Understanding the spectrum of far away worlds: lessons learned from hot giant planets

Vivien Parmentier — University of Oxford
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The future of exoplanets: Ariel

- **Hot Jupiters**
- **Warm Neptunes**
- **Hot super Earths**
Detecting molecules

Transmission spectrum
Apparent planet size vs. wavelength
Look for deviation from flat line

Emission spectrum
Planet’s brightness vs. wavelength
Look for deviation from blackbody

Transmission spectrum for HD 209458b

Emission spectrum for WASP-43b
Atmospheric modelling recipe

Temperature profile

Chemical profile

Cloud profile

Stellar model

Molecular/atom/ions opacities

Cloud opacities
Atmospheric modelling recipe
Atmospheric modelling recipe

Transit Depth

$\lambda (\mu m)$

HD 209458b

Best-fit Model
Binned Model
Data

Scale Heights
Atmospheric modelling recipe
Atmospheric modelling recipe

- Temperature profile
- Chemical profile
- Cloud profile
- Stellar model
- Molecular/atom/ions opacities
- Cloud opacities

Atmospheric modelling recipe for HD 209458b
What is the magic unicorn doing?
What is the magic unicorn doing?

\[
A = \begin{pmatrix}
\frac{\partial (\text{Obs}_1)}{\partial (\text{physics}_1)} & \frac{\partial (\text{Obs}_1)}{\partial (\text{physics}_2)} & \cdots & \frac{\partial (\text{Obs}_m)}{\partial (\text{physics}_1)} & \frac{\partial (\text{Obs}_m)}{\partial (\text{physics}_2)} & \cdots \\
\frac{\partial (\text{Obs}_1)}{\partial (\text{Obs}_2)} & \frac{\partial (\text{Obs}_1)}{\partial (\text{Obs}_2)} & \cdots & \frac{\partial (\text{Obs}_m)}{\partial (\text{Obs}_2)} & \frac{\partial (\text{Obs}_m)}{\partial (\text{Obs}_2)} & \cdots \\
\vdots & \vdots & \ddots & \vdots & \vdots & \ddots \\
\frac{\partial (\text{Obs}_1)}{\partial (\text{physics}_1)} & \frac{\partial (\text{Obs}_1)}{\partial (\text{physics}_2)} & \cdots & \frac{\partial (\text{Obs}_m)}{\partial (\text{physics}_1)} & \frac{\partial (\text{Obs}_m)}{\partial (\text{physics}_2)} & \cdots \\
\end{pmatrix}
\]

- Things we want with observations we can get
- Nuisance physics we don’t want to deal with but have to (blah, star)
- Observations we want but can’t yet get (will 2020 be the decade JWST launches?)
- Things we don’t know we want with observations we don’t know we need

**We often debate what “Things” we want…

\[
\overrightarrow{\text{Physics}} = A^{-1} \overrightarrow{\text{Obs}}
\]
<table>
<thead>
<tr>
<th></th>
<th>Less assumptions</th>
<th>More parameters</th>
<th>More assumptions</th>
<th>Less parameters</th>
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</thead>
<tbody>
<tr>
<td><strong>Temperature profile</strong></td>
<td>Free</td>
<td>1D Radiative/conv eq.</td>
<td>2D/3D radiative/conv eq.</td>
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<td></td>
<td>Semi-grey</td>
<td>Non-grey</td>
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<td><strong>Chemistry</strong></td>
<td>Free chemistry</td>
<td>Equilibrium</td>
<td>1/2/3D disequilibrium</td>
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<td>— Choice of species</td>
<td>Choice of free parameters [M/H], [C/O] others</td>
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<td>— Vertical profile</td>
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<td><strong>Clouds</strong></td>
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<td>Simple equilibrium clouds</td>
<td>Microphysics</td>
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<td>Absorbing</td>
<td>Scattering, non-grey</td>
<td>bin vs. moment ?</td>
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<td>Grey</td>
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<td><strong>Geometry</strong></td>
<td>1D</td>
<td>2D — Lat/long</td>
<td>3D radiative transfer</td>
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<td>2D — Limb depth</td>
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<td><strong>Stars</strong></td>
<td>Blackbody</td>
<td>1D stellar model</td>
<td>Inhomogeneous stellar model</td>
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</table>
«Free» vs. «self-consistent» thermal and chemistry 1D retrievals

Hot Jupiter WASP-18b
Teq~2500K

Self-Consistent 1D grid
MCMC interpolation

Sheppard+2018

“Free Retrieval”

~300x Solar C/O~1
CO=20% of

Solar Comp!

Sheppard+2018

CO@4.5μm
CO@1.6μm

Arcangeli+2018

log C/O = -0.31 \pm 0.17
K2-18b: water on a temperature sub-Neptune or in M dwarf starspots?

Based on Tsiaras+2019

Water in cooler spots
No water elsewhere

Data
Planet only (Xi2~13, BIC~27)
Star only (Xi2~20, BIC~28)
3D effects: non-uniform temperatures in emission

CH4 detection!
3D effects: non-uniform temperatures in transmission

A 1D model would retrieve a carbon to oxygen ratio 100x too large!

Pluriel et al. in prep.

Water feature due to the cold, small scale height gas

CO feature due to the hot, large scale height gas

A 1D model would retrieve a carbon to oxygen ratio 100x too large!
3D effects: non-uniform clouds

Line & Parmentier 2016; MacDonald & Madhusudhan 2017
Data analysis — different analysis leads to different conclusions

HD 209458b

Diamond-Lowe et al.

HAT-P-11b

Chachan et al.
Statistical inference: did I really detect this gas?

If that solution were the real thing, I would have 1 chance over a million to observe a dataset with such a bad \( \chi^2 \)!

A lot of interesting consequences! Needs a replenishment of 1 Eros worth of material every 4 years and new physics so that the TiH stays in gaseous form.

Bayesian evidence says that the model with TiH is a significantly better fit!
Which data sets to include?

IR Only: \( \chi^2 = 31.9, \text{DOF}=31 \rightarrow p\text{-val}=0.42 \)
IR+Optical: \( \chi^2 = 88.1, \text{DOF}=65 \rightarrow p\text{-val}=0.03 \)
We’ve seen water in almost all planets we looked for it.

To first order, the size of the feature does not depend on the water abundance but on the water/cloud abundance.

The shape of the feature depends on other factors, such as pressure, but is currently unreliable.

We’ve seen clouds/hazes in almost all planets when looking for other stuffs.

We can be order-of-magnitude precise on abundances but we can be inaccurate because driven by the not-robustly-measured shape of the feature!
Haze! haze haze haze ....

HD189733b: 1200K planet best fit by hazes! Even though we don't see any CH4!

Experiments can form hazes in H2-CO2 mix @ 1500K!

All smaller, cooler guys have some sort of cloud and hazes

Haze is a pain, and it’s not limited to cool planets with CH4 like Titan ...
I’m sad now, is there hope?
The future of exoplanets: Ariel

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The future of exoplanets: Ariel

- **Hot Jupiters**
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The future of exoplanets: JWST

JWST
100x more precise
10x more planets

HST/WFC3

Spitzer

Line & Parmentier 2016
Feng+2016
JWST and rocky planets?

TRAPPIST-1e, Clear Modern Earth at 100 RP

Pidhorodetska et al. 2020
JWST and rocky planets?

Great, a few 10s’ of transit nails it!

TRAPPIST-1e, Cloudy Modern Earth at 100 RP

Noise floor!
Greene et al. 2016

Pidhorodetska et al. 2020
Detecting atmospheres around rocky things

If we’re lucky:  
*Clouds or hazes won’t block much of our view and we’ll see some CO2*

HOWEVER:  
it will be extremely hard to quantify abundances, or even total atmospheric pressure (degenerate with cloud pressure level)

<table>
<thead>
<tr>
<th>Type of Atmosphere</th>
<th>1 bar H₂O cloudy</th>
<th>1 bar H₂O</th>
<th>10 bar CO₂</th>
<th>92 bar CO₂</th>
<th>10 bar Venus</th>
<th>92 bar Venus</th>
<th>10 bar O₂ outgassing</th>
<th>100 bar O₂ outgassing</th>
<th>10 bar O₂ desiccated</th>
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Lustig-Yaeger 2019
We likely won’t be able to see any O2 is earth-like planet soon

Barclay et al. 2018

Rodler et al. 2014
Questions for rocky exoplanets atmospheric observations

Current status

Most ~50-ish gas planets with atmospheric measurements are compatible with physics and solar composition of carbon and oxygen +/- 1dex.

Most of these atmospheres are cloudy.
A majority show their 3D-ness in the observations

Expectations

JWST will give us *WAY* better data for the hot planet, so we’ll see all we got wrong before, good lessons.

JWST/ARIEL data for rocky stuff will be of similar-ish quality than hot Jupiter now.
Learn from our mistakes.

Advices

What’s a « detection » ? *Every* retrievals contains model assumptions.

Detection* is much easier than *quantification*. Think what you can do/constrain with detections only.

M dwarfs have water… think about other molecules not present in the star!

Tidally locked rocky planets will be highly 3D! Always keep that in mind.