Exoplanet atmosphere Spectroscopy
present observations and expectations for the ELT

Hành tinh ngoài không khí phổ
quan sát và kỳ vọng đối với các kính viễn vọng
cực kỳ lớn

Ignas Snellen, Leiden University

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Challenges for Ground-based Observations

Measure $<10^{-3-4}$ variations in flux as function of $\lambda$ over 1-5 hour time scales

Transits and Secondary Eclipses

Earth Atmosphere:
- Variations in turbulence / seeing
- Variations in absorption & scattering
- Variations in thermal sky emission

Instrumental:
- Variations in gravity vector or field rotation
- Variations in thermal behaviour
Solutions for Ground-based Observations

Measure $<10^{-3-4}$ variations in flux as function of $\lambda$ over 1-5 hour time scales

Transits and Secondary Eclipses

Observe target + reference stars simultaneously

- Atmospheric variations similar for target & refs
- Different optical paths through telescope + instruments

Bean et al., *Nature* 2010

GJ1214b
Solutions for Ground-based Observations

High-Dispersion Spectroscopy ($\lambda/\Delta\lambda=100,000$)

- Molecular Bands are resolved in tens of individual lines
- Strong Doppler effects due to orbital motion of the planet (upto >150 km/sec)
- Moving planet lines can be distinguished from stationary telluric & stellar lines
HD209458b in transmission, CO -2.3 um

Detector 1 - Reduction Process

Step 1

Common wavelength-frame

Step 2

Telluric line removal-I

Step 3

Telluric line removal-II + column-scaling

Step 3 - 20x artificial CO
CO in transmission in HD209458b (CRIRES@VLT) (Snellen et al. *Nature* 2010)

- Reveals planet orbital velocity
- Solves for masses of both planet and star (model independent)
- Evidence for blueshift (high altitude winds?)
CO in dayside spectrum of tau Bootis b (CRIRES@VLT)
(Brogi et al. *Nature* 2012 – see also Rodler et al. 2012)

First detection of non-transiting planet → inclination, mass
CO in dayside spectra of hot Jupiters

Brogi et al. 2012

Brogi et al. 2013

De Kok et al. 2013

Birkby et al. 2013

HD189733b - Water!

CRIRES@VLT Upgrade (2015) → 6x larger wavelength coverage
CO, H2O, CH4, NH3, H3+,.....

VLT ESPRESSO (Optical → TiO, VO, FeH...)

Stepping-stone for the ELTs

Now also with Keck!
Lockwood et al. 2014
Carbon monoxide and water vapour in the atmosphere of the non-transiting exoplanet HD 179949 b

M. Brogi¹, R. J. de Kok¹,², J. L. Birkby¹, H. Schwarz¹, and I. A. G. Snellen¹

[Graphs and images showing data and analysis related to CO and water vapour in the exoplanet's atmosphere.]

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¹ Universiteit Utrecht, Netherlands
² Universiteit van Amsterdam, Netherlands
• Orbital inclinations and masses of >100 non-transiting planets
• Detection of the individual lines (instead of cross-correlation) → T/P profile; unambiguous detections of inversion layers
• Line broadening → planet rotation and circulation

Showman et al. 2012
Extremely Large Telescopes

- Molecular spectra (CO, CO2, H2O, CH4) as function of orbital phase → photochemistry, T/P versus longitude
- Isotopologues? → evolution of planet atmosphere
The Ultimate ELT Science Case: Characterizing twin-Earths

- too high background for 9.6 um Ozone
- $O_2$ in transmission is possible!

Remco de Kok
Extremely Large Telescopes

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**Table:**

<table>
<thead>
<tr>
<th>Stellar type</th>
<th>R* (R_\odot)</th>
<th>M* (M_\odot)</th>
<th>a_{HZ} (au)</th>
<th>Prob [%]</th>
<th>P_{HZ} (days)</th>
<th>I (η_e=1)</th>
<th>Line</th>
<th>SNR</th>
<th>Time (yrs)</th>
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<tbody>
<tr>
<td>G0-G5</td>
<td>1.00</td>
<td>1.00</td>
<td>1.000</td>
<td>0.47</td>
<td>365.3</td>
<td>13</td>
<td>4.4 - 6.1</td>
<td>2×10(^{-6})</td>
<td>1.1-2.5</td>
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<tr>
<td>M0-M2</td>
<td>0.49</td>
<td>0.49</td>
<td>0.203</td>
<td>1.12</td>
<td>47.7</td>
<td>4.1</td>
<td>7.3 - 9.1</td>
<td>8×10(^{-6})</td>
<td>0.7-1.5</td>
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<tr>
<td>M4-M6</td>
<td>0.19</td>
<td>0.19</td>
<td>0.058</td>
<td>1.52</td>
<td>11.8</td>
<td>1.4</td>
<td>10.0-11.8</td>
<td>5×10(^{-5})</td>
<td>0.7-1.7</td>
</tr>
</tbody>
</table>

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**Figure a:**

- **O_2 Earth transmission spectrum around M5V star**

**Figure b:**

- **CO dayside spectrum τ Bootis b**

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**Notes:**

- Brightest expected systems
- SNR for ELT in 1 transit

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Snellen et al. 2013
Life after the ELTs?
Flux Collector Telescopes

• ELTs optimised for sensitivity, angular resolution over large FOV.
• Only collecting area is important for HR spectroscopy
• Bright stars require PSF of 5-10”
• Spectrograph design → extreme slicing for Echelle?
Arrays of dedicated flux collectors with high-dispersion spectrographs can provide the collecting area needed to perform a statistical study of life-bearing planets in the solar neighborhood

I. Snellen, R. De Kok, R. Le Poole, M. Brogi, J. Birkby, 2013
What about dayside spectroscopy?
Combining High-Dispersion Spectroscopy (HDS) with High Contrast Imaging (HCI)

Classical HDS

\[ \text{Limits: } 10^{-5} \text{ with VLT} \]

\[ \text{SNR} = \frac{S_{\text{planet}}}{\sqrt{S_{\text{star}} + \sigma_{bg}^2 + \sigma_{RN}^2}} \]

HDS + HCI

\[ \text{Limits: } 10^{-5}/\sqrt{K} \text{ with VLT} \]

\[ \text{SNR} = \frac{S_{\text{planet}}}{\sqrt{S_{\text{star}}/K + \sigma_{bg}^2 + \sigma_{RN}^2}} \]

How far can we push this with the ELTs?
All the light in this image has the spectrum of the star, except that from the planet. Speckles can be removed (down to $<10^{-5}$ level).

This idea is **not** new (at lower resolution).
Sparks & Ford 2003
Konopacky et al. 2013

Comparison to “classical” high-contrast imaging

Here SDI and ADI work well.

Kuzuhara et al. 2013, K-band
E-ELT simulations - CASE 1
A Super-Earth in the Habitable Zone of Cen A at 4.85 um

METIS+E-ELT PSF simulation in M-band (Strehl=0.9), baseline METIS set-up. 30 hours Earth-spectrum, T=300 K, 1.5 R_earth.
CASE 2: A Super-Earth in the Habitable Zone of Proxima

E-ELT (Strehl=0.5), 10 hours, \( R=100,000 \), \( \Delta \lambda = 600 – 900 \) nm
Earth-spectrum, \( T=280 \) K, 2 \( R_{\text{earth}} \).

Planet spectrum is a copy of that of the star, but velocity shifted
METIS @ E-ELT, Snellen et al. In prep.
Can we test this with current instrumentation?

Snellen, Brandl, de Kok, Brogi, Birkby, Schwarz

*Nature* – May 1st issue

Emargoed
Beta Pictoris b – CRIRES@VLT

Mass = 11 (+-5) Mjup
Radius ~ 1.65 Rjup
Orbit: 17-20 years
1 hour DDT time (1-1.3” seeing)
22x4x10 seconds
Fast spin of a young extrasolar planet

Snellen et al. - embargoed
Fast spin of a young extrasolar planet  

*Snellen et al.* - embargoed

Length of Day on Beta Pictoris b = ~8 hours