Presentation Scope

- Exoplanet Time Domain Spectroscopy
- Outstanding Issues
- How Can JWST Help?
- Optimum Targets
- Planet Models
- Simulated Spectra and Potential Science
- Takeaways
Exoplanet Spectroscopy Status

Figure courtesy of M. Swain

Swain et al. 2008

HD 189733b
Transmission

HD 189733b
Emission

Grillmair et al. 2008
Exoplanet Spectroscopy: The Ground

- The ground is trying. Enough aperture but control of systematic noise is difficult.

Broadband Transmission Spectrum of GJ 1214b

- Croll et al. 2011 photometry
- See also Ian Crossfield et al. Poster (Keck NIRSpec GJ 1214b)
- Swain and others doing spectroscopy
Some Outstanding Issues

• Are observed strengths of spectral features due to abundances or temperature profiles?
  – Distinguish temperatures, T profiles, compositions
  – Are Ice giants overabundant in carbon like Neptune?

• How is energy absorbed and transported in highly irradiated planets?
  – Measure & determine causes of temperature inversions
  – Study transport via day / night side differences

• Is there non-equilibrium chemistry at work?
  – Hydrocarbons like C\textsubscript{2}H\textsubscript{2} (acetylene), C\textsubscript{2}H\textsubscript{6} (ethane) indicate photo-chemical production

• What is the composition of mini-Neptune atmospheres?

• Can we detect any features in Super-Earth atmospheres?
Unidentified features in high insolation

- Excess Spitzer IRAC Band 3 emission seen in exoplanets with hot stratospheres / high altitude inversions like HD 209458
- Common to many planets, most highly insolated
- Is it enhanced continuum or an unknown spectral feature
  - Current models can't fit it with continuum or a species (TiO / VO tried & non-equiib processes suggested)
  - Useful in understanding energy transport in atmosphere and compositions of planets
JWST in a nutshell

- 6.5-m primary mirror; 18 segments.
  - $T \sim 40K$, bkg. limited
- $\lambda < 1 - 28 \mu m$
  - Zodi-limited to 10$\mu m$
- Instruments:
  - NIRCam $1 - 5 \mu m$
  - NIRSpec $1 - 5 \mu m$
  - MIRI $5 - 28 \mu m$
    (cam + spec)
  - FGS w/TF $1 - 5 \mu m$
- 201X launch
  - Arianne V to L2
  - 5 yr req life
  - 10 yr goal
  - No cryogens
- Instruments view different parts of JWST focal plane
- Little parallel operation currently planned
How Can JWST Help?

- JWST has 6.5 m aperture vs. 2.4 m for HST and 0.85 m for Spitzer
  - Photon-noise limited SNR goes as aperture size, so JWST should be capable of SNR ~ 3 – 8 times present values

- JWST has great spectroscopic capabilities, particularly:
  - $\lambda = 1 – 5 \, \mu m$, $R \sim 100$ mode with NIRSpec prism
  - $\lambda = 5 – 12+ \, \mu m$, $R \sim 70$ mode with MIRI LRS prisms (slitless)

- JWST is being designed and will be operated to maximize exoplanet spectroscopy SNR
  - Wide NIRSpec slit (1400 mas) and slitless mid-IR spectroscopy
  - Testing spectrophotometric precision and simulating operations
  - Large NIRSpec pixels may reduce precision (see P. Deroo poster); mitigation possible?
JWST Observational Constraints

• JWST instantaneous field of regard is limited
  - Sun angles between 85 and 135 degrees (35% of sky)
  - Two 50-day visibility windows per year near ecliptic

• JWST is optimized for long exposures of faint objects but subarrays do provide reasonable bright limits:
  - K ~ 5 mag for R=1700 NIRCam grism (2.4 – 5 µm)
  - K ~ 7 mag for NIRSpec R ~ 33 – 315 prism (0.7 – 5 µm)
  - Low overhead for long sequence of identical integrations if not too bright

• Ground bright limits are similar for R ~ 20,000 Keck NIRSpec & IRTF CSHELL / iSHELL
  - Narrow-band imaging could have similar limits if subarrays used
What are the optimum JWST targets?

• Ideally we need planets transiting / eclipsing IR bright nearby but small stars
  – Star SNR $\sim \sqrt{\text{Signal}}$ and transit depth $\sim (R_{pl} / R^*)^2$
  – M stars are ideal if stable
  – Kepler planets are too faint / distant for spectroscopy

• Planets with large atmospheric scale heights $kT/(\mu g)$ will have relatively high SNR spectra
  – Gas giants, ice giants, mini-Neptunes will be good

• Impossible to detect atmospheric features in true Earth / Sun analog

• **We need an all-sky transit survey mission to find good planets:** ELEKTRA (or TESS) Explorer
Planet Models (J. Fortney & Collaborators)

- “Hot Jupiters”, “Neptunes”, “mini-Neptunes”
- Absorption and Emission models
- Variations for re-radiation geometry (2 pi / 4 pi), abundances, chemistry

<table>
<thead>
<tr>
<th>Planet</th>
<th>Star SpT</th>
<th>V* (mag)</th>
<th>R* (Rsun)</th>
<th>R_pl (Rj)</th>
<th>t_trans (m)</th>
<th>t_ecl(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 189733b</td>
<td>K1.5</td>
<td>7.7</td>
<td>0.79</td>
<td>1.15</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>HD 209458b</td>
<td>G0V</td>
<td>7.7</td>
<td>1.15</td>
<td>1.38</td>
<td>144</td>
<td>144</td>
</tr>
<tr>
<td>HD8606b</td>
<td>G5</td>
<td>8.9</td>
<td>0.98</td>
<td>0.92</td>
<td>728</td>
<td>101</td>
</tr>
<tr>
<td>TrES-3</td>
<td>G</td>
<td>12.4</td>
<td>0.81</td>
<td>1.31</td>
<td>78</td>
<td>78</td>
</tr>
<tr>
<td>WASP-12b</td>
<td>G0V</td>
<td>11.7</td>
<td>1.57</td>
<td>1.79</td>
<td>162</td>
<td>162</td>
</tr>
<tr>
<td>WASP-17b</td>
<td>F6</td>
<td>11.6</td>
<td>1.38</td>
<td>1.74</td>
<td>262</td>
<td>262</td>
</tr>
<tr>
<td>WASP-18b</td>
<td>F9</td>
<td>9.3</td>
<td>1.23</td>
<td>1.17</td>
<td>135</td>
<td>135</td>
</tr>
<tr>
<td>GJ 436b</td>
<td>M2.5V</td>
<td>10.7</td>
<td>0.46</td>
<td>0.37</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>GJ1214b</td>
<td>M4.5V</td>
<td>14.7</td>
<td>0.21</td>
<td>0.24</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>
JWST Simulations

- Semi-realistic model of telescope and instrument wavelength-dependent resolution and throughput
- Photon noise and systematic noise added
- Systematic noise is difficult to predict
  - May have large wavelength dependencies (See P. Deroo poster)
  - Currently assumed to be 50 ppm (max SNR = 20,000)
- Compare simulations of model variants to determine what science issues can be addressed with JWST data
HD 189733b Gas Giant

- Only 1 transit (top) or eclipse (bottom) plus time on star for each (1 NIRSPec + 1 MIRI)
- Multiple features of several molecules separate compositions, temperature, and distributions
GJ 436b (warm Neptune) transmission spectra simulations

- Simulated single transit model absorption spectra distinguish between equilibrium (black, blue, red) or non-equilibrium chemistries where H$_2$O and CH$_4$ are absent in favor of higher order hydrocarbons HCN, C$_2$H$_2$, and other molecules (purple, cyan and green curves). See Shabram et al. (2011).
**JWST transit / eclipse spectra**

---

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

**Orbital Phase Variations**
See cyclical variations in brightness of planet

---

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

---

See radiation from star transmitted through the planet’s atmosphere

---

---

---
MIRI detection of CO$_2$ in Super-Earths?

- JWST MIRI filters (red boxes, left) can be used to detect deep CO2 absorption in Super-Earth atmospheres in emission observations (Miller-Ricci 2009 model, left).

- Modelling shows that modest S/N detections possible on super-Earth planets around M stars (Deming et al. 2009).

Deming et al. (2009) showing Miller-Ricci Super-Earth (2009) and MIRI filters.
Some Takeaways

- Expect exquisite JWST spectra of gas giants
  - Determine abundances, temperature profiles, and energy transport in hot Jupiters with little degeneracy using transit and eclipse spectra over 0.8 – 10+ microns.

- Mid-IR spectra can identify unknown emission in Spitzer IRAC 5.8 µm band of planets with suspected hot stratospheres

- Easily constrain compositions of mini-Neptunes like GJ 1214b (down to 2 R₆ and smaller)

- Possibly detect CO₂ absorption in Super-Earths

- **We need an all-sky transit survey mission to find good planets**: ELEKTRA (or TESS) Explorer