Are we ready to characterize exoplanet atmospheres with the James Webb Space Telescope observations ?

Jean-Loup Baudino[1] , Pierre-Olivier Lagage[2], Patrick Irwin[1] , Paul Mollière[3], Pascal Tremblin[2]

1: University of Oxford, 2: CEA Saclay, 3: MPIA Heidelberg

September 22, 2017

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Why this title ?

Why ?

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Future instruments to detect and characterise extrasolar planets

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JWST

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- spectroscopy in NIR and MIR

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Analysing observations with something:

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Analysing observations with something:

Models

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Analysing observations with something:

Models

- forward, retrieval

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Future instruments to detect and characterise extrasolar planets

JWST

- spectroscopy in NIR and MIR
- high resolution, S/N

Analysing observations with something:

Models

- forward, retrieval
- hypothesis, unknowns ???

JWST

October 2018

JWST

October 2018

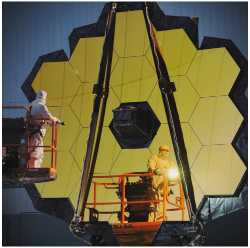
- NASA, ESA, CSA-ASC, 6.5 m

JWST

October 2018

- NASA, ESA, CSA-ASC, 6.5 m
- 4 instruments, 4 main topics (including exoplanet)

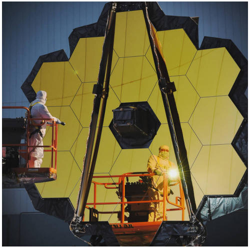
JWST



NASA-C. Gunn

Exoplanet characterisation

JWST

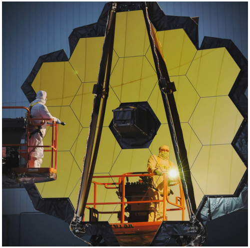


NASA-C. Gunn

Exoplanet characterisation

- Direct imaging (DI) and transit

JWST



NASA-C. Gunn

Exoplanet characterisation

- Direct imaging (DI) and transit
- photometry and spectroscopy, 0.6-13 microns

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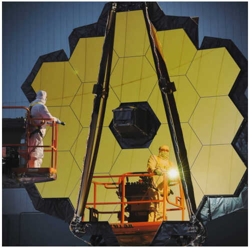
JWST



NASA-C. Gunn

Exoplanet characterisation

- Direct imaging (DI) and transit
- photometry and spectroscopy, 0.6-13 microns
- 2 instruments developed in Europe: NIRSpec and MIRI

JWST S/N

Expected in good cases, for spectroscopy with NIRSpec and MIRI

Baudino et al. submitted to ApJ

JWST S/N

Expected in good cases, for spectroscopy with NIRSpec and MIRI

- DI: S/N=100 (30 min)

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JWST S/N

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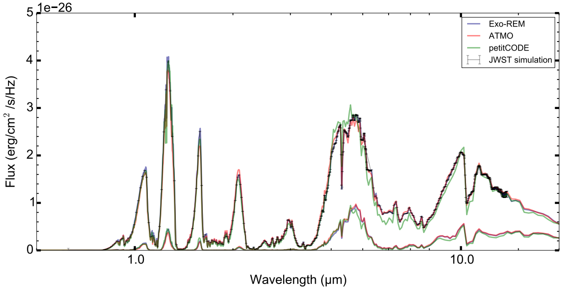

Emission spectra of VHS 1256-1257 b (top) and GJ 504 b (bottom). The black uncertainties correspond to the combination of simulated NIRSpec/Prism and MIRI/LRS noise level for VHS 1256-1257 b for 0.5 hour of integration.

Baudino et al. submitted to ApJ

Models

Forward

Models

Forward

Retrieval

Models

Forward

- compute the thermal and chemical structure of a planet

Retrieval

Models

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- compute the thermal and chemical structure of a planet
- generate spectra and profiles consistent with radiative-convective equilibrium and chemistry

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Retrieval

- solve the inverse problem

Models

Forward

- compute the thermal and chemical structure of a planet
- generate spectra and profiles consistent with radiative-convective equilibrium and chemistry

Retrieval

- solve the inverse problem
- find the combination of abundances and parameters that reproduces the observations

Problems

Various approaches, hypothesis, opacity sources

Problems

Various approaches, hypothesis, opacity sources

Identify

Find the differences:

Problems

Various approaches, hypothesis, opacity sources

Identify

Find the differences:

- emission and transmission

Problems

Various approaches, hypothesis, opacity sources

Identify

Find the differences:

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- abundances

Problems

Various approaches, hypothesis, opacity sources

Identify

Find the differences:

- emission and transmission
- abundances

Benchmark

To define a minimal agreement between models to be able to find the differences.

Benchmark protocol

Baudino et al. submitted to ApJ

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Benchmark protocol

A restrain number of absorbers

Baudino et al. submitted to ApJ

Benchmark protocol

A restrain number of absorbers

- NH_3, CH_4, CO, CO_2, H_2O, PH_3, Na, K

Baudino et al. submitted to ApJ

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Benchmark protocol

A restrain number of absorbers

- NH_3, CH_4, CO, CO_2, H_2O, PH_3, Na, K
- H_2–H_2 and H_2–He CIA

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Alkali wing shape

Voigt profile

Baudino et al. submitted to ApJ

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Alkali wing shape

Voigt profile

Elemental abundances

Solar (Asplund et al. 2009)

Baudino et al. submitted to ApJ

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Alkali wing shape

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Solar (Asplund et al. 2009)

same chemical reactions

Baudino et al. submitted to ApJ

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Benchmark protocol

A restrain number of absorbers

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Alkali wing shape

Voigt profile

Elemental abundances

Solar (Asplund et al. 2009)

same chemical reactions

no cloud

Baudino et al. submitted to ApJ

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Two kinds of test

Baudino et al. submitted to ApJ

Two kinds of test

Imposed temperature profile

Baudino et al. submitted to ApJ

Two kinds of test

Imposed temperature profile

test of the radiative transfer part

Baudino et al. submitted to ApJ

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Two kinds of test

Imposed temperature profile

test of the radiative transfer part

Self-consistent

Baudino et al. submitted to ApJ

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Two kinds of test

Imposed temperature profile

test of the radiative transfer part

Self-consistent

test of the full model

Baudino et al. submitted to ApJ

Profiles imposed

5 given temperature profiles

Baudino et al. submitted to ApJ

Profiles imposed

5 given temperature profiles

- abundance profiles at chemical equilibrium + spectra

Baudino et al. submitted to ApJ

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Profiles imposed

5 given temperature profiles

- abundance profiles at chemical equilibrium + spectra
- thermal profiles of Guillot et al. 2010

Baudino et al. submitted to ApJ

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Profiles imposed

5 given temperature profiles

- abundance profiles at chemical equilibrium + spectra
- thermal profiles of Guillot et al. 2010
- $\log_{10}(g[\mathrm{cgs}])$=3.7, solar metallicities, T_{eff}= 500 K, 1000 K, 1500 K, 2000 K, and 2500 K

Baudino et al. submitted to ApJ

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Profiles imposed

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- For T_{eff} = 1000 K + metallicity: 3 and 30 times the solar value.

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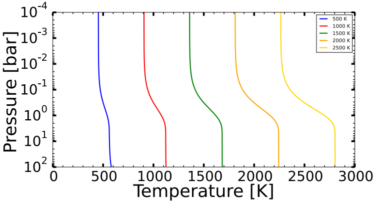

Input pressure-temperature profiles used in the benchmark

Baudino et al. submitted to ApJ

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Self coherent models

DI

Baudino et al. submitted to ApJ

Self coherent models

DI

Transit

Baudino et al. submitted to ApJ

Self coherent models

DI

- GJ 504 b T_{eff}=510 K, log(g)=3.9, z=0.28 dex

Transit

Baudino et al. submitted to ApJ

Self coherent models

DI

- GJ 504 b T_{eff}=510 K, log(g)=3.9, z=0.28 dex
- VHS 1256–1257 b T_{eff}=880 K, log(g)=4.24, z=0.21 dex

Transit

Baudino et al. submitted to ApJ

Self coherent models

DI

- GJ 504 b T_{eff}=510 K, log(g)=3.9, z=0.28 dex
- VHS 1256–1257 b T_{eff}=880 K, log(g)=4.24, z=0.21 dex

Transit

- GJ 436 b, T_{eff}=712 K, 0.38 R_{Jup}, 0.07 M_{Jup}

Baudino et al. submitted to ApJ

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Self coherent models

DI

- GJ 504 b T_{eff}=510 K, log(g)=3.9, z=0.28 dex
- VHS 1256–1257 b T_{eff}=880 K, log(g)=4.24, z=0.21 dex

Transit

- GJ 436 b, T_{eff}=712 K, 0.38 R_{Jup}, 0.07 M_{Jup}
- WASP 12 b, T_{eff}=2536 K, 1.736 R_{Jup}, 1.04 M_{Jup}

Baudino et al. submitted to ApJ

Models used

Forward models, Baudino et al. submitted to ApJ

- ATMO (Tremblin et al. 2015)
- Exo-REM (Baudino et al. 2015)
- petitCODE (Mollière et al. 2015)

Models used

Forward models, Baudino et al. submitted to ApJ

- ATMO (Tremblin et al. 2015)
- Exo-REM (Baudino et al. 2015)
- petitCODE (Mollière et al. 2015)

Retrieval, Baudino et al. in prep.

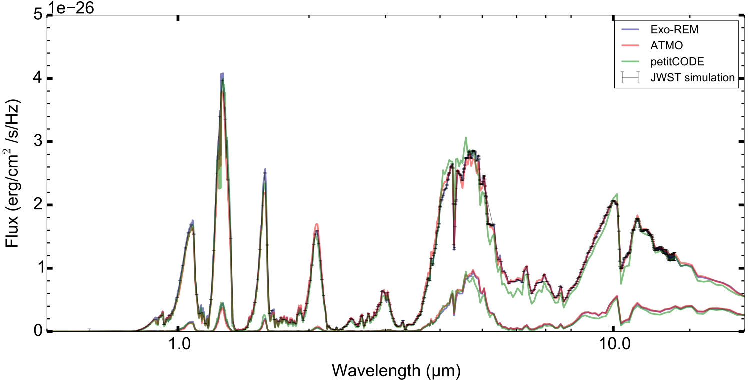
- NEMESIS (Irwin et al. 2008)

Difference opacities

Baudino et al. submitted to ApJ

Difference opacities

petitCODE (unlike the other models) didn´t use NH_3 and PH_3 linelist from Exomol



Emission spectra of VHS 1256-1257 b (top) and GJ 504 b (bottom)

Baudino et al. submitted to ApJ

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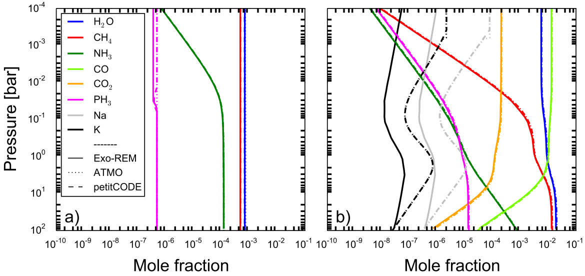
Differences chemistry

Baudino et al. submitted to ApJ

Differences chemistry

Exo-REM impose a cold-trap (unlike the other forward models) that effect abundance but not spectra



Abundance profiles of the defined molecules for the case with a T_{eff} =500 K at solar metallicity (a) and 1000 K at 30 $\times$ solar metallicity (b). The curves for the models are often superposed, except for alkalies where *Exo-REM* is not.

Baudino et al. submitted to ApJ

Convergence step-by-step

Convergence step-by-step

During Benchmark

Convergence step-by-step

During Benchmark

1. alkali far wings $\rightarrow$ first update of the benchmark protocol

Convergence step-by-step

During Benchmark

1. alkali far wings → first update of the benchmark protocol
2. *petitCODE* was considering calculations without any cut-off. We apply the same profile as *Exo-REM* in *petitCODE* for the benchmark.

Convergence step-by-step

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3. PH_3 in *ATMO* and *Exo-REM*

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Convergence step-by-step

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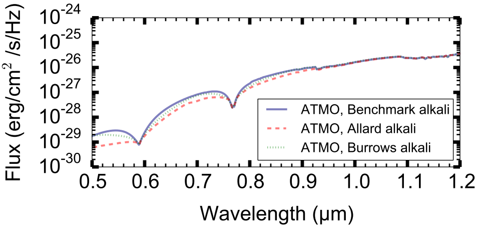
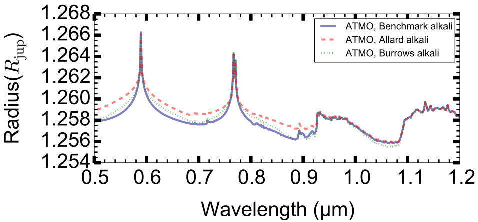
3. PH_3 in *ATMO* and *Exo-REM*
4. CH_4 Hitran vs Exomol
5. H_2-He CIA Hitran not complete before 1 micron

Alakli



Effects of the different alkali treatments on the emission spectra for the Guillot profile with T_{eff}=1500K



Effects of the different alkali treatments on the transmission spectra for the Guillot profile with T_{eff}=1500K

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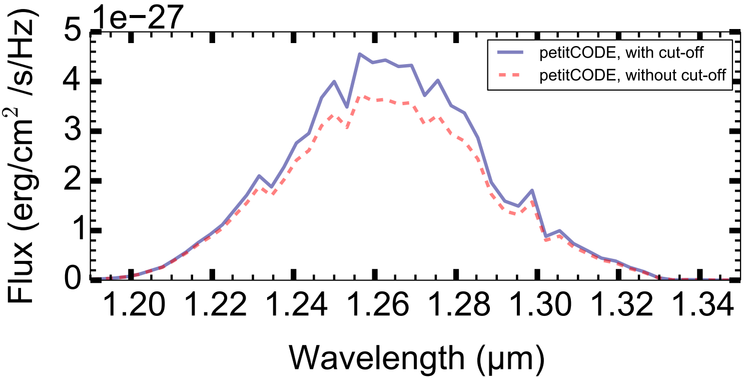
Far wing lineshape



Emission spectra for GJ 504 b calculated using the nominal temperature structure of the case including sub-Lorentzian far wings. We show the resulting spectrum of the nominal case (blue solid line) as well as the case with full Voigt profiles (red dashed line)

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NEMESIS

Updates

NEMESIS

Updates

- PH_3

NEMESIS

Updates

- PH_3
- update of the CIA

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Updates

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To test

NEMESIS

Updates

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To test

- radiative transfer in the Benchmark condition

NEMESIS

Updates

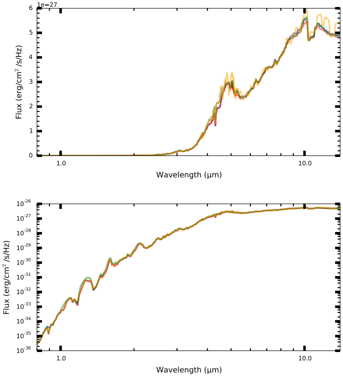
- PH_3
- update of the CIA

To test

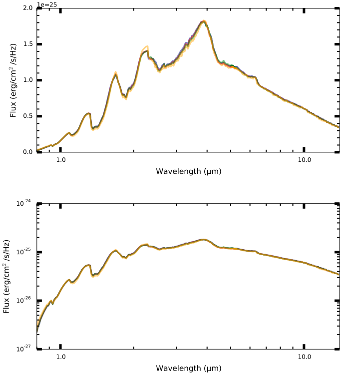
- radiative transfer in the Benchmark condition
- retrieval of the output spectra

Radiative transfer: Work in progress

500 K



1500 K



Conclusions

Key points

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Approaches with impact on spectra

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Approaches with impact on spectra

- Alkali wing lineshape

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Approaches with impact on spectra

- Alkali wing lineshape
- adding PH_3 in the opacity sources
- sub-Lorentzian lineshape

Conclusions

Key points

- definition of a benchmark
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Approaches with impact on spectra

- Alkali wing lineshape
- adding PH_3 in the opacity sources
- sub-Lorentzian lineshape
- selecting linelists carefully

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Perspectives

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- To apply this benchmark on other models !

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- To use JWST observations to discriminate the approaches

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Do you want to try the benchmark ?

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Do you want to try the benchmark ?

- The paper will be publish with full protocol and the resulting output sources (Baudino et al. submitted to ApJ)

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email: jean-loup.baudino@physics.ox.ac.uk
twitter: @DrJLoupBaudino

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