Super Earths: Reflection and Emission Spectra

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Direct Imaging
Giant planets found so far, Planetscope targets

Terrestrial planets we hope to find, in a future space mission
The Earth at 10 pc
Planetscope could measure colors of gas giants

Solar system planets have colors that label them by type.

Blue (0.4-0.6 μm), Green (0.6-0.8 μm), Red (0.8-1.0 μm)
Example exoplanets. Over 400 are known.
Visible and Far-infrared Earth Spectra

Refs.: (left) Woolf et al. 2002; (right) Kaltenegger et al. 2007, and Christensen & Pearl 1997
Brightness of Earth at 10 pc, in photons

Ref.: DesMarais et al., 2002
Species SNRs for an 8-m telescope, 6 day integration

**Table 1: Habitability and Bio-Signature Characteristics**

<table>
<thead>
<tr>
<th>Feature</th>
<th>$\lambda$ (nm)</th>
<th>$\Delta \lambda$ (nm)</th>
<th>SNR</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference continuum</td>
<td>~750</td>
<td>11</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Air column</td>
<td>500</td>
<td>100</td>
<td>4</td>
<td>Protective atmosphere</td>
</tr>
<tr>
<td>Ozone ($O_3$)</td>
<td>580</td>
<td>100</td>
<td>5</td>
<td>Source is oxygen; UV shield</td>
</tr>
<tr>
<td>Oxygen ($O_2$)</td>
<td>760</td>
<td>11</td>
<td>5</td>
<td>Plants produce, animals breathe</td>
</tr>
<tr>
<td>Cloud/surface reflection</td>
<td>750</td>
<td>100</td>
<td>30</td>
<td>Rotation signature</td>
</tr>
<tr>
<td>Land plant reflection</td>
<td>770</td>
<td>100</td>
<td>2</td>
<td>Vegetated land area</td>
</tr>
<tr>
<td>Water vapor ($H_2O$)</td>
<td>940</td>
<td>60</td>
<td>16</td>
<td>Needed for life</td>
</tr>
</tbody>
</table>

Characterizing Earths: Transits
Three Geometries

- Primary Transit
- Secondary Eclipse
- Direct Imaging
Transit Geometry

\( h \) is the effective height of an opaque atmosphere:

\[
\textcolor{black}{h(\lambda) = \int (1-T) \, dz}
\]

So

\[
\textcolor{black}{R(\lambda) = R_0 + h(\lambda)}
\]

Note: The scale height is \( H \sim 1/R_0 \)
i.e., smaller for Super-Earths.
Ray-by-ray spectra, visible & near-infrared

Short wavelength range of transmission spectrum.

Note:
- strong O3 bands at 0.3 & 0.6 um,
- weak H2O bands in visible,
- strong Rayleigh in blue,
- low transmission below 10 km.

Enric Palle et al. showed an observed spectrum from a lunar eclipse, but with additional dimer features.

Ref.: Kaltenegger & Traub 2009

KISS Exoplanet Workshop
Visible & near-infrared segment

Ref.: Kaltenegger & Traub 2009

KISS Exoplanet Workshop
1-transit SNRs for the nearest star

<table>
<thead>
<tr>
<th>Feature</th>
<th>G2V</th>
<th>M0V</th>
<th>M1V</th>
<th>M2V</th>
<th>M3V</th>
<th>M4V</th>
<th>M5V</th>
<th>M6V</th>
<th>M7V</th>
<th>M8V</th>
<th>M9V</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td>12.5</td>
<td>1.8</td>
<td>1.5</td>
<td>1.8</td>
<td>1.4</td>
<td>2.0</td>
<td>2.4</td>
<td>1.1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>H₂O</td>
<td>3.5</td>
<td>1.0</td>
<td>0.9</td>
<td>1.2</td>
<td>1.0</td>
<td>1.7</td>
<td>2.7</td>
<td>1.5</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>CO₂</td>
<td>6.3</td>
<td>1.9</td>
<td>1.8</td>
<td>2.4</td>
<td>2.1</td>
<td>3.5</td>
<td>5.8</td>
<td>3.3</td>
<td>1.8</td>
<td>2.0</td>
<td>1.9</td>
</tr>
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<td>H₂O</td>
<td>8.1</td>
<td>2.5</td>
<td>2.4</td>
<td>3.2</td>
<td>2.8</td>
<td>4.7</td>
<td>7.8</td>
<td>4.4</td>
<td>2.4</td>
<td>2.8</td>
<td>2.7</td>
</tr>
<tr>
<td>CH₄</td>
<td>1.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
<td>0.6</td>
<td>1.0</td>
<td>1.7</td>
<td>1.0</td>
<td>0.5</td>
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Most likely transits, in each sub-spectral type, will be at 10-20 pc, so 100 times fainter, & 10 times smaller SNR

where \( \text{SNR} = N^{1/2} \text{(total)} \times 2hR_p/R_s^2 \)

Ref.: Kaltenegger & Traub 2009
## Results & Examples

**SNR(sec)/SNR(pri)**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SNR</th>
<th>Best Type</th>
</tr>
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<tr>
<td>Earth, G star, visible</td>
<td>1/500</td>
<td>primary best</td>
</tr>
<tr>
<td>Earth, M star, visible</td>
<td>1/50</td>
<td>primary best</td>
</tr>
<tr>
<td>Hot Jupiter, G star, visible</td>
<td>1</td>
<td>both OK</td>
</tr>
<tr>
<td>Earth, G star, infrared</td>
<td>1/2000</td>
<td>primary best</td>
</tr>
<tr>
<td>Earth, M star, infrared</td>
<td>40</td>
<td>secondary best</td>
</tr>
<tr>
<td>Hot Jupiter, G star, IR</td>
<td>200</td>
<td>secondary best</td>
</tr>
</tbody>
</table>

So, in the visible, for Earth around a G or M dwarf, the primary transit is best; likewise in the infrared for Earth around a G star.

So for these cases, the small SNR values for primary transits are the best we can do.

Super Earths will be similar.
Planetscope: A Coronagraph on a Balloon Platform or on the ISS
Contrast level dependence on altitude

Contrast Limit vs. Float Altitude

P. Chen & W. Traub, 2009
Contrast & known RV exoplanets vs angle

"Dome Seeing" Contribution:

C(1 sec) assumes night best (rms = 1 nm) but only 0.1 nm of this going to speckles in the range IWA-OWA, with 0.9 nm going to piston and tilt.

C(1 hr) assumes above reduced by (1 sec / 1 hr)\(^{1/2}\), i.e., this is the uncertainty in the average background speckle level.

\[
C = \pi(2\pi\sigma/N\lambda)^2
\]

for \(\sigma = \lambda/1000\)

& \(\sigma = \lambda/10000\)

& \(N = 60\)

Expected dome-seeing contrast uncertainty in 1 hour

Expected free-atmosphere speckle contrast

Expected PSF from coronagraph

P. Chen & W. Traub, 2009
Summary

• Giant planets are accessible with a coronagraph on a balloon platform or on the ISS, with a 1-3 m telescope.

• Colors and low-resolution spectra are feasible from both cases.

• Terrestrial planets will need a larger (3-8 m) telescope.
Thank you!