Biogenic O$_2$ detection on the Earth observed as a transiting exoplanet and perspectives with future ELTs for nearby Earth twins

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Aims:
- Characterize the Earth seen as a transiting planet (its atmospheric signature, biogenic species, etc.)
- Compare with / validate the model(s)
- Provide inputs for future observations, with larger telescopes (E-ELT).

Follow-up of first test observations with SOPHIE, August 2008 lunar eclipse (Vidal-Madjar et al 2010)

New results from HARPS and UVES dec. 2010 lunar eclipse
The Earth eclipses the Sun or *transits* across the Sun ...
Full moon spectrum \( F(\lambda) \)

Eclipse (penumbra) spectrum \( E(\lambda) \)

\[
E(\lambda) = F(\lambda) \times \frac{S - L \times h(\lambda)}{S_\odot}
\]

(Vidal-Madjar et al. 2010)

where \( S_\odot = \text{surface of the solar disk} \)

\( S = \text{surface of the solar crescent} \)

\( L \times h(\lambda) = \text{surface of the arc of Earth atmosphere in front of the Sun} \)

\(-\) if we are interested in \( h(\lambda) \) \(-\) we need to know \( S \) and \( L \)!
$S$ is easily retrieved from flux ratio at an unabsorbed wavelength $\lambda_0$ for which $h(\lambda_0)=0$:

$$E(\lambda_0) = F(\lambda_0) \times \frac{S}{S_\odot}$$

- Once $S$ is known, the length $L$ can be calculated
- **we are interested in $h(\lambda)$, and $S$ and $L$ are now known!**
In practice:
• Correct $S$ for Limb Darkening (even for $LD(\lambda)$, Hestroffer & Magnan 1998)

• To fix the solar crescent at a given size $S$ during the exposures, the telescope has to track neither the stars nor the Moon, but a point *attached* to the Penumbra -> the Moon shifted in front of the spectrograph -> correct $E$ and $F$ for moon albedo variations along the slit path with Clementine data:

*Reconstructed path of HARPS fibers over the Moon during one of the exposures.*
• We want to correct all spectra for the signature of the atmosphere above the telescope

\[ T(\lambda) = \left[ \frac{F_1^{AM_1}(\lambda)}{F_2^{AM_2}(\lambda)} \right]^{1/(AM_1-AM_2)} \]

Fig. 4. La Silla atmosphere transmission function \( T(\lambda) \) for \( AM = 1 \)

Fig. 7. Paranal atmosphere transmission function \( T(\lambda) \) for \( AM = 1 \)
Calculation of $h(\lambda)$: 2 methods

• 1/ from one penumbra spectrum (Arnold et al. 2014)

$$h(\lambda) = \left( 1 - \frac{E_A(\lambda)}{E_A(\lambda_0)} \times \frac{F_A(\lambda_0)}{F_A(\lambda)} \right) \times \frac{S_A}{L_A}$$

• 2/ from a pair of penumbra spectrum (SOPHIE has 2 fibers! Vidal-Madjar et al. 2010)

$$\left( \frac{E_A(\lambda)}{E_A(\lambda_0)} \times \frac{F_A(\lambda_0)}{F_A(\lambda)} - \frac{E_B(\lambda)}{E_B(\lambda_0)} \times \frac{F_B(\lambda_0)}{F_B(\lambda)} \right) = \left( \frac{L_B}{S_B} - \frac{L_A}{S_A} \right) \times h(\lambda)$$

$\Rightarrow$ Vidal-Madjar et al. 2010 == difference between spectra gives better results
RESULTS

Signatures from:
• O₂
• Na
• Ozone: Chappuis band
• Rayleigh signature
Not detected (or barely):
• Water vapour
• In green:
  Ehrenreich et al. 2006 model
PRINCIPLE

A 3rd method: *direct measurement* of the Earth radius versus wavelength!
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*But this method is biased by refraction (use of photons from the Umbra = refracted photons, which are lost in a real transit)*

Refraction of red light in the deep atmospheric layers makes the Earth smaller than reality in the red!

Fortunately, it can be corrected (at least partially)
RESULTS

HARPS

UVES
RESULTS

- HARPS and UVES detect O3, O2, Water (> 7000Ang), Na, Rayleigh scattering
- O2 A-band peaks at about 30 km above the continuum

DISCUSSION

- Observation in acceptable agreement with the models (Ehrenreich et al. 2006)

Refraction slightly reduces the effective height for a exoplanet transit (Bétrémieux & Kaltenegger 2014, submitted)
DISCUSSION

The big question: Will O$_2$ A-band (7600 Ang) be detectable with the E-ELT?

- Model from Hedelt et al. 2013 A&A
- G2V star @ 10 pc, 1 single transit
- E-ELT 39m telescope
- Detector CCD charact. from EPICS
- Broad filters (selecting O$_2$-A etc.)

Assuming *perfect sky, no atmospheric perturbation*

Use High-Resolution Spectroscopy to better isolate the exo O$_2$ from the terrestrial O$_2$, and benefit from the numerous O$_2$ lines in the A-band (Vidal-Madjar et al. 2010, Snellen et al. 2013, Rodler & Lopez-Morales 2014, ...)

DISCUSSION

- Improve duty cycle
- Use Image slicer
  
  Reduce time from 33-65 to approx. 3 years without red noise

From Rodler & Lopez-Morales 2014:
- For red noise level = 40% white noise -> x 2 the required observing time
- Target observability constraints (airmass >2, night time etc.)

>> 10 years at least ?
CONCLUSION

• Observations of the Earth as a transiting planet confirm the model
• O₂ is detected for Earth

• Will O₂ be detectable on an nearby Earth twin around a G2V star with ground based ELTs?

• If we are lucky enough to detect a Earth-like planet around a nearby solar-like star...
  • probably >>10 transits (10 years) will be needed
    • High-resolution spectroscopy O₂
    • Needed (?)
      • dedicated instrument (not CCD-based?)
      • progress in real-time atmospheric monitoring (LIDAR)