Characterizing exoplanet atmospheres with the James Webb Space Telescope

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Molecules in Space
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Known Exoplanets (August 2017)

2925 EOD Planets
2950 Total Confirmed Planets
2337 Unconfirmed Kepler Candidates
5287 Total Planets

EOD Planets: Planets with good orbits listed in the Exoplanet Orbit Database
Other Planets: Including microlensing and imaged planets
Total Confirmed Planets
Unconfirmed Kepler Candidates
Total Planets: Confirmed planets + Kepler Candidates

Kepler motherlode
Many known planets can be characterized.
Planet-to-stellar mass-radius relation

Chen & Kipping (2016)
Planet Characterization: What is on the inside?

• **We wish to know:**
  – How and where did the planets form?
  – How are they similar to and influenced by their host stars?
  – What are their temperature profiles and 3D heat distribution?
  – What are the compositions, locations, and impacts of clouds?

• **How we can find out (or at least get clues):**
  – Observe spectra to probe compositions and temperatures
  – Compare compositions to host star to understand formation process (core accretion) and location in disk
  – Observe a large, diverse population to correlate results with bulk parameters (mass, density, insolation, host star)
Probe planet formation via C/O abundance

Figure 1. C/O ratio in the gas and in grains, assuming the temperature structure of a “typical” protoplanetary disk around a solar-type star ($T_0$ is 200 K and $q = 0.62$). The H$_2$O, CO$_2$, and CO snowline are marked for reference.
Specific questions about exoplanet atmospheres

• **What are their compositions?**
  – *Elemental abundances*
    • C/O and [Fe/H]: Both are formation diagnostics
  – *Molecular components and chemical processes*
    • Identify equilibrium & disequilibrium chemistry:
      – Vertical mixing, photochemistry, ion chemistry…
    – 3-D effects: spatial variations

• **Energy budget and transport**
  – 1-D structure: measure profiles, inversions present?
  – Dynamical transport: day/night differences

• **Clouds**
  – Cloud composition, particle sizes, vertical & spatial distribution
  – Remove cloud effects to determine bulk properties

• **Anything about low mass / small r< ~2R_e planet atmospheres**

• **Trends with bulk parameters** *(mass, insolation, host stars, …)*
  – Requires a population of diverse planets
Transmission & Emission Spectroscopy

Secondary Eclipse
See thermal radiation and reflected light from planet disappear and reappear

Orbital Phase Variations
See cyclical variations in brightness of planet

Transit
See radiation from star transmitted through the planet’s atmosphere

2 $R_{\text{Earth}}$ super Earth, a smaller GJ 1214b analog

Absorption %

- $H_2O$
- $H_2O$
- $CH_4$
- $CO_2$
- $CH_4$

Wavelength (\(\mu m\))

6 8 10 12

Doylsid Emission (e\(^{-}\))

- $H_2O$
- $CH_4$

Wavelength (\(\mu m\))

6 8 10 12
Transmission & Emission Spectroscopy

Secondary Eclipse
See thermal radiation and reflected light from planet disappear and reappear

Orbital Phase Variations
See cyclical variations in brightness of planet

传导与发射光谱学

次级日食
见来自行星的热辐射和反射光消失并重新出现

轨道相位变化
见周期性变化的亮度

2R_{\text{Earth}} super Earth, a smaller GJ 1214b analog

See radiation from star transmitted through the planet's atmosphere

见来自恒星的辐射通过行星的大气传播

20 August 2017

ACS / Molecules in Space
Some progress from transit spectroscopy

- **Molecules & atoms identified** in exoplanet atmospheres
  - H2O, CO (CH4, CO2), Na, other alkali, HI, CII, OI,…
  - Most planets have been found to be partially clear to cloudy

- **Measured temperature-pressure profiles** from hot Jupiter emission spectra
  - Few with high confidence T inversions

- **Some Neptune-sized planets have been studied**
  - HAT-P-11 (Fraine+ 2014) and GJ 436b (Knutson+, etc.)

- **Sub-Neptunes and super-Earths have been difficult**
  - GJ 1214b: flat absorption, no sec. eclipse (many people…)
  - Promise of cooler planets like K2-3 (Crossfield+ 2015) and K2-18b (Montet+ 2015): T = 300 – 500K, different clouds?
Transit Spectroscopy Status 2016

Clear atmospheres show spectral features

Clear-to-cloudy hot Jupiter transmission spectra from visible to mid-IR

Cloudy or hazy have strong blue scattering slopes and weak spectral features

Sing+ (2015)
WASP-43b: HST Emission + transmission

- Emission samples the bulk atmosphere (up to $P \sim 1$ bar) while transmission samples the stratosphere ($P \sim 1$ mbar)

![Emission Spectrum](image1.png)

![Transmission Spectrum](image2.png)

![Water volume mixing ratio](image3.png)

Kreidberg+ (2014)
James Webb Space Telescope (JWST)

- 6.5-m primary mirror; 25 m²
- 18 segments
  - T~40K, bkg. limited
- ⌦ <1 - 28 μm
  - zodiacal-limited to 10 μm
- Instruments:
  - NIRCam: 0.7 – 5 μm
  - NIRSpec: 0.6 – 5 μm
  - MIRI: 5 – 28 μm
  - NIRISS/FGS: .7–5 μm
- 2018 October launch
  - Arianne V to L2
  - Science starts April 2019
  - 5 yr req life, >10 yr goal
- ERS proposals due Aug 18
  - only 500 hours
- GO Cycle 1 due Mar 2018
The James Webb Space Telescope will launch in 2018
JWST vs. HST IR transit spectroscopy

- **HST and JWST both have some capabilities at visible wavelengths and HST can also work in the UV**

CHIMERA model by E. Schlawin

24 August 2017
Almost too many JWST spectroscopic modes!

J. Christiansen / Beichman+ 2014

Some modes may deliver better precision than others; will not know until after launch

- Numerous modes for transits and direct (IFU) exoplanet spectroscopy
- **Covering 0.6 – 12 μm requires 2 – 4 separate transits or eclipses**
Best JWST modes for transit spectra

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Mode</th>
<th>$\lambda$ (µm)</th>
<th>$R$ $\lambda/\delta\lambda$</th>
<th>PSF (pixels)</th>
<th>Saturation (K mag)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIRISS</td>
<td>SOSS</td>
<td>0.6 – 2.8</td>
<td>~700</td>
<td>~25</td>
<td>6.2 – 7.5</td>
<td>Slitless</td>
</tr>
<tr>
<td>NIRSpec</td>
<td>Prism</td>
<td>0.6 – 5.3</td>
<td>~100</td>
<td>&lt; 2</td>
<td>10.2</td>
<td>Wide Slit BOTS</td>
</tr>
<tr>
<td>NIRSpec</td>
<td>G140M/H+F100LP</td>
<td>1.0 – 1.9</td>
<td>~1000 / 2700</td>
<td>&lt; 2</td>
<td>8.0 / 6.8</td>
<td>Wide Slit BOTS</td>
</tr>
<tr>
<td>NIRSpec</td>
<td>G235M/H+F170LP</td>
<td>1.7 – 3.2</td>
<td>~1000 / 2700</td>
<td>&lt; 2</td>
<td>7.5 / 6.3</td>
<td>Wide Slit BOTS</td>
</tr>
<tr>
<td>NIRSpec</td>
<td>G395M/H+F290LP</td>
<td>2.9 – 5.3</td>
<td>~1000 / 2700</td>
<td>&lt; 2</td>
<td>6.5 / 5.5</td>
<td>Wide Slit BOTS</td>
</tr>
<tr>
<td>NIRCams</td>
<td>Grism+F322W2</td>
<td>2.4 – 4.0</td>
<td>~1500</td>
<td>≤ 2</td>
<td>4.4</td>
<td>Slitless</td>
</tr>
<tr>
<td>NIRCams</td>
<td>Grism+F444W</td>
<td>3.9 – 5.0</td>
<td>~1500</td>
<td>≥ 2</td>
<td>3.7</td>
<td>Slitless</td>
</tr>
<tr>
<td>MIRI</td>
<td>LRS</td>
<td>~5 – ~12</td>
<td>100</td>
<td>&lt;2 – 3</td>
<td>5.7</td>
<td>SLITLESPRISM</td>
</tr>
</tbody>
</table>
JWST Simulation / Retrieval Assessment

Model some known planet types, simulate spectra, assess information & constraints

1. Select archetypal planets from known system parameters
2. Create model transmission and emission spectra (M. Line)
3. Simulate JWST spectra using performance models (TG)
   – Simulate slitless modes with large bandpasses & good bright limits: NIRISS SOSS, NIRCam grisms, MIRI LRS slitless 1 – 11 μm
   – 1 transit or eclipse per spectrum
4. Perform atmospheric retrievals (M. Line) to assess uncertainties in molecules, abundances, T-P profiles
   – Focus on uncertainties, not absolute parameters

• Identify what wavelengths give most useful information for what planets
Use 1-D forward models


Transmission model has 11 free parameters

- $T(SH)$, $R(P=10b)$, hard clouds ($P_c$, $\sigma_0$, $\beta$), $H_2O$, $CH_4$, $CO$, $CO_2$, $NH_3$, $N_2$
- Absorbers, constant with altitude

Emission model has 1D T-P profile & 10 free params

- $H_2O$, $CH_4$, $CO$, $CO_2$, $NH_3$, 5 gray atm parameters for T-P (Line+ 2013a)

CHIMERA Bayesian retrieval suite (Line+ 2013a,b)

- Updated with emcee MCMC
- Uniform & Jeffreys priors
Simulated JWST Transmission (1 transit per \( \lambda \))

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Greene+ (2016)
Simulated JWST Emission (1 eclipse / \( \lambda \))

- Hot Jupiter R=100, 1 eclipse
- Clear Solar
- T Inversion
- HST WFC3 IR
- H\(_2\)O
- CO\(_2\)
- CO

- Warm Neptune R=35, 1 eclipse
- Clear Solar
- 1000x Solar
- HST WFC3 IR
- H\(_2\)O
- CH\(_4\)
- NH\(_3\)

- Warm Sub-Neptune R=35, 1 eclipse
- Clear Solar
- 1000x Solar
- HST WFC3 IR
- CH\(_4\)

- Cool Super Earth R=35, 1 eclipse
- Clear Solar or 100% H\(_2\)O
- HST WFC3 IR
- NH\(_3\)

Greene+ (2016)

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M. Line CHIMERA models & retrievals, GJ 436b – like system (Greene+ 2016)

Different planets will require observations with different modes to measure specific quantities & address particular questions.
M. Line CHIMERA models & retrievals, GJ 436b – like system (Greene+ 2016)

Different planets will require observations with different modes to measure specific quantities & address particular questions
Retrieval: Warm Sub-Neptune Gasses

- $H_2O$
- $CH_4$
- CO
- $CO_2$
- $NH_3$
- C/O
- [Fe/H]

- Emission Clear Solar
- Emission Clear High MMW
- Transm. Clear High MMW
- Transm. Cloud Solar
- Transm. Clear Solar

- $\log(H_2O)$
- $\log(CH_4)$
- $\log(CO)$
- $\log(CO_2)$
- $\log(NH_3)$
- $\log(C/O)$
- [Fe/H]
- $\log(P_{cloud})$

Priors

NIRISS+NIRCam+MIRI (1-11μm)-NIRISS+NIRCam (1-5μm)-NIRISS (1-2.5μm)

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Mass – Metallicity with JWST

Transmission spectra

Adapted from Kreidberg+ 2014b
How to optimize JWST observations?

- NIRISS (1 – 2.5 μm) transmission spectra alone sometimes constrain mixing ratios of dominant molecules in clear solar atmospheres (H₂O, CH₄, NH₃)
- Cloudy solar atmospheres are often constrained (~ 1 dex or better mixing ratios) with λ = 1 - 11 μm spectra
- High MMW atmospheres identified by high [Fe/H]
- C/O is constrained to 0.2 dex for hot Jupiters with λ = 1 – 5+ μm spectra
  - Probe C/O for hot planets via H₂O; also C₂H₂, HCN (Venot+)
- σ[Fe/H] < 0.5 dex for warm, clear planets (λ = 1-5+ μm)
- λ = 2.5 – 11 μm emission spectra probe bulk atmospheres of T > 700 K planets, R > ~few Re
THE END
GTO Program Science Goals

• Exoplanet atmosphere compositions, metallicity, C/O?
  – How do they vary with planet mass, and how does this compare to host stars and the Solar System?
• Search for non-equilibrium chemistry
• Probe clouds and hazes
• Measure temperature-pressure profiles
• Global structure and energy transport (transmission + emission)
• Study a range of ice- and gas-giant planets
  – 20 $M_E$ to 1 $M_J$ and $T_{eq} = 700 – 1200$ K
Why are JWST / space transit data so good?

High precision is enabled by three factors:

- JWST provides a large aperture with greater spectral range (0.6–12+ μm).
- High Stability:
  - Precise pointing, stable background, no atmospheric emission or attenuation.
- Slitless Spectroscopy:
  - No jitter-modulated variations due to slit losses.
  - Very low background (~1 e⁻/s/pixel at λ = 1–5 μm).

JWST background ~10 ph/s/pixel
λ = 5 μm (R ~ 4)

Stockman+ 1997

24 August 2017
### Selected Model Systems

<table>
<thead>
<tr>
<th>Planet Type</th>
<th>System Parameters</th>
<th>Composition</th>
<th>Clouds</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Jupiter</td>
<td>HD 209458b</td>
<td>1x Solar</td>
<td>Clear</td>
<td>Trans, Emis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000x Solar</td>
<td>1 mbar</td>
<td>Trans</td>
</tr>
<tr>
<td>Warm Neptune</td>
<td>GJ 436b</td>
<td>1x Solar</td>
<td>Clear</td>
<td>Trans, Emis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000x Solar</td>
<td>1 mbar</td>
<td>Trans</td>
</tr>
<tr>
<td>Warm Sub-Neptune</td>
<td>GJ 1214b</td>
<td>1x Solar</td>
<td>Clear</td>
<td>Trans, Emis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000x Solar</td>
<td>1 mbar</td>
<td>Trans</td>
</tr>
<tr>
<td>Cool Super-Earth</td>
<td>K2-3b</td>
<td>1x Solar</td>
<td>Clear</td>
<td>Trans, Emis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100% H₂O</td>
<td>1 mbar</td>
<td>Trans</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Planet Type</th>
<th>System Parameters</th>
<th>(T_e) (K)</th>
<th>(R_e) ((R_\oplus))</th>
<th>(K) (mag)</th>
<th>(T_{eq}^a) (K)</th>
<th>(M_p) ((M_\oplus))</th>
<th>(R_p) ((R_\oplus))</th>
<th>(H^b) (km)</th>
<th>(T_{14}) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Jupiter</td>
<td>HD 209458b</td>
<td>6065</td>
<td>1.155</td>
<td>6.3</td>
<td>1500</td>
<td>220</td>
<td>15</td>
<td>560</td>
<td>11,000</td>
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<tr>
<td>Warm Neptune</td>
<td>GJ 436b</td>
<td>3350</td>
<td>0.464</td>
<td>6.1</td>
<td>700</td>
<td>23</td>
<td>4.2</td>
<td>190</td>
<td>2740</td>
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<tr>
<td>Warm Sub-Neptune</td>
<td>GJ 1214b</td>
<td>3030</td>
<td>0.211</td>
<td>8.8</td>
<td>600</td>
<td>6.5</td>
<td>2.7</td>
<td>230</td>
<td>3160</td>
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<tr>
<td>Cool Super-Earth</td>
<td>K2-3b</td>
<td>3900</td>
<td>0.561</td>
<td>8.6</td>
<td>500</td>
<td>5.3^c</td>
<td>2.1</td>
<td>150^c</td>
<td>9190</td>
</tr>
</tbody>
</table>

**Note.** — Tabulated system values were taken from the exoplanets.org compilation (Han et al. 2014) and Crossfield et al. (2015).

\(^a\) Equilibrium temperature \(T_{eq}\) was computed from the listed system values assuming albedo = 0 and energy re-distribution over \(4\pi\) str.

\(^b\) The planetary atmosphere scale height \(H = kT_{eq}/(\mu m_H g)\) for the clear solar atmosphere of each planet (\(\mu = 2.3\)) is provided as a convenience for scaling to other systems.

\(^c\) The mass of this planet has been recently measured to be \(8.4 \pm 2.1M_\oplus\) (Almenara et al. 2015), somewhat higher than the tabulated value we used in our investigation. This increased mass would decrease the scale height, decrease the SNR of transmission spectral features, and worsen the derived abundance precisions by roughly 40%.
Emission retrievals: T-P Profiles

Dashed: True value
Solid line: Retrieved mean value
Shaded: 1 sigma

Detect inversion at 4 sigma with NIRISS only (red)
Why are Earth & Venus atmospheres hard?

- $O_3$ & $CO_2$ features in transmission spectra of Earth- or Venus-like planets of M5V stars are in $\sim 10$ ppm range.
- This is undetectable with HST precision; JWST maybe also.