High-fidelity simulations of planetary transit spectroscopy with JWST/NIRSpec
This talk is brought to you by:


The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007–2013) under grant agreement n° PITN-GA-2008–214227 – ELIXIR
The Instrument Performance Simulator (IPS)

- Developed by CRAL for EADS Astrium GmbH and ESA (Piqueras et al. 2008, 2010)
- End-to-end simulation for NIRSpec calibration and science exposures
- Includes Fourier optics, radiometry, and coordinate transforms
- Output:
  - Noiseless electron rates
  - NIRSpec raw data cube
- Additional tools:
  - Data handling framework
  - Science data input interface
  - Data reduction pipeline
Instrument model status

• As-built optical models almost complete
• Realistic geometries (accurate down to ±3 px)
• Measured subsystem efficiencies
• Field dependent wavefront errors
• Detector: Spatially uniform efficiency, optimistic model
• Full model not yet verified
• Telescope: data similar to specifications
Throughput: total efficiency
Simulation scenery

- Single star (point source) in 1.6" square aperture
- Different NIRSpec modes (filters, dispersers)
- Subarray readout (2048 x 32 pixels)
  - Accommodate spectrum curvature
  - Reference pixels needed
- No dithering
- Wavelength coverage:
  - PRISM + R1000: full
  - R2700: detector gap

Simulation scenery diagram
Poiting and photometric stability

- Truncation of PSF in slit and pupil at disperser
- Position dependent
- Random jitter in slit: <7 mas (1 σ) during 10,000 sec (requirement)
- Simple drift on very short timescales
- Characterize with RMS in radial distance
Impact of drift

- Relative error of throughput should be $<10^{-5}$
- Maximal drift during one exposure: 1 mas
### Observability and exposure times

**HD189733**  
G5, 19.45 pc  

**GJ1214**  
M4.5V, 12.95 pc

<table>
<thead>
<tr>
<th>Planet</th>
<th>NIRSpec mode</th>
<th>Maximum frame number $n_f$</th>
<th>Duration $T_{trans}$ / sec</th>
<th>Effective exposure time $t_{eff}$ / sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD189733b (eclipse)</td>
<td>R2700 band III</td>
<td>2</td>
<td>3456 (Knutson et al. 2007)</td>
<td>1145</td>
</tr>
<tr>
<td>HD189733b (transit)</td>
<td>R2700 band III</td>
<td>2</td>
<td>3600 (Winn et al. 2007)</td>
<td>1199</td>
</tr>
<tr>
<td>GJ1214b</td>
<td>R2700 band I</td>
<td>20</td>
<td>2406 (Berta et al. 2010)</td>
<td>2056</td>
</tr>
<tr>
<td>GJ1214b</td>
<td>R2700 band II</td>
<td>20</td>
<td>2406</td>
<td>2056</td>
</tr>
<tr>
<td>GJ1214b</td>
<td>R2700 band III</td>
<td>38</td>
<td>2406</td>
<td>2001</td>
</tr>
<tr>
<td>GJ1214b</td>
<td>R1000 band I</td>
<td>7</td>
<td>2406</td>
<td>1785</td>
</tr>
<tr>
<td>GJ1214b</td>
<td>R1000 band II</td>
<td>7</td>
<td>2406</td>
<td>1785</td>
</tr>
<tr>
<td>GJ1214b</td>
<td>R1000 band III</td>
<td>14</td>
<td>2406</td>
<td>1992</td>
</tr>
</tbody>
</table>
Signal and SNR for transits

• Only photon noise considered

• Primary transit:
  ‣ signal: transit depth  \[ d = \frac{R_{out} - R_{in}}{R_{out}} \]
  ‣ SNR:  \[ \frac{d}{\sigma_d} = \sqrt{R_{out} t_{eff}} \sqrt{\frac{d^2}{d^2 - d + 2}} \]

• Eclipse:
  \[ d = \frac{R_{out} - R_{in}}{R_{in}} \]
  \[ \frac{d}{\sigma_d} = \sqrt{R_{out} t_{eff}} \sqrt{\frac{d^2}{d^2 + d + 2}} \]
Primary transit: detection of atmosphere with effective height $h$ around planet with radius $r_{Pl}$
(Kaltenegger & Traub 2009)

- **signal:**
  \[ d_A = \frac{2r_{Pl}h}{r_{Star}^2} \]

- **SNR:**
  \[ \frac{d_A}{\sigma d_A} = \frac{2r_{Pl}}{r_{Star}^2} \sqrt{R_{out}t_{eff}} \cdot h \]
HD189733b: eclipse
HD189733b: primary transit depth

HD189733b SNR of single primary transit

NIRSpec F290LP, G395H, R=2700 (dlambda=0.67 nm)
GJ1214b: atmospheric height

NIRSpec F100LP, G140M, R=1000 (average step: 0.64nm), smoothed with 11px median
Earth-like planet around M4.5V star

- Put GJ1214 at 10 pc distance
- Earth-size planet in habitable zone
  - Semimajor axis: $a_{HZ} = 0.0558$ AU
  - Orbital period: $P_{HZ} = 12.18$ days
  - Transit duration: $T_{\text{trans}} = 1.60$ h
Earth-like planet around M4.5V star

- Atmospheric feature detection:
  - SNR in single transit
  - $N_5$: number of transits for SNR=5
  - $T_5$: Time needed for $N_5$

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Center wavelength $\lambda$ / µm</th>
<th>Feature width $\Delta \lambda$ / µm</th>
<th>Effective height $h$ / km</th>
<th>NIRSpec mode</th>
<th>single SNR</th>
<th>$N_5$</th>
<th>$T_5$ / years</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>1.9</td>
<td>0.2</td>
<td>5</td>
<td>R1000 band II</td>
<td>0.420</td>
<td>141.4</td>
<td>4.74</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>2.8</td>
<td>0.1</td>
<td>20</td>
<td>R1000 band II</td>
<td>0.757</td>
<td>43.7</td>
<td>1.47</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>3.3</td>
<td>0.25</td>
<td>20</td>
<td>R1000 band III</td>
<td>1.34</td>
<td>13.9</td>
<td>0.47</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>4.3</td>
<td>0.4</td>
<td>20</td>
<td>R1000 band III</td>
<td>1.26</td>
<td>15.8</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Large features within reach during mission
Conclusion and outlook

• IPS allows generation of accurate mock NIRSpec observations

• As-built instrument models almost complete and partially verified

• In-depth evaluation of NIRSpec performance and operational constraints has begun (see also poster by Jeff Valenti, Missions 31)

• First results are very encouraging

Stay tuned!