Exploring the ARIEL Capabilities to Constrain Exoplanet Atmospheres

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Transiting Exoplanet Characterization
Atmospheric Retrieval Framework

**Python Radiative Transfer in a Bayesian framework:** (Cubillos & Blecic, in prep.)

**Forward modeling**
- $T(p)$
- $\text{comp}(T,p)$
- spectra($\lambda$)
- opacity
- mcmc

**Atmospheric modeling**
- Radiative transfer
- MCMC

**Follow best-coding practices**
(e.g., PEP 8, PEP 20, PEP 257)

**Used in retrieval comparison:**
Kilpatrick et al. (2019), Venot et al. (2020).

**Code** 62%
**Documentation** 21%
**Testing** 17%

Follow best-coding practices (e.g., PEP 8, PEP 20, PEP 257)

**Read the Docs**

**pytest**  Travis CI
Validation (1)

Compare against ExoMol/TauREx opacities (Chubb et al, in prep)
Validation (2)

Compare against petitDARTRANS spectra (Molliere et al, 2019)
https://petitradtrans.rtfd.io/

**Transmission spectra**

**Emission spectra**
The HST/WFC3 Transmission Sample (Cubillos & Blecic, in prep.)
Degenerate/multi-modal Posterioris

HAT-P-41b

(best-fit model, data)
- **Cloudy mode**: H2O correlates with cloud top pressure
- **Cloudy mode**: H2O correlates with cloud top pressure
- **High-µ mode**: H2O in high mean-molecular-mass atmosphere
Degenerate/multi-modal Posteriors
Degenerate/multi-modal Posteriors

\[ \mathcal{T} \sim 1 \text{ (optically thin)} \]

\[ \mathcal{T} \sim 0 \text{ (optically thick)} \]
Degenerate/multi-modal Posteriors

WFC3 band

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>Transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^-6</td>
<td>0.0</td>
</tr>
<tr>
<td>10^-5</td>
<td>0.0</td>
</tr>
<tr>
<td>10^-4</td>
<td>0.0</td>
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<tr>
<td>10^-3</td>
<td>0.0</td>
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<tr>
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<td>0.0</td>
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<tr>
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<td>0.0</td>
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<td>10^0</td>
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<tr>
<td>10^1</td>
<td>0.0</td>
</tr>
<tr>
<td>10^2</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Wavelength (µm) | 0.6 | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 8.0
Transmittance   | 0.38 | 0.39 | 0.40 | 0.41 | 0.42 | 0.43 | 0.44

best-fit model  
data
Degenerate/multi-modal Posteriors

WFC3 band

WFC3 probes narrow pressure range
(isothermal/isobaric OK-ish)
Degenerate/multi-modal Posteriors

ARIEL: wide simultaneous coverage

WFC3 probes narrow pressure range (isothermal/isobaric OK-ish)
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ARIEL will probe much wider pressure range!

ARIEL: wide simultaneous coverage

Degenerate/multi-modal Posteriors
The Challenge

We wish to increase complexity:
- Non-isothermal profiles
- Non-isobaric abundances (Changeat et al., 2019)
- > 1D geometry (Taylor et al.; Irwin et al., 2019)
- Complex clouds (Blecic et al., in prep)

But, restrained by data quality:
- Unwieldy parameter space
- Unconstrained posteriors
- Modeling choices impact outcome
  physics
data bases
  what to include/exclude

Restrained by CPU power
GPU no longer (e.g., Al-Refaie, Zalesky, Malik)

Increase complexity,
be aware of assumptions,
keep results insightful
The Precision of Mass Measurements Required for Robust Atmospheric Characterization of Transiting Exoplanets

Natasha E. Batalha\textsuperscript{1,} \textsuperscript{a}, Taylor Lewis\textsuperscript{1}, Jonathan J. Fortney\textsuperscript{1,} \textsuperscript{a}, Natalie M. Batalha\textsuperscript{1,} \textsuperscript{a}, Eliza Kempton\textsuperscript{2,} \textsuperscript{b}, Nikole K. Lewis\textsuperscript{3,} \textsuperscript{c}, Michael R. Line\textsuperscript{4,} \textsuperscript{c}
Mass-retrieval Setup

Same assumptions as retrieval challenge:
- Isothermal profile
- Isobaric abundances (H2O, CO, CO2, CH4, TiO)
- Radius at 10 bar
- Gray cloud deck

Additionally:
- Retrieve planetary mass, assuming Gaussian priors
- Test multiple mass-uncertainties

What’s the impact on the abundance posteriors?
ARIEL Mass-retrieval Setup

Hydrostatic equilibrium:

\[ \frac{dr}{r^2} = - \frac{kT}{\mu GM_p} \frac{dp}{p} \]

Hill Radius:

\[ R_H = a \sqrt[3]{\frac{M_P}{3M_s}} \]
Hydrostatic equilibrium:
\[
\frac{d r}{r^2} = - \frac{k T}{\mu G M_P} \frac{d p}{p}
\]

Hill Radius:
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R_H = a \sqrt[3]{\frac{M_P}{3M_s}}
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Hill Radius:
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\]

ARIEL Mass-retrieval Setup
Hot Jupiter (0.7 $M_{\text{Jup}}$)

$\sigma_M = 0$

$\sigma_M/M_p = 1\%$

$\sigma_M/M_p = 5\%$

$\sigma_M/M_p = 10\%$
Mini-Neptune 1 \( (20~M_{\text{Earth}}) \)

\[
\sigma_M = 0
\]

\[
\sigma_M/M_p=5\%
\]

\[
\sigma_M/M_p=10\%
\]

\[
\sigma_M/M_p=40\%
\]
Mini-Neptune 2 (3.2 \( M_{\text{Earth}} \))

\[ \sigma_M = 0 \]

\[ \sigma_M/M_p=10\% \]

\[ \sigma_M/M_p=40\% \]

\[ \sigma_M/M_p=80\% \]
Conclusions

The broader simultaneous spectral coverage of ARIEL will let us aim for an increased model/retrieval complexity.

Mass uncertainties might not have a large impact in abundance retrievals of H/He planets.

There’s a long list of improvements for retrieval (2D/3D, consistent equilibrium/disequilibrium chemistry, advanced cloud schemes, etc).

We must be aware of assumptions. Open-source code will help to understand impact.