Hands-on: Exoplanet atmospheres with SPIRou

Baptiste Klein, Benjamin Charnay & Florian Debras

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Atmospheric characterisation at high spectral resolution for transit spectroscopy

- Distinguish planetary signal from telluric and stellar lines thanks to intrinsic molecular lines and doppler shift
- Cross-correlation between the high-passing observed spectrum $S_{obs}$ and a model spectrum $S_{th}$

**Detection of a planetary signal from cross-correlation at high resolution**

**Atmospheric characterisation with MCMC calculation from cross-correlation at HR**

\[
CCF(dV_0) = \sum_i \frac{S_{obs}(\nu_i) \times S_{th}(\nu_i + \nu_i \times dV_0 / c)}{\sigma_i^2}
\]
Objectives of the hands-on session

Goals:

• Detect the planetary signal and molecules from two exoplanets (a hot Jupiter and a warm sub-Neptune), whose signal has been injected in SPIRou data
• Test the influence of the planetary rotation and atmospheric superrotation

Methods:

1) Inject the planetary signal in SPIRou data of Gl15A
2) Data reduction to remove telluric and stellar contamination
3) Retrieve the planetary signal and molecules

\[
F_{\text{in}}(t, \lambda) = T_{\text{atm}}(t, \lambda) \times F_{\text{star}}(t, \lambda) \times \left(1 - \left(\frac{R_p(\lambda)}{R_{\text{star}}}\right)^2\right)
\]

Key steps are:

- Division by the out-transit spectrum:  \( F_{\text{out}}(t, \lambda) = T_{\text{atm}}(t, \lambda) \times F_{\text{star}}(t, \lambda) \)
- Division by the smoothed spectrum
- Detrending with airmass and filtering correlated noise with PCA
- Cross-correlation with model spectra
Jupyter notebook

- Download the notebook and all files at: [https://github.com/baptklein/Tutorial_atmosphere](https://github.com/baptklein/Tutorial_atmosphere)
- For your laptop, you need: python (version 3 preferentially) jupyter, astropy and scipy
- Otherwise, use sciserver (https://apps.sciserver.org/dashboard/): create an account and upload all files in tmp.
Injected planets

**Gl15A:**
SPIRou data (PI: Donati), date: 2020-10-08
Spectral type= M2
Mag(K) =4.02
R\_star=0.386R\_Sun
V0 = 11.73 km/s #Stellar Systemic velocity

**Hot Jupiter:**
R\_p=10.9 R\_Earth
T\_eq=1500K
Metallicity= 1xsolar
Ks = 154 km/s #Planet semi-amplitude
P\_orb = 2.22 d #Planet orbital period

**Warm sub-Neptune:**
R\_p = 3 R\_Earth
T\_eq = 600K
Metallicity = 30xsolar
Ks = 62 km/s #Planet semi-amplitude
P\_orb = 2.22 d #Planet orbital period

Equilibrium temperature:
\[ T_{eq}^4 \propto a^{-2} \]

Planet semi-amplitude:
\[ K_p = \sqrt{GM_s/a} \propto a^{-0.5} \]
\[ K_p \propto T_{eq}^{-1} \]

Variation of transit depth:
\[ \Delta \delta_{tra} \propto \frac{R_p H}{R_*^2} \]

For Gl15A:
- Hot Jupiter (T=1500 K, g=25 m s\(^{-2}\), M=2.3 g/mol): \( \delta_{tra} \approx 0.07 \), \( \Delta \delta_{tra} \approx 2 \times 10^{-3} \)
- Warm Neptune (T=600 K, g=10 m s\(^{-2}\), M=3.0 g/mol): \( \delta_{tra} \approx 5.10^{-3} \), \( \Delta \delta_{tra} \approx 4 \times 10^{-4} \)
Atmospheric model

Calculation of TP profiles and chemical composition with Exo-REM

**Exo-REM model:**
- 1D radiative-convective model
- Iterative model
- non-equilibrium chemistry
- opacities with kcoefficients
- Clouds with simple microphysics or fixed radii
- Emission/transmission spectra (R=50-20000)

(Baudino et al. 2015, Charnay et al. 2018, Blain et al. 2020)

Exo-REM available at: https://gitlab.obspm.fr/dblain/exorem

Reference: (1) Rey et al. (2017); (2) Rothman et al. (2010); (3) Bernath (2020); (4) Azzam et al. (2016); (5) Harris et al. (2006); (6) Kramida et al. (2019); (7) Coles et al. (2019); (8) Yurchenko (2015); (9) Sousa-Silva et al. (2014); (10) Schwenke (1998); (11) McKemmish et al. (2016)
Planetary spectra and molecular templates

HR spectra computed with a line-by-line model (same opacities as Exo-REM)

Example: PetitRadTrans (https://petitradtrans.readthedocs.io/en/latest/)
Atmospheric characterisation at medium/high spectral resolution

- **Low resolution:** \( R = \frac{\lambda}{\Delta \lambda} < 1000 \) (e.g. HST, ARIEL)
  → absorption bands

- **Medium resolution:** \( R = \frac{\lambda}{\Delta \lambda} \sim 1000 - 20000 \) (e.g. JWST, VLT/SINFONI)
  → strong molecular lines

- **High resolution:** \( R = \frac{\lambda}{\Delta \lambda} > 20000 \) (e.g. SPIRou, VLT/CRIRES, VLT/ESPRESSO)
  → resolve line shape and doppler shift