AND NIRCam will both extend the sensitivity of such studies via higher S/N photometry.

Thus, although ground-based observatories have begun to produce high fidelity transit light curve photometry (Johnson et al. 2008), with its 25 m^2 collecting area obtained outside Earth's atmosphere, JWST will move light curve analysis into a S/N regime unavailable from the ground.

Spectroscopy

It is in the field of spectroscopic characterization that JWST is going to make major contributions to exoplanet science. Impressive progress has been made with Spitzer and HST in obtaining the first spectral diagnostics of exoplanets. In the case of Spitzer this is illustrated in Figure 2 from Charbonneau et al. (2008b) that shows a simulated spectrum of HD 189733b and the coverage provided by JWST's instruments.

Figure 2: Model infrared spectrum of HD189733b, with Spitzer spectroscopic points shown in red. Overlaid are red arrows showing the coverage of NIRCam, NIRSpec and MIRI spectroscopic modes. Courtesy T. Greene and D. Charbonneau



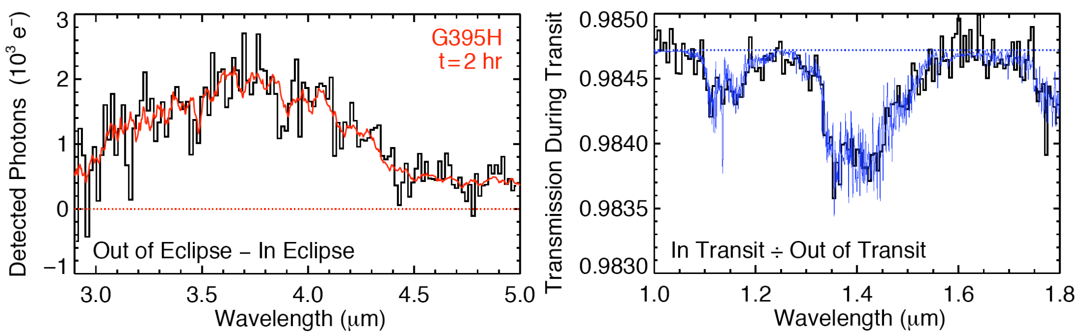
Two techniques can be used to probe transiting extrasolar planet atmospheres with JWST. The absorption spectrum of the planet can be measured by detecting the signatures imposed on stellar light transmitted through the planet's atmosphere during transit. The emission spectrum of the planet can also be measured using the secondary eclipse technique. Emission spectra produce potentially larger signals than transmission spectra at infrared wavelengths. However, features in transmission spectra will be present even in the extreme case when the atmospheric temperature profile of the exoplanet is isothermal - which would produce a featureless spectrum in emission. Gas giant planets will present many molecular features (H_2, CO, H_2O, CH_4), strong atomic lines (Na, K), and a spectral shape (due to Rayleigh scattering) that leave distinct imprints on transmission spectra. High quality spectra also probe energy redistribution within the atmospheres (see Figure 2). With its large collecting area JWST will be able to conduct detailed comparative studies of gas giant atmospheres and their composition both in transmission and emission, including many of the transiting gas giants discovered by Kepler. The NIRSpec team simulated JWST observations of a transiting gas giant planet of the kind that would be found by Kepler. These simulations are shown in Figure 3.

MIRI will complement NIRcam and can also obtain quality R~100 spectra of gas giant planets in a single transit over the 5 μm to 10 μm bandpass.

JWST will be capable of R=100 – 3000 follow-up spectroscopy of gas giants expected to be found by ground and space-based surveys over the 0.7 μm to 10 μm wavelength range. For exoplanets with bright parent stars, it can deliver R~2700 spectra from 1μm -

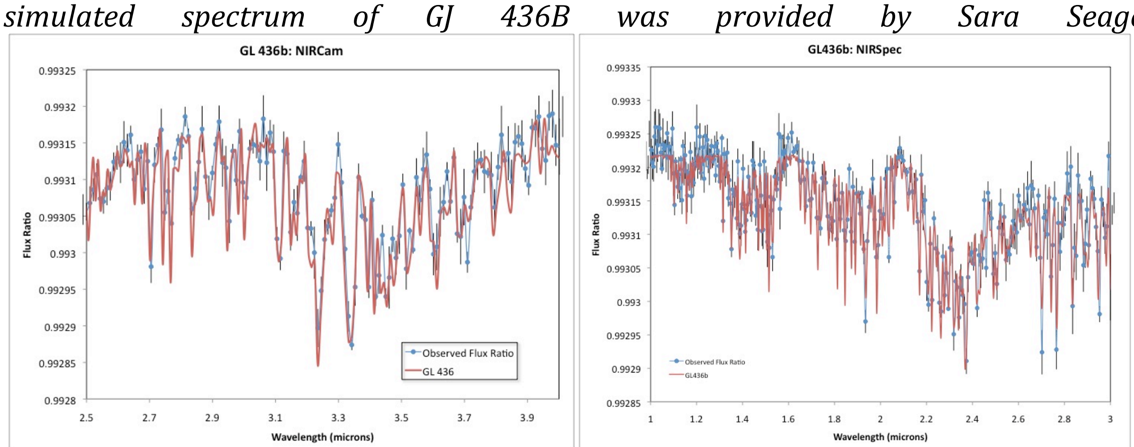
5μm wavelength range, and for the first time provide high quality line diagnostic of these exoplanets.

Figure 3: On the left Simulation of a Kepler hot Jupiter emission observation with JWST. The red curve is a model by Seager et al. (2005, ApJ, 632, 1122) of thermal emission from HD 209459b. The parent star has K=12, V=13.4 to simulate a hot Jupiter found by Kepler. The simulated G395H observation (in black) has been numerically degraded from R=2700 to R=100. On the right is a NIRSpec simulation of a Kepler transiting hot Jupiter transmission observation with JWST, based on a planetary atmosphere transmission model (Brown 2001) for HD 209458b (in blue).The parent star is star K=12, V=13.4. The simulated observation (in black) has been numerically degraded from R=2700 to R=100, and a 6 hour exposure, centered on a 2 hour planetary transit. Courtesy Jeff Valenti.



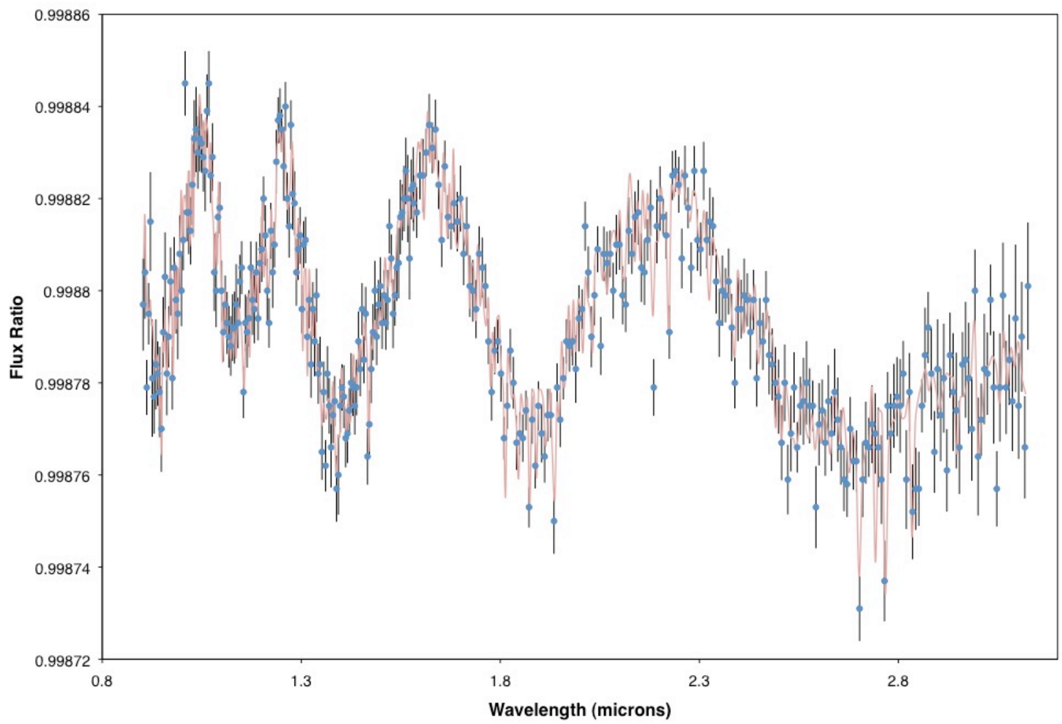
Radial velocity surveys are starting to find intermediate mass planets, and in the coming decade transiting planets surveys will find many more transiting intermediate mass planets which can be observed in emission and transmission with JWST. Currently, GJ 436b is the only example of a hot Neptune, with a mass 0.072 MJ, and a period of 2.6 days. In Figure 4 we show a simulated NIRSpec observation of GJ 436, combining transits to achieve a R-300 spectrum.

Figure 4: Simulated NIRSpec and NIRCam spectra of GJ 436b's hot Neptune exoplanet combining four transit observations. The simulation includes the effects of real contributions from pointing jitter, flat field errors and pixel response functions. The simulated spectrum of GJ 436B was provided by Sara Seager.



Charbonneau et al. (2008c) and Charbonneau and Deming (2007) have identified the opportunity presented by observing transiting exoplanets around late spectral-type stars. The relatively small stellar radius yields transit depths that can potentially enable low-resolution spectral characterization of some superearth atmospheres, in emission and transmission. In Figure 5 we use a model superearth spectrum generated by Miller-Ricci et al. (2009) to show the simulated transmission spectrum observed for a hydrogen rich $R=1.3R_{\otimes}$ superearth obtained with NIRSpec.

Figure 5: A Simulated NIRSpec spectrum (Clampin 2009) of a hydrogen rich superearth exoplanet combining 20 transit observations. The simulation includes the effects of real contributions from pointing jitter, flat field errors and pixel response functions. The simulated exoplanet spectrum was provided by Miller-Ricci and Seager (Miller-Ricci et al 2009), and assumes the parent star has the properties of Gl 581 (d = 6pc , V=10.3). The spectrum is shown in red and the blue points are the simulated observation with error bars.



Summary

JWST provides a unique facility that will serve through the next decade as the mainstay for characterization of transiting exoplanets. The main transit studies that JWST will be able to undertake are summarized in Table 2.

Table 2: Exoplanet transit investigations enabled by JWST

Application	Exoplanet Type	R	Science
Transit light curves	**- Gas Giants - Intermediate mass - Superearths and terrestrial planets**	**5 5 5**	**- Exoplanet properties (with RV data) .e.g. Mass, radius → physical structure - Detection of terrestrial planet transits - Transit timing: detection of unseen planets**
Phase light curves	**- Gas Giants - Hot Neptunes**	**5 5**	**- Day to night emission mapping: dynamical models of exoplanet atmospheres**
Transmission Spectroscopy	**- Gas Giants - Gas giants - Intermediate mass - Superearths**	**3000 100-500 100-500 ≤100**	**Spectral line diagnostics - atmospheric composition e.g. C, CO_2, Ch4 - follow-up of survey detections e.g. Kepler, TESS**
Emission Spectroscopy	**- Gas Giants - Gas giants - Intermediate mass - Superearths**	**3000 100-500 100-500 ≤100-**	**- Spectral line diagnostics - Planet temperature measurements -- follow-up survey detections e.g. Kepler, TESS**

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