Hands-on:
Exoplanet atmospheres with SPIRou

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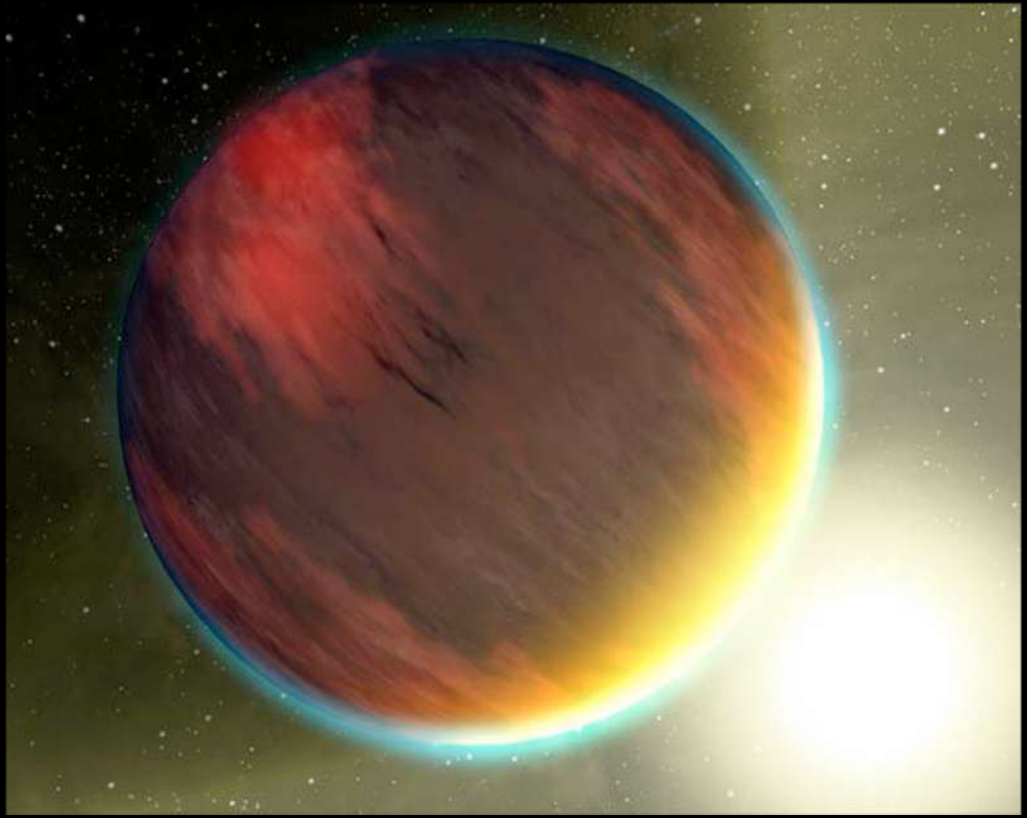


Ecole Evry Schatzman 2021

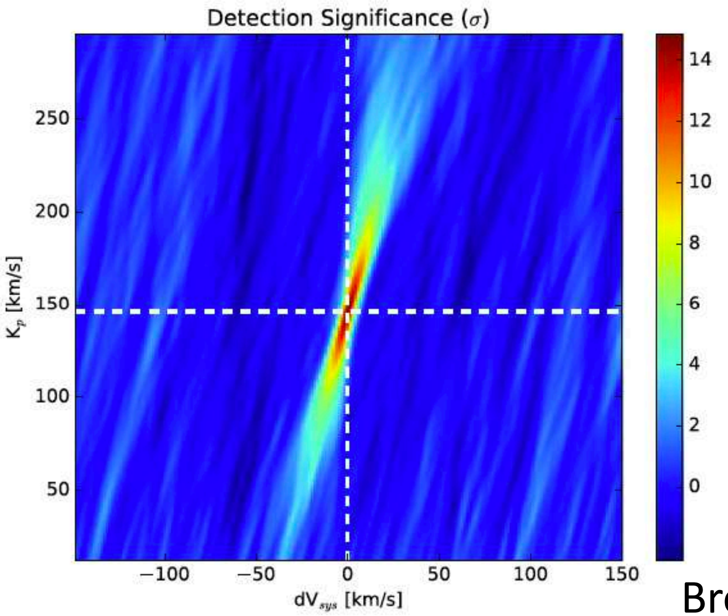
Atmospheric characterisation at high spectral resolution

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}

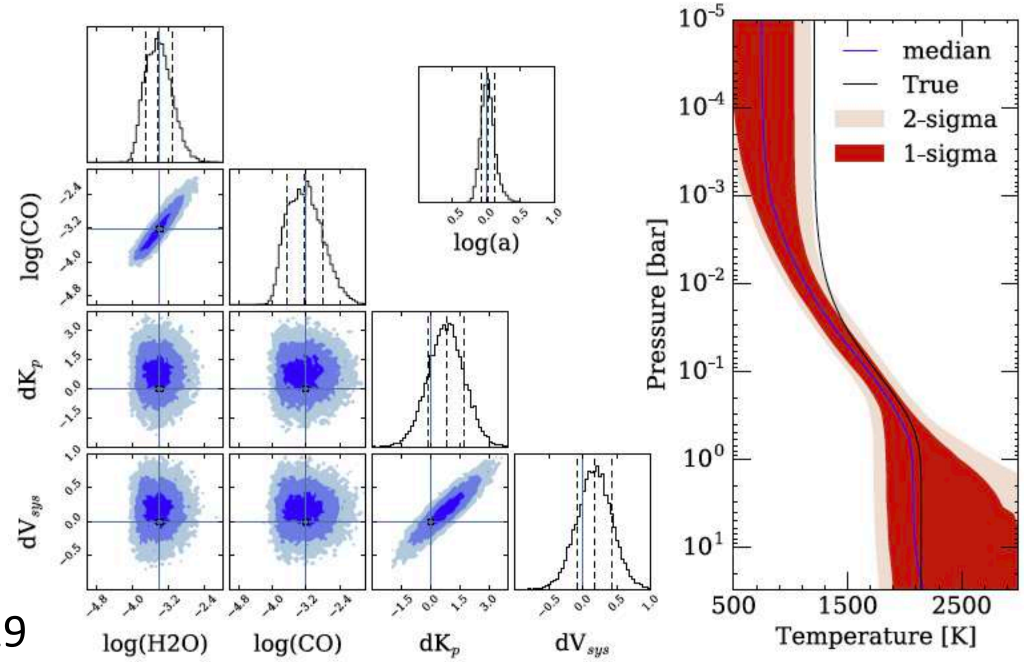
$$CCF(dV_0) = \sum_i \frac{S_{obs}(\nu_i) \times St_h(\nu_i + \nu_i \times dV_0/c)}{\sigma_i^2}$$

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



Brogi & Line 2019

Atmospheric characterisation with MCMC calculation from cross-correlation at HR



Objectives of the hands-on session

SPiRou

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**

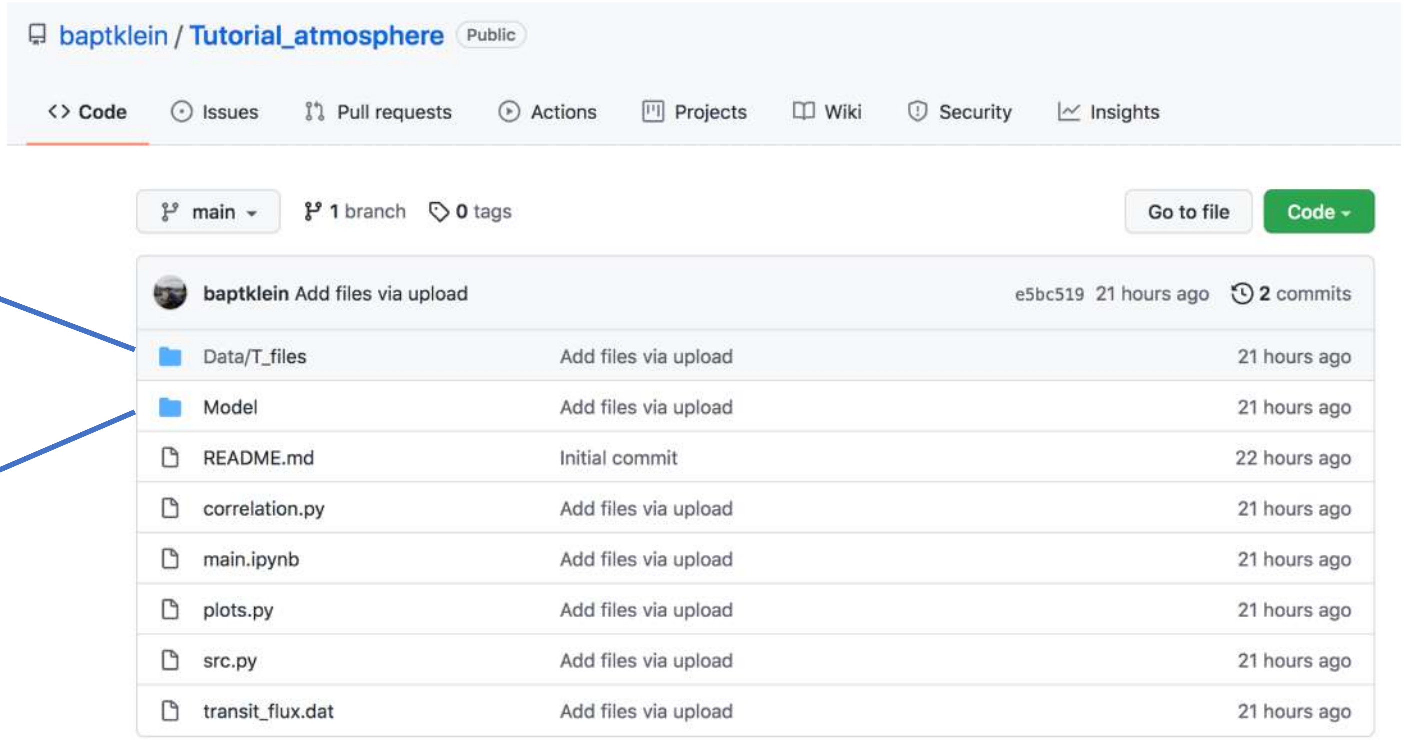
$$\underbrace{F_{in}(t,\lambda)}_{\text{Flux during transit}} = \underbrace{T_{atm}(t,\lambda)}_{\text{Atmospheric transmission}} \times \underbrace{F_{star}(t,\lambda)}_{\text{Stellar flux}} \times \left(1 - \underbrace{\left(\frac{R_p(\lambda)}{R_{star}}\right)^2}_{\text{Transit depth}}\right)$$

Key steps are:

- Division by the out-transit spectrum: $F_{out}(t,\lambda) = T_{atm}(t,\lambda) \times F_{star}(t,\lambda)$
- 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
- 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.



SPIRou data of Gl15A

Planetary spectra and molecular templates

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

Equilibrium temperature:

$$T_{eq}^{4} \propto a^{-2}$$

Planet semi-amplitude:

$$K_p = \sqrt{GM_s/a} \propto a^{-0.5}$$

$$\Rightarrow K_p \propto T_{eq}^{-1}$$

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

Variation of transit depth:

$$\Delta\delta_{tra} \propto \frac{R_P H}{R_\star^{2}}$$

For Gl15A :
- Hot Jupiter (T=1500 K, g=25 m s^{-2}, M=2.3 g/mol): $\delta_{tra} \approx 0.07$, $\boldsymbol{\Delta\delta_{tra} \approx 2.10^{-3}}$
- Warm Neptune (T=600 K, g=10 m s^{-2}, M=3.0 g/mol): $\delta_{tra} \approx 5.10^{-3}$, $\boldsymbol{\Delta\delta_{tra} \approx 4.10^{-4}}$

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

$^{12}CH_4$, $^{13}CH_4$, $^{12}CH_3D$ → CH_4

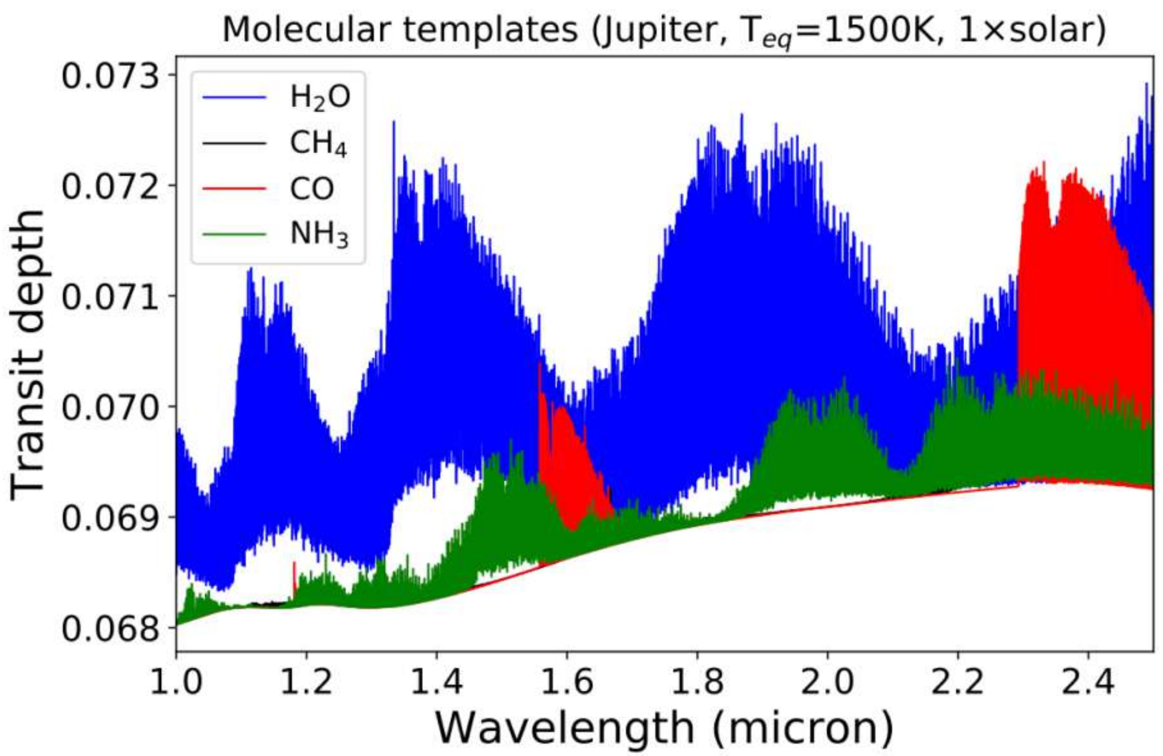
Species	Wavenumber range (cm^{-1})	$\Delta\nu$ (cm^{-1})	Intensity cutoff ($cm \cdot molecule^{-1}$)	Lines references
CH_4	30 – 13330	250	10^{-36} at 2000 K	TheoReTS (1)
CO	30 – 8330	120	10^{-27} at 3000 K	HITEMP (2)
CO_2	30 – 8130	120	10^{-25} at 3000 K	HITEMP (2)
FeH	30 – 14830	120	10^{-30} at 4000 K	ExoMol (3)
H_2O	30 – 26430	120	10^{-27} at 2000 K	HITEMP (2)
H_2S	30 – 10830	120	10^{-27} at 2000 K	ExoMol (4)
HCN	30 – 12530	120	10^{-25} at 3000 K	ExoMol (5)
K	1030 – 50030	9000	10^{-27} at 2500 K	NIST (6)
Na	1030 – 50030	9000	10^{-27} at 2500 K	NIST (6)
NH_3	30 – 11830	120	10^{-30} at 1500 K	ExoMol (7, 8)
PH_3	30 – 9830	120	10^{-30} at 2500 K	ExoMol (9)
TiO	230 – 29230	120	10^{-30} at 4000 K	ExoMol (10)
VO	30 – 19830	120	10^{-30} at 4000 K	ExoMol (11)

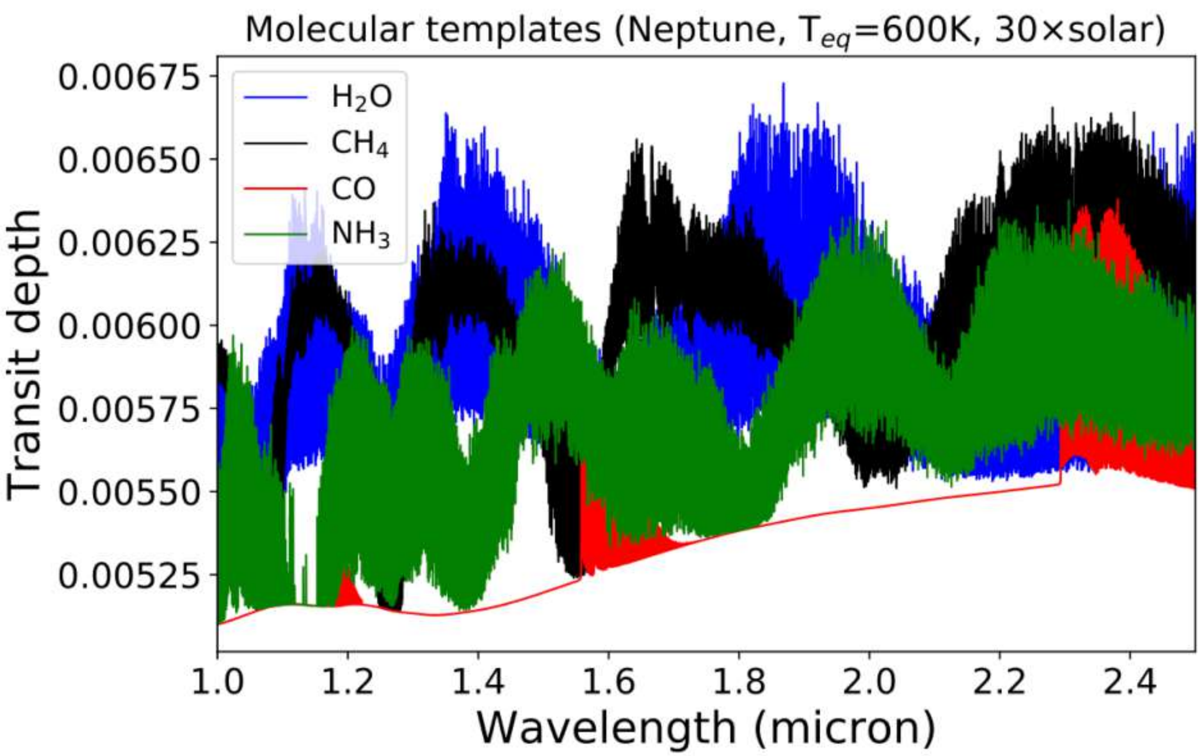
References. (1) Rey et al. (2017); (2) Rothman et al. (2010); (3) Bernath (2020); (4) Azzam et al. (2016); (5) Harris et al. (2006); (6) Kramida et al. (2019); (7) Coles et al. (2019); (8) Yurchenko (2015); (9) Sousa-Silva et al. (2014); (10) Schwenke (1998); (11) McKemmish et al. (2016).

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