Study of synthetic observables in reflexion spectroscopy for next-generation instruments at the ELT

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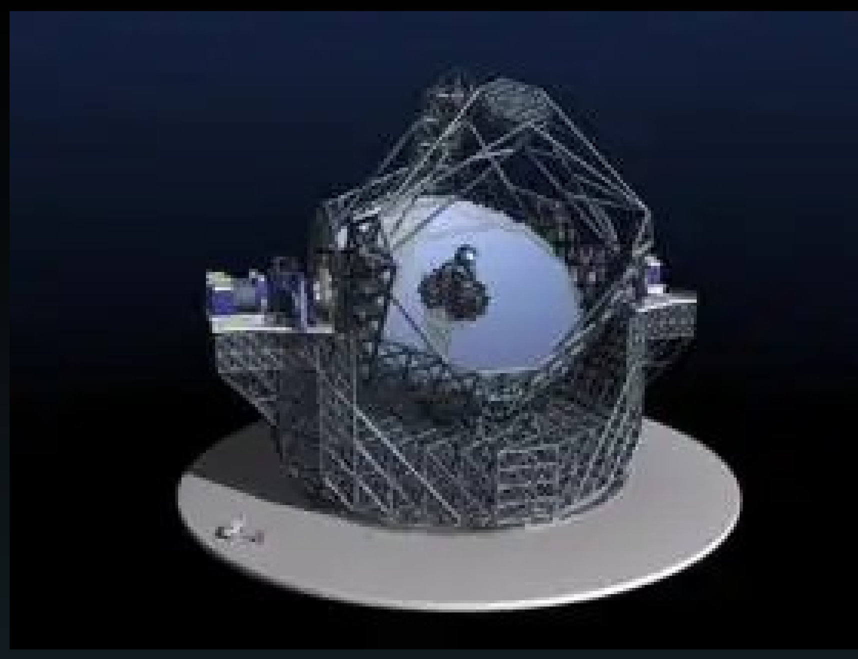


I. Context

The characterization of **exoplanetary atmospheres** has already began with the JWST or HST, using the transit method. However, stronger constraints will arise from **reflexion spectroscopy**, thanks to an important work on instrumentation and target definition (**Golden Sample for ANDES & PCS**). Indeed, ANDES itself is planned to reach a **spectral resolution** of 100 000. Preparing such observations requires a preliminary work of studying **synthetic observables**.

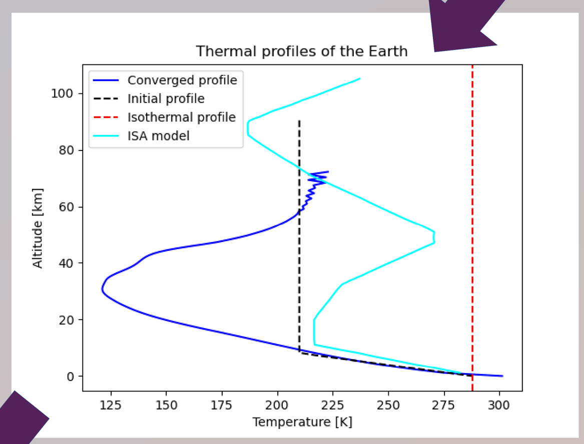
II. Methodology

Atmospheric and opacity data

Exo_k

- Exo_k **[2]** for climate modeling

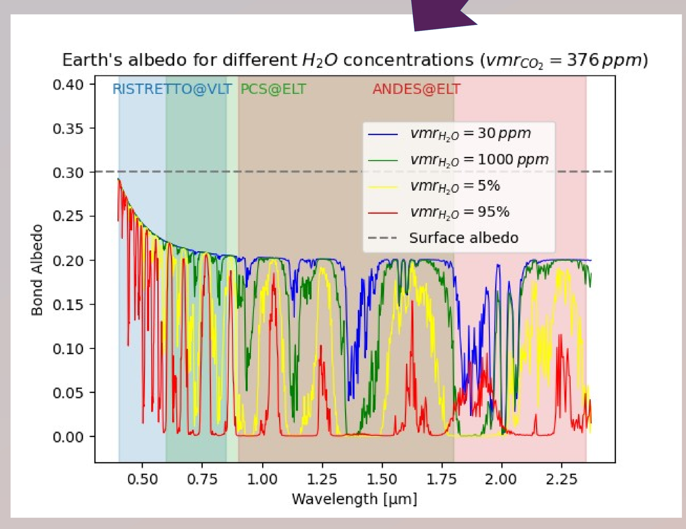
- Pytmosph3r **[3]** for radiative modeling



Thermal profiles of the earth for different parametrization of the atmosphere

Thermal profile

Pythmosph3r



Spectral albedo of the Earth depending on the water vapor concentration

Final spectral albedo

III. Opacity Data

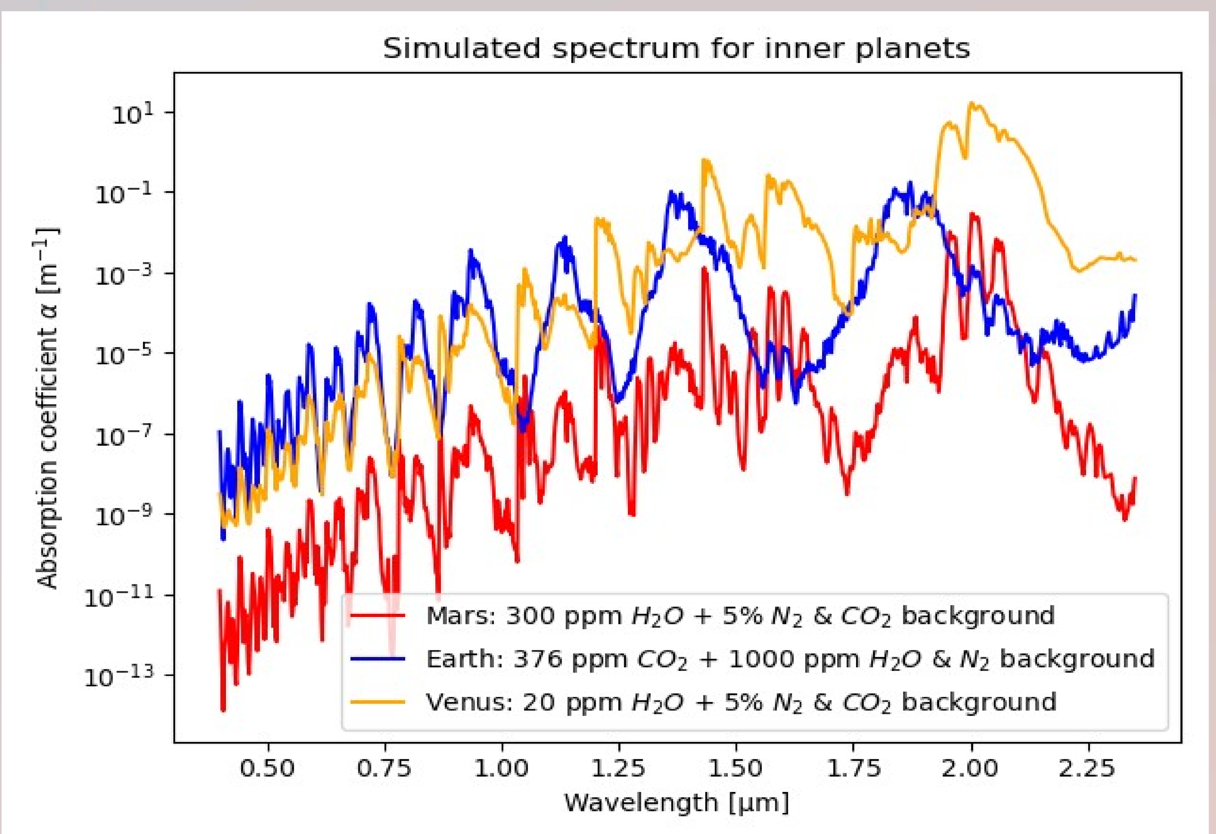
To probe a large panel of gas mixtures, I used several **correlated-k** tables and **CIA** tables derived from SpeCT **[1]**.

- Chemical species : **CO_2 -- H_2O – N_2**

- Spectral interval : **[0.4 μm, 2.4 μm**] linked to the spectral range of **RISTRETTO**, **ANDES** and **PCS**.

- Final absorption in m^{-1} from the sum of the **two contributions** (C_k in m² and $C_{i,j}$ in $cm^{-1}.amagat^{-2}$) :

$$k_{abs} = k_{corrk} + k_{cia} = C_k.\left(\frac{p}{k_b.T}\right) + 100.\left(\frac{273.15 \times p}{101325 \times T}\right)^2.\sum_{i,j} C_{i,j} x_i x_j$$



Total absorption spectrum of the Earth, Venus and Mars

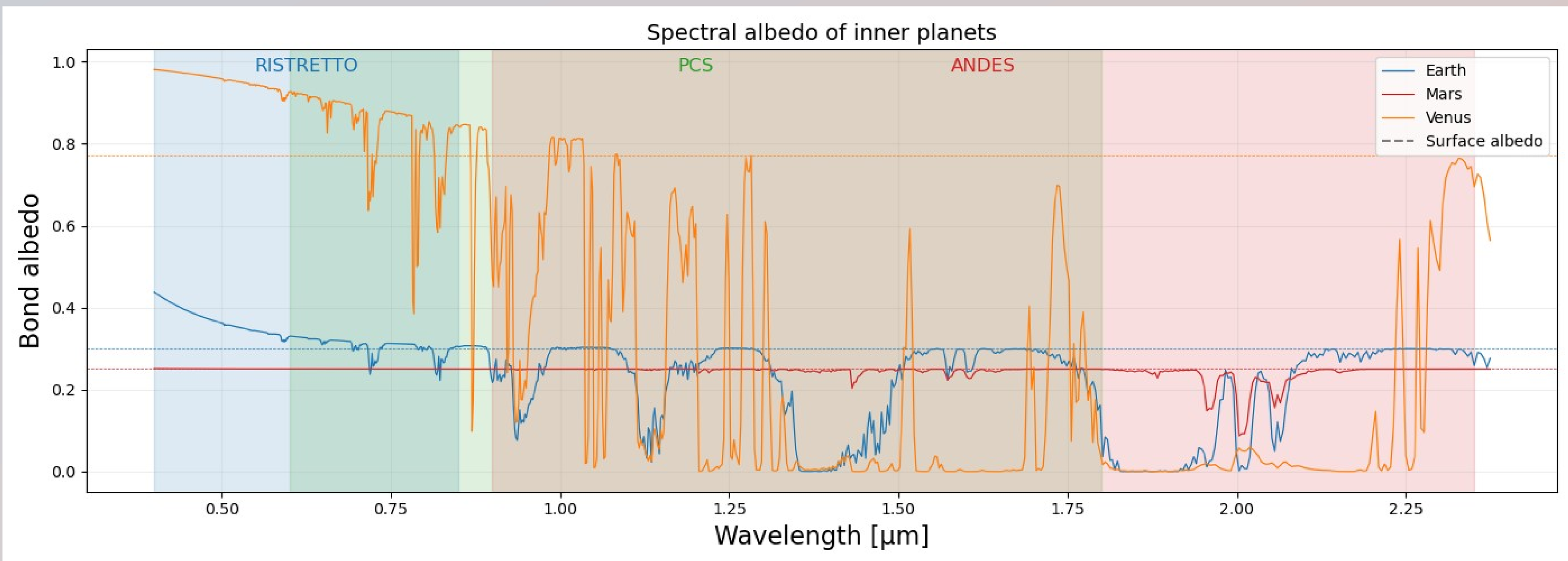
IV. Albedos

We derive the **Bond albedo** of the three studied planets, thanks to there known visible surface albedo (extended in near IR) :

- Earth : large water bands, **Rayleigh scattering** at low wavelength, several transparency windows

- Venus : high Rayleigh scattering from dense and hot CO_2 atmosphere, complete saturated windows
→ **call for line wings study**

- Mars : mostly transparent, shallow water bands, major CO_2 bands around 2 µm
→ **call for line cores study**

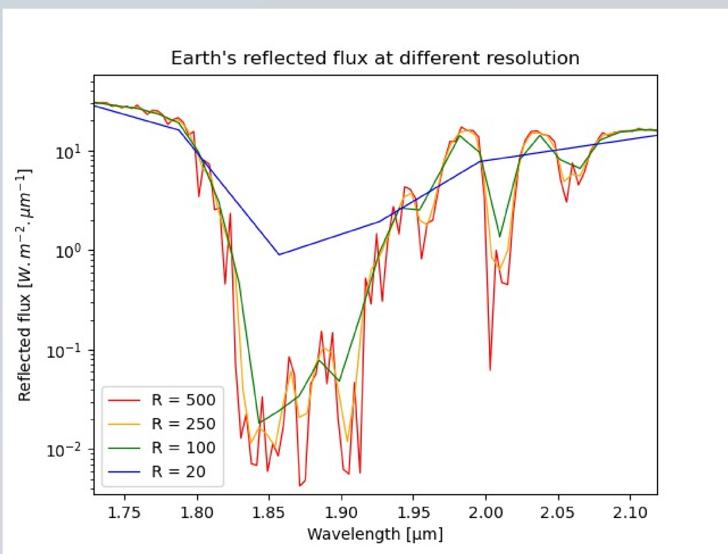


Spectral Bond albedo of the three studied planets, with their constant surface albedo in dotted curve

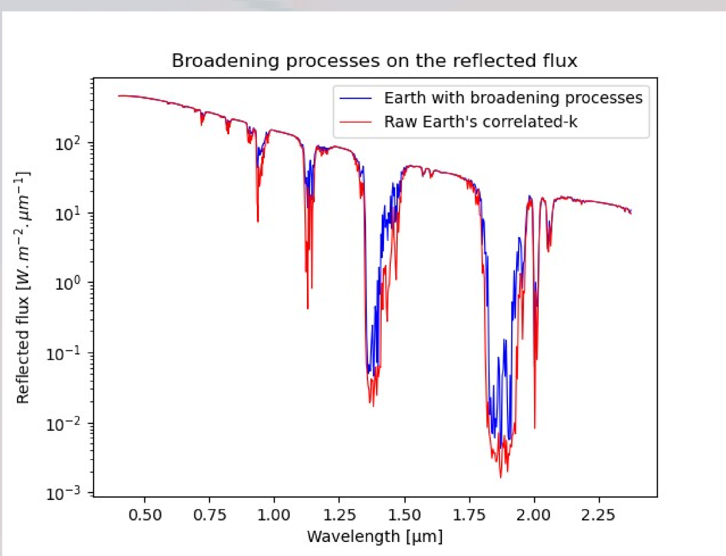
V. Spectral Information

Resolution

Spectral resolution is, with the **planet-to-star contrast**, the main limits for reflexion spectroscopy. It's always an equilibrium between high spectral precision and data volume. Here, our opacity tables have a resolution **R = 500**. Downgrading this value allows us to demonstrate how secondary spectral information, **especially line wings for saturated albedos**, disappear easily at medium resolution. For my incoming PhD, working with tables at R = 100 000 will show the power of such resolution for faint molecular line core or wing.



Reflected flux of the Earth zoomed on the 1.9 µm water band, for different spectral resolutions



Reflected flux of the Earth depending on the presence of broadening processes

Broadening

Additionally to **ro-vibrationnal absorption rays**, several secondary absorption processes can modify the final spectrum. Some of them are known as **broadening processes**. They include the thermal Doppler broadening, collisional broadening, pressure broadening…

Their effect in opacity tables is often absent, for simplicity. However, we show that negliging them bring decent error on the final reflected flux (**red curve overestimates the depth of water bands**), even for the thin Earth's atmosphere.

Broadening processes matter !

VI. Conclusion

This whole methodology is **redundant**. Studying exoplanets will give new insights on their atmospheric structures, enabling our work to become more precise, enabling **closer fits with the observed spectral albedos**.
Line wings cannot be forgotten, as they provide most of the **spectral information** for dense atmospheres.
Finally, reaching high resolution values, with instruments such as ANDES or PCS, will uncover **tremendous amount of new molecular lines, even in dense line cores**.

Observatoire de Paris

Key references : *[1] Chaverot+2025, [2] Leconte 2021, [3] Falco+2022 & Lovis+2017*

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