Earth's transmission spectrum from lunar eclipse observations

Pallé et al. 2009, Nat.

Nowadays we can monitor night lights, atmospheric changes, plankton blooms, forest health, etc...
But, how does our planet look like to ET?
When observing an exoplanet, all the light will come from a single point.

We will need a detailed understanding of the “micro-scale” processes to interpret the observed “macro-scale” properties.
Observing the Earth as a planet (no spatial resolution)

- Earth–as-a-point observations with a very remote sensor
- A compilation of high spatial resolution data into a global spectra or photometry, and modeling
- Earthshine Observations: The Earthshine is the ghostly glow on the dark side of the Moon
The Earthshine on the moon

\[ ES/MS = \text{albedo} \ (\text{+ geometry and moon properties}) \]
The page is titled

"Of the Moon:
No solid body is lighter than air."

Here Leonardo repeats his belief that the moon shines because it is covered with water, and says that he believes the moon to be a heavy body with its own gravity and atmosphere.

Here he explains how sunlight, reflected from the earth's oceans at sunset, causes the ghostly glow of the whole moon inside the crescent moon.

"...that glimmer visible in the middle between the horns of the new moon... this brightness at such a time being derived from our oceans, which are at that time illuminated by the sun, which is then on the point of setting..."
But isolating the light from the planet is VERY challenging, what if direct detection is not possible?

Atmospheric characterization of *Hot Jupiters* has already been achieved through transit spectroscopy.

What about transiting Earths?
We can observe it during a lunar eclipse.
Lunar eclipse
August 16th 2008
Earth’s Transmission Spectrum

The pale red dot

Transmission spectra VIS+ZJ+HK
Earth’s Transmission Spectrum
Visible

NOT visible spectra

Ca II
H₂O
O

0.4 0.5 0.6 0.7 0.8 0.9 μm
Fraunhofer lines structure

Ca II

NO ?

α

H

Ca II
Earth’s Transmission Spectrum
Near-IR ZJ
Atmospheric Dimers:

Van de Waals molecules: Weakly bound complexes

They are present as *minor* rather than *trace* species.

One likely origin of continuum absorption.

Observed on Earth (gas) and Jupiter (gas; \((\text{H}_2\text{)}^2\)), Ganymede, Europa and Callisto (condensed), and in the laboratory (gas/condensed).

Never on Venus/Mars, where there must be \text{CO}_2 – \text{X}

NOT contained in the common spectral libraries
Earth’s Transmission Spectrum
Near-IR   HK

- H$_2$O
- CH
- CO
How deep we see in the planet atmosphere?

- Are anthropogenic signatures visible in the lower layers?
- Is there a surface signal?

Traub, 2009
Evolution of the Earth’s Transmission Spectrum during the eclipse
How deep we see in the planet atmosphere?

Ref.: Kaltenegger & Traub 2009
Reflection vs Transmission
Earth’s Reflectance Spectrum: Earthshine

Same instrumentation only two months apart

Reflectance spectra VIS+ZJ+HK

Relative brightness

μm
Reflected spectrum

Transmission Spectrum

Blue planet?

Transmission vs Reflectance spectra

Palle et al, 2009
<table>
<thead>
<tr>
<th>Atmospheric species</th>
<th>Filter wavelengths</th>
<th>Transmission Spectra</th>
<th>Reflection spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>6850 – 6950</td>
<td>2.4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>8100 – 8200</td>
<td>6.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>9300 – 9400</td>
<td>28.1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>11200 – 11300</td>
<td>44.0</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>13500 – 13600</td>
<td>53.5</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>18300 – 18400</td>
<td>69.4</td>
<td>4.7</td>
</tr>
<tr>
<td>O₂</td>
<td>7850 – 7680</td>
<td>26.1</td>
<td>1.5</td>
</tr>
<tr>
<td>O₂ · O₂</td>
<td>5700 – 5800</td>
<td>12.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>10600 – 10700</td>
<td>23.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>12540 – 12640</td>
<td>29.0</td>
<td>2.4</td>
</tr>
<tr>
<td>O₂ · O₂ , O₂ · N₂</td>
<td>12650 – 12750</td>
<td>35.6</td>
<td>2.8</td>
</tr>
<tr>
<td>CO₂</td>
<td>15700 – 15800</td>
<td>23.0</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>16000 – 16100</td>
<td>21.8</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>20100 – 20200</td>
<td>24.2</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>20600 – 20700</td>
<td>26.1</td>
<td>5.3</td>
</tr>
<tr>
<td>CH₄</td>
<td>16400 – 16500</td>
<td>9.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>22300 – 22400</td>
<td>2.7</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>22500 – 22600</td>
<td>5.4</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>22900 – 23000</td>
<td>6.6</td>
<td>4.2</td>
</tr>
</tbody>
</table>
Thus, the transmission spectrum of telluric planets contains more information for the atmospheric characterization than the reflected spectrum.

And it is also less technically challenging.

But, how far are we from making the measurements?
Terrestrial inner-orbit planets based on their transits:

- About 50 planets if most have $R \sim 1.0$ Re
- About 185 planets if most have $R \sim 1.3$ Re
- About 640 planets if most have $R \sim 2.2$ Re
(Or possibly some combination of the above)

About 12% of the cases with two or more planets per system
Differential transit spectroscopy M star + Earth : 1 (2) measurement

\[ \frac{S_{s+p}}{S_p} \]
M8 star + 1 Earth ... with the E-ELT

Work in progress ...
Still, we must pursue the characterization with direct observations

- **Exploration of surface features**
  - Presence of continents
  - Rotational period
  - Localized surface biomarkers (vegetation)
- ** Orbital light curve**
- **Ocean glints and polarization effects**
Conclusions

- We have obtained the Earth's transmission spectra 0.4-2.5 μm
  - First order detection and characterization of the main constituents of the Earth's atmosphere
  - Detection of the Ionosphere: Ca II, (Mg, Fe, ??)
  - Detection of O₂•O₂ and O₂•N₂ interactions
  - Offers more information than the reflectance spectra

- Using the measured Earth transmission spectrum and several stellar spectra, we compute the probability of characterizing a transiting earth with E-ELT
  - For a Earth in the habitability zone of an M-star, it is possible to detect H₂O, O₂, CH₄, CO₂ (= Life) within a few tens of hours of observations.
Thank you
Thank you
**Figure S4:** A detail of the umbra spectrum (broken line), the bright Moon spectrum (dotted line) and their ratio spectrum (umbra/bright) around the hydrogen alpha (Hα) line (0.6568 µm). The Hα solar line is a great example to illustrate the high S/N of our observations. In this figure, one can see that the Hα is present in the raw spectra of the umbra and the bright Moon, but not in the final transmission spectra. The S/N ratio in all the spectra is so large that the ratio umbra/bright completely removes any contribution from the solar spectrum and the local telluric atmosphere.
The Ring effect

Rotational Raman Scattering (RRS)

Early evidence:

Sky-scattered Fraunhofer lines were less deep but broader than solar lines

$\lambda_{ex} - \Delta \lambda, \lambda_{ex}, \lambda_{ex} + \Delta \lambda$

frequency redistribution

Incident $\lambda +$ Stokes +

Anti-Stokes branches

Incident exiting

$\lambda_{ex}$

incident photon
difference/
ratio
The Ring effect: Rotational Raman scattering

Vountas et al. (1998)

Transmission spectrum
Solar spectrum