Finding extraterrestrial life using ground-based high-dispersion spectroscopy

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de Kok R., le Poole R., Brogi M., Birkby J., Albrecht S., de Mooij E., Schwartz H., Di Gloria E., Hoeijmakers J., Keller C.
Exoplanet atmospheres

Transmission spectroscopy

Eclipse spectroscopy

Towards Earth
Ground-based High-dispersion spectroscopy

- At R=100,000 molecular bands are resolved in tens of individual lines.
- Strong doppler effects due to the orbital motion of the planet (up to >150 km/s).
- Moving planet lines can be distinguished from stationary telluric + stellar lines.
Observational technique and data analysis

Observing philosophy: no external calibration → removal of telluric features by “self calibration”

Retrieve signal by combining lines through cross-correlation

CRIRES →
CRIRES@VLT
Detection of CO in transmission of HD209458b
(Snellen et al. Nature 2010)

- Reveals planet orbital velocity
- Solves for masses of both planet and star (model independent)
- Evidence for blueshift (~2 km/sec [2σ] - high altitude winds?)
CRIRES@VLT

Detection of CO in dayside spectrum of tau Bootis b

(Matteo Brogi et al. Nature 2012 – see also Rodler et al. 2012)

First detection of non-transiting planet\(\rightarrow\) inclination, mass
CO in dayside spectra of hot Jupiters

Brogi et al. 2012
Brogi et al. 2013
De Kok et al. 2013

51 Peg Caveat: no detection on third night. Planet weather or instrumental issue?
Detection of H2O in HD189733b (Jayne Birkby et al. in prep.)

CRIRES@VLT Upgrade (2015) $\Rightarrow$ 6x larger wavelength coverage CO, H2O, CH4, NH3, H3+,.....
VLT ESPRESSO (Optical $\Rightarrow$ TiO, VO, FeH,.....)
Unique ELT Science in the JWST/EChO era

- HIRES (<2.5 μm) and METIS (>2.9 μm) R=100,000 → a SNR increase of factor 5-10
- High resolution spectroscopy gives unambiguous detections of molecules → every molecule has unique signature

Seager & Deming

TrES-4b Hot Jupiter day-side spectrum

CO dayside spectrum τ Bootis b
Unique ELT Science in the EChO/JWST era

- Determination of orbital inclination for up to 100 non-transiting planets \(\rightarrow\) masses
- Detection of the individual lines (instead of ensemble via cross-correlation) \(\rightarrow\) strong constraints on T/P profile; unambiguous detections of inversion layers
Unique ELT Science in the EChO/JWST era

- Line broadening $\rightarrow$ Planet rotation and circulation

Showman et al. 2012
Unique ELT Science in the EChO/JWST era

- Molecular spectra (CO, CO$_2$, H$_2$O, CH$_4$) as function of orbital phase $\rightarrow$ photochemistry, T/P versus longitude

Cho et al. 2003
Unique ELT Science in the EChO/JWST era

- Isotopologues? → evolution of planet atmosphere

$^{12}\text{C}^{16}\text{O}$
The Ultimate ELT Science Case: Characterizing twin-Eartths

- Too high background for 9.6 um Ozone
- H₂O, CO₂, CH₄ absorption in the same regions as telluric
- O₂ in transmission is possible!
**High-dispersion spectroscopy**

- **a.** Earth transmission spectrum around M5V star
- **b.** CO dayside spectrum τ Bootis b

<table>
<thead>
<tr>
<th>Stellar type</th>
<th align="right">$R_*$</th>
<th align="right">$M_*$</th>
<th align="right">$a_{HZ}$</th>
<th align="right">Prob</th>
<th align="right">$P_{HZ}$</th>
<th align="right">Dur.</th>
<th align="right">$I(\eta_e=1)$</th>
<th align="right">Line</th>
<th align="right">SNR</th>
<th align="right">Time</th>
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<td align="right">1.00</td>
<td align="right">1.000</td>
<td align="right">0.47</td>
<td align="right">365.3</td>
<td align="right">13</td>
<td align="right">4.4 - 6.1</td>
<td align="right">2×10^{-6}</td>
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<td align="right">7.3 - 9.1</td>
<td align="right">8×10^{-6}</td>
<td align="right">0.7-1.5</td>
<td align="right">20-90</td>
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<tr>
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<td align="right">1.4</td>
<td align="right">10.0-11.8</td>
<td align="right">5×10^{-5}</td>
<td align="right">0.7-1.7</td>
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</tr>
</tbody>
</table>

**Snellen et al. 2013**

- **Brightest expected systems**
- **SNR for ELT in 1 transit**