Detection of Planetary Transits with the James Webb Space Telescope

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1. Introduction

The James Webb Space Telescope (Gardner et al. 2006) will be capable of characterizing extrasolar planets to significantly greater sensitivity than the current Spitzer detections (Charbonneau et al. 2005, Deming et al. 2005, 2006). In combination with ground-based transit surveys and scientific results from the Kepler and Corot missions, JWST will be able to address the detailed physical characterization of up to 250 exosolar planets (Mountain et al. 2006; Beichman et al. 2006). Transit studies of exosolar planets are currently unique in providing measurements that permit comparative exoplanetology. Specifically, photometric and spectroscopic measurements yield the following measurements of planetary properties.

- Transit photometry $(R_p/R_*)^2 \sim 10^{-2}$
  - Transit radius -> density
- Emission spectra $T_p/T_*(R_p/R_*)^2 \sim 10^{-3}$
  - Emitting atmosphere $\tau \sim 2/3$
  - Temperature and ΔT
- Transmission spectra $[atm/R^*]2 \sim 10^{-4}$
  - Upper atmosphere
  - Exosphere (0.05-0.15)
- Reflection spectra $p[R_p/a]^2 \sim 10^{-5}$
  - Albedo, phase curve
  - Scattering atmosphere
  - Polarization

2. JWST Instrument Complement

JWST's science payload comprises four science instruments (SI). NIRCam is a wide field, deep imaging camera that will also make the wavefront sensing and control (WFS&C) measurements, necessary to phase the telescope. NIRSpec is a multi-object spectrometer provided contributed by the European Space Agency (ESA). MIRI provides mid-infrared (5-28.5 μm) imaging and spectroscopy. The Tunable Filter Imager (TFI) is a camera contributed by the Canadian Space Agency. Each of these science instruments features capabilities that enable either transit imaging or spectroscopy and these are summarized in Table 1.

Transit studies using these JWST capabilities will require support for time-series observations to be executed at specific times. Transits discovered by other programs will have very precisely known windows in which observations should be obtained. Transits will in some cases be associated with nearby stars (e.g. the edge-on system HD 209458b with host star V = 7.6, H = 6.1). The instrument capabilities summarized in Table 1 show that JWST instrument modes will allow observations of such bright objects. The detection of transiting Earths or giant planet moons, and the characterization of giant planet atmospheres, will be possible if the cycle time between successive integrations in the near-IR can be kept very short (~1 second). Transit timescales will range from 1-2

Table 1: JWST instrument modes suitable for transiting planet studies

SI	λ (μm)	Spectral Resolution (λ/Δλ)	FOV	Mode	Comments	Application
NIRCam	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')	Imaging Imaging		High precision light curves of transits from photometry of point source images. Wavelength coverage permits photometric monitoring of primary or secondary eclipses.
NIRCam	0.6 – 2.3	4, 10, 100	2 x (2.2' x 2.2')	Phase diversity imaging	Defocusing of images to 57 or 114 pixel diameters	High precision light curves of transits associated with bright objects which need to be defocused to avoid saturation within the minimum integration time
NIRCam	2.4 – 5.0	2000	2 x (2.2' x 2.2')	Long-λ Grism	Backup capability for WFSC. Used with F277W, F322W, F356W, F410M or F444W	Emission spectroscopy of hot gas giant transiting planets
NIRSpec	1.0 – 5.0	100, 1000, 2700	0.1" x 2.0", 0.2" x 3.5", 0.4"x 4.0"	Spectroscopy	Fixed long slits	Low and intermediate resolution transmission and emission spectroscopy of transiting planets.
NIRSpec	0.7 - 5.0	2700	3" x 3"	Spectroscopy	Integral Field Unit	Intermediate resolution, transmission and emission spectroscopy of transiting planets.
MIRI	5 – 29	4-6	1.9' x 1.4'	Imaging	Direct imaging	
MIRI	5 - 11	100	5" x 0.2"	Spectroscopy	Fixed Slit	Light curves of transits from photometry of point source images.
MIRI	5.9 – 7.7 7.4 – 11.8 11.4 – 18.2 17.5 – 28.8	3000 3000 3000 3000	3.7" x 3.7" 4.7" x 4.5" 6.2"x 6.1" 7.1"x7.7"	Spectroscopy	Integral field unit	Intermediate resolution, emission spectroscopy of transiting planets.
TFI	1.6 – 2.5	100	2.2' x 2.2'	Imaging	Selectable central λ	High precision light curves of transits from photometry of point source images. Wavelength coverage permits photometric monitoring of primary eclipses.
TFI	3.2 – 4.9	100	2.2' x 2.2'	Imaging	Selectable central λ	High precision light curves of transits from photometry of point source images. Wavelength coverage permits photometric monitoring of secondary eclipses.

hours for the shortest period systems (HD 209458b has a 3.1 hour transit every 3.52 days) to 10-15 hours for planets in Earth-like systems repeating on timescale of about a year.

In the case of NIRCam, NIRSpec and TFI the detector readout rates are determined by the subarray size, and range from ~3 ms for a 16x16 pixel array to 1 s for a 320 x 320 array which would be required for a spectral region in NIRSpec or defocused image in NIRCam when the phase diversity optical element is used to spread the image. The minimum integration time for MIRI is 3 secs. Data handling is accomplished by means of the Spacewire protocol offering 100 Mbs data rates to the solid state recorders. Absolute time-stamp observations will be possible within JWST's event-driven operations, although there may be a penalty observational efficiency In summary, both the instruments and their data handling interfaces are capable of supporting the needs of transit observations.

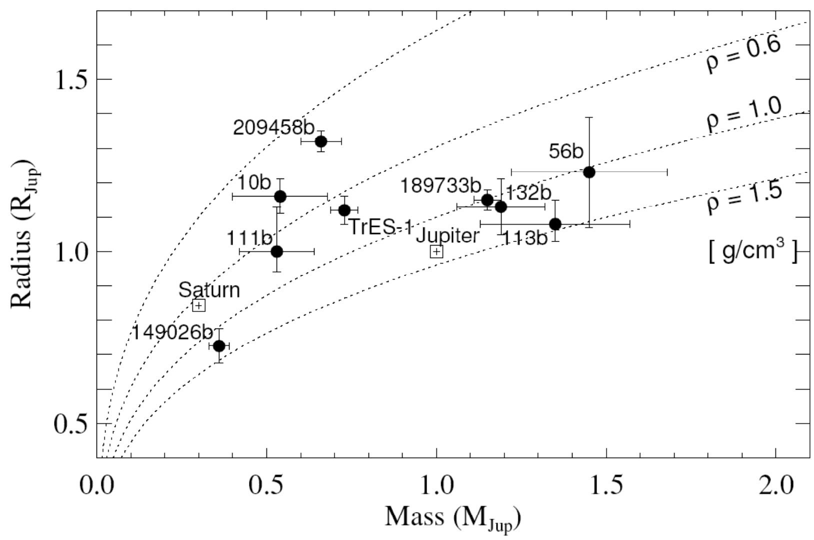


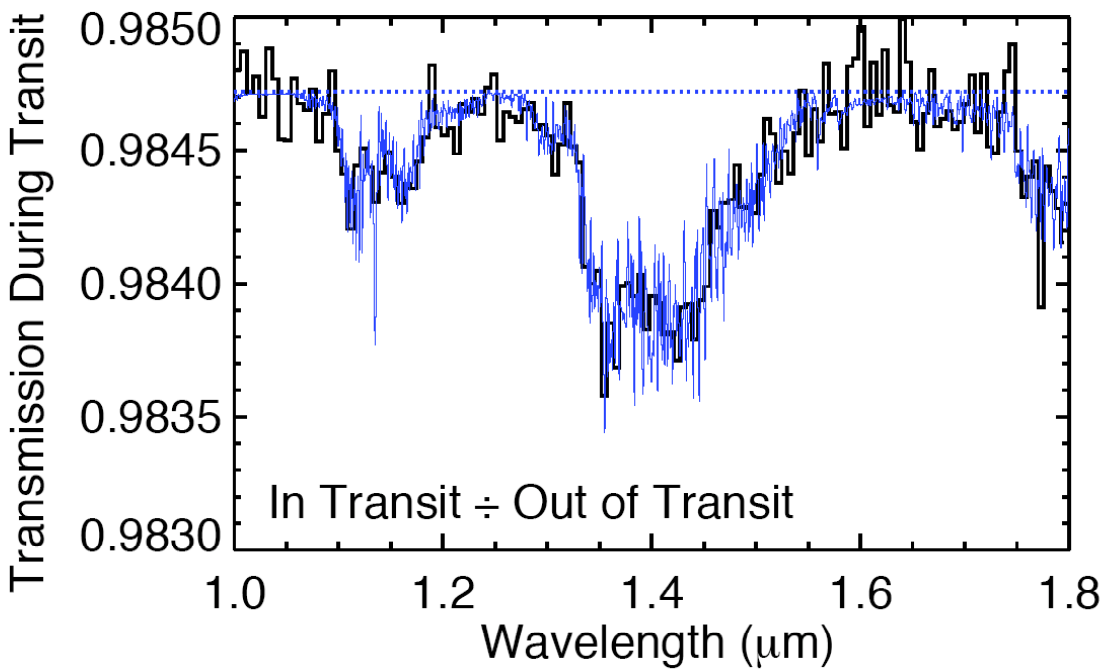
Figure 1: Extracted from Charbonneau (2007), this figure shows masses and radii for the 9 transiting planets, as well as Jupiter and Saturn. The data are gathered from Bakos et al., in preparation, Bouchy et al. (2004, 2005b), Brown et al., in preparation, Charbonneau et al. (2006), Holman et al. (2005), Knutson et al. (2006), Laughlin et al. (2005a), *Moutou et al.* (2004), *Pont et al.* (2004), *Sato et al.* (2006), *Sozzetti et al.* (2004), *Torres et al.* (2004a), and *Winn et al.* (2005).

3.0 Transit Science with JWST

3.1 Probing atmospheric properties of extrasolar giant planets with JWST.

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 (Brown et al. 2001, Charbonneau et al. 2002, see Fig. 2 for a JWST simulation). The emission spectrum of the planet can also be measured using the secondary eclipse technique (Richardson et al. 2007, Grillmair et al. 2007, see Fig. 3 for a JWST simulation). The two techniques are complementary. 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. Note also that JWST thermal emission spectra can be binned to lower resolution, producing the equivalent of secondary eclipse photometry. In this case, the dispersion of the light on the detector can help to alleviate potential saturation for bright systems.

Figure 2: 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 G140H observation (in black) has been numerically degraded from R=2700 to R=100, which is adequate for the broad features in the model. The simulation is a 6 hour NIRSpec/G140H observation, centered on a 2 hour planetary transit.

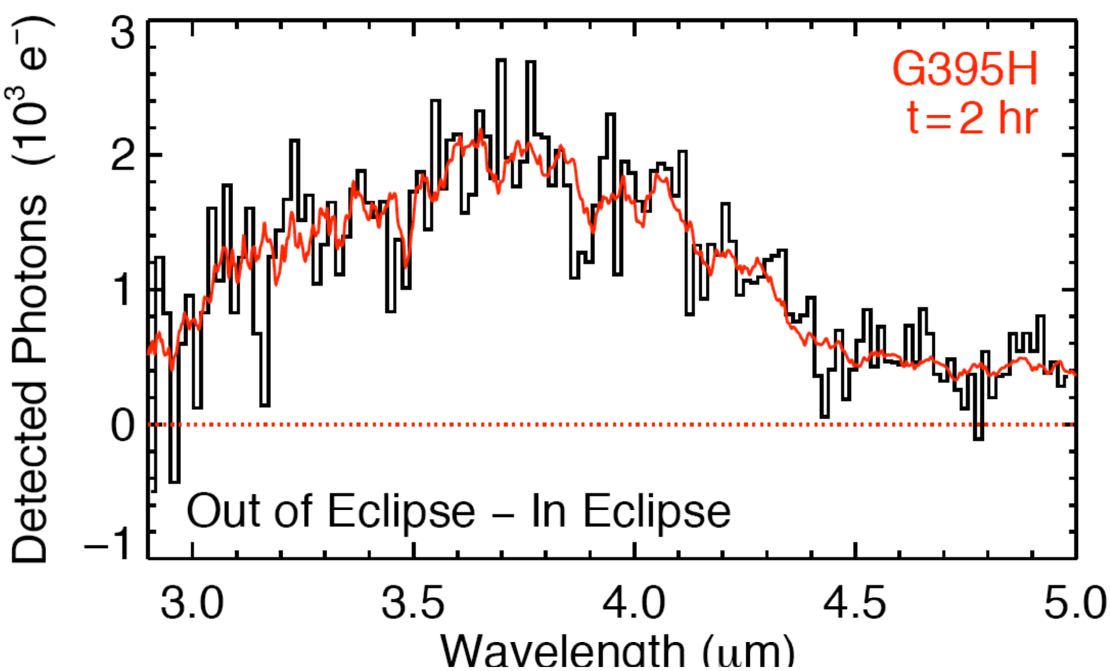


Transmission spectroscopy of transiting planet atmospheres is simple in concept. During transit, a planet atmosphere will allow some wavelengths to pass through relatively deep layers, while other wavelengths will be blocked at smaller optical depths. This is the case for the resonance line of sodium, where there is extra blockage (compared to the continuum) during the occultation event of HD 209458b. Detailed discussion of diagnostics that are possible with transmission spectra of extrasolar giant planet atmospheres have been provided in Brown (2001a) and Charbonneau et al (2007). In particular, EGPs like HD 209458b 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. Brown (2001a, esp. Section 5.1 and Figure 22) provided direct simulations of JWST/NIRSpec observations at a resolution of 1000 over 1.65 - 2.5 microns for HD 209458 itself.

Recently, observations with Spitzer have produced infrared thermal emission spectra from HD 209458b (Richardson et al. 2007) and HD 189733b (Grillmair et al. 2007). In the case of the former, a broad 9.65 μm spectral feature suggests emission by silicate clouds. Rauscher et al. (2007) have proposed that infrared ingress/egress light curves could be used to constrain current atmospheric models of tidally locked hot gas-giants, which experience extreme heating on their permanent daysides. The photometric precision enabled by JWST would permit eclipse mapping that could place constraints on their circulation regime and global wind speeds.

Charbonneau et al. (2007) have summarized the different transit surveys currently underway. Many more giant transiting planets are virtually certain to be discovered in the next few years. Several search programs (TrES, XO, HAT) currently have specific candidates in the final stages of screening. Eventually, some transiting planets will be found at large orbital radii, permitting atmospheric properties to be studied as a function of orbital scale. Currently all known transiting planets are gas giants, but transiting terrestrial planets will inevitably be found, assuming that terrestrial exoplanets are not extraordinarily rare. Missions such as Kepler and Corot are likely to discover planets over a range of sizes with orbital scales of an AU around other stars.

Figure 3: 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 ratio of stellar to planetary emission is 10^3 at 4 μm, which is relatively easy by comparison to other direct detection methods. The black histogram shows the difference of spectra in and out of eclipse, with the planet occulted by the star leaving only planetary emission. The simulated G395H observation (in black) has been numerically degraded from R=2700 to R=100, which is adequate for the broad features in the model.



JWST will be able to conduct a program of transmission and emission spectroscopy of gas giants discovered by Kepler and Corot. In Figure 2 we present a simulated NIRSpec planetary transmission spectrum for a Kepler source with a stellar spectrum similar to HD209458, while Figure 3 shows the simulated thermal emission spectrum. JWST will clearly be capable of quantitative atmospheric diagnostics of transiting planets found by Kepler and Corot.

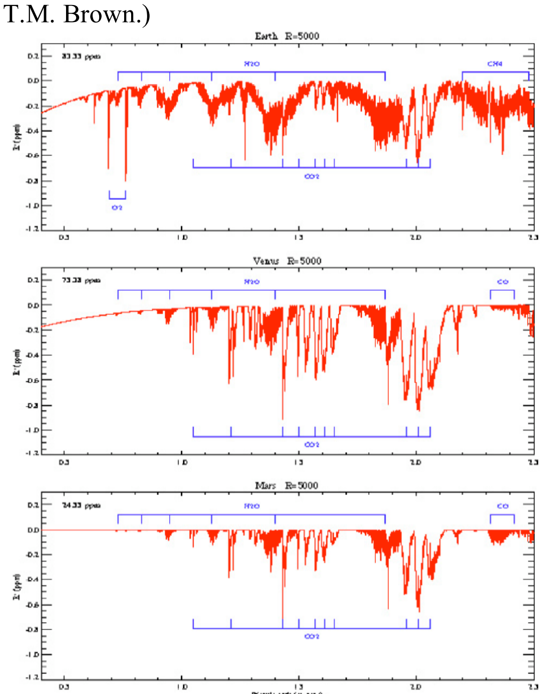
3.2 Detecting terrestrial planets and giant planet moons around EGPs.

The original HST observations of HD 209458b transits were already sufficient to set an upper limit to moons (not a full phase space search) slightly larger than the Earth, as well as ring systems comparable to Saturn's but scaled up by the relative planetary radii. JWST, with four times the collecting area, could make comparable observations to systems up to 4 magnitudes fainter and could thus make similar observations of edge-on systems found by Kepler (the distances of which will typically be about 300 pc). Beichman et al. (2007) report simulations indicating a 3 hour NIRSpec observation of HD209458b could produce a 35σ transit detection of an earth size moon.

3.3 Can we study extrasolar terrestrial planet atmospheres with JWST?

Being able to study the atmosphere of an Earth-like planet with sufficient fidelity to determine if life is likely present (e.g. existence of free Oxygen, molecules out of equilibrium without life) is one of the grand long-term NASA goals. JWST was not envisioned to address this, but neither was HST envisioned to provide the first evidence of atmospheric constituents on an extrasolar planet, nor was Spitzer envisioned to detect thermal emission from exoplanets. Could JWST provide early (relative to TPF and other missions directed at this) observations relevant to life's existence on other planets? Surprisingly, the answer may be yes. What would it take to enable this?

Figure 4: Predicted, relative transmission spectra for Earth, Venus and Mars calculated as the ratio of spectra observed during transit to the stellar spectrum out of transit. Continuum level offsets during transit (upper left number in panels) in parts per million have been suppressed. Note the significantly different balance between H_20 and CO_2 features in the transmission spectra of Earth and Venus.(Courtesy of T.M. Brown.)



Assuming that terrestrial planets are common, then the brightest star with a such a transiting planet will be V = 6 - 7th mag. (Finding such a planet is a separate issue that JWST will not address. If an 8 - 10 times Earth mass planet exists in the habitable zone of a K star, then such a planet is likely to be detected by ongoing radial velocity surveys over the next decade.) The sensitivity for JWST to thermal emission from such a planet - thereby establishing its temperature - is readily argued. The highest S/N Spitzer case is the recent detection of HD 189733b thermal emission at 8 microns, to 60-sigma significance (Knutson et al. 2007). Scaling that source-photon-limited result to the greater aperture of JWST projects a 300-sigma detection of that giant planet (using MIRI). Reducing the size of the planet, with other parameters (stellar host, distance, orbit, etc.) held fixed, gives a 3-sigma detection limit close to an Earth radius. Since any such planet would justifiably be observed over multiple eclipses, JWST will be able to accurately characterize "hot Earths" transiting K-dwarfs such as HD 189733 (K0V). Proceeding down the main sequence to M-dwarfs (Tarter et al. 2006), JWST will have even greater sensitivity, since the planet-to-star contrast ratio will be more favorable (see Valenti's whitepaper submission)

As for transmission spectra, Brown (2001b) has simulated transmission spectra for the Earth, Venus and Mars (see Figure 1), degraded to the R = 1000 spectral resolution of NIRSpec. A transit detection level of ~500-sigma would be necessary to detect water and CO_2 features in a terrestrial planet atmosphere, and this could distinguish Earth and Venus-like atmospheres. An alterative approach is to look for M stars with transiting terrestrial planets. In this case the spectroscopic problem is less challenging and it will be easier to find biosignatures. Valenti address this specific problem in a Whitepaper submitted via STScI.

3.4 Establishing Kepler terrestrial planet candidates as real.

If terrestrial planets are common in other systems, the Kepler Mission, scheduled for launch in 2007 will have detected many tens of such planets by 2011. The Kepler project has in place adequate procedures to eliminate most false positive detections through follow-up analysis of the Kepler data itself. Ground-based radial velocity observations will eliminate some fraction of the remaining false positives, and AO or high resolution space imaging can largely eliminate the remaining possibilities. For the most reliable claims of Earth-like planet detections, especially for a few cases in which the planet seems to be in the habitable zone, JWST could provide invaluable confirmation and further study of such objects. JWST can return individual transit detections in a few hours to 35σ at 0.7 μm (Beichman et al. 2007)

4.0 References:

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