Retrieval Challenges for the ARIEL Mission

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Pat Irwin, Ryan Garland (University of Oxford)
Mike Line (ASU)
Quality of ARIEL spectra substantially better than what we can currently achieve

Similar wavelength coverage to JWST

Figure from Tinetti et al, 2016, ExpAst, 46, 135
Resolving the challenges: comparative approaches

Benchmark models: if you put in the same stuff, do you get the same answer? (Hopefully, yes...)

Image shows synthetic, noise-free JWST spectra for a cloudy, H2-He dominated super Earth/mini Neptune generated using 3 different forward model codes.

They’re the same.... right?

NEMESIS (Irwin et al. 2008), TauREX (Waldmann et al. 2015) and CHIMERA (Line et al. 2013). NEMESIS originally Solar System, TauREX and CHIMERA both developed for exoplanets.
NEMESIS-TauREX-CHIMERA retrieval comparison

100 ppm – Cloudy SE, NEMESIS retrieval

Good match for all parameters!

30 ppm – Cloudy SE, NEMESIS retrieval

Offsets in CH4, H2O – tiny differences in models matter when precision is high

Blue = CHIMERA, Red = TauREX
NEMESIS-TauREX-CHIMERA retrieval comparison

100 ppm – cloudfree hot Jupiter, TauREX retrieval

100 ppm – cloudy hot Jupiter, TauREX retrieval

Good match for all parameters!

Still a good match, but distribution widths increase

Blue = CHIMERA, Black = NEMESIS
NEMESIS-TauREX-CHIMERA retrieval comparison

100 ppm – high mean molecular weight SE, TauREX retrieval

Challenging if bulk atmospheric composition not known

100 ppm – high mean molecular weight SE, CHIMERA retrieval

Could force sum to 1 - but what if not all gases present are included in retrieval models?

Blue = CHIMERA, Black = NEMESIS

Red = TauREX, Black = NEMESIS
Observed differences are a good analogy for instrument systematics + astrophysical systematics.

Plus: there is no such thing as a ‘right’ model, all approximations.

Testing a variety of approximations and approaches is probably what will get us closest to the truth.
ARIEL Retrieval Challenge

Simple models generated using TauREX

4x known input models, 4x fully blind models

Good match for true values, good consistency between different models, good spectral matches
Opaque deep atmosphere

Transparent upper atmosphere

Opacity

Opaque deep atmosphere

Cloudy upper atmosphere

Opaque deep atmosphere

Cloudy GJ 1214b’s flat spectrum – taken from Kreidberg et al. 2014, Nature, 505, 69

How should cloud be represented?
Limited information content of spectra requires something simple, but many different approaches.
Parameterisations: a selection

Barstow et al 2017 (B17).

Pinhas et al. 2019 (P19)

Fisher & Heng 2018 (F18)

Tsiaras et al 2018 (T18).

\[ Q_{\text{ext}} \propto \lambda^y \]

\[ Q_{\text{ext}} \propto \left( Q_0 x^r + x^{0.2} \right)^{-1} \]

\[ x = 2\pi r / \lambda \]

Opaque grey cloud

\[ \text{Pressure (bar)} \]

\[ P_{\text{base}} \]

\[ P_{\text{top}} \]
Test case planets:

HD 209458b:
- \( R = 1.38 \) R\(_J\)
- \( M = 0.69 \) M\(_J\)
- \( T_{\text{eff}} = \sim 1400 \) K
- Previously claimed to be cloudy (muted features)

HD 189733b:
- \( R = 1.138 \) R\(_J\)
- \( M = 1.162 \) M\(_J\)
- \( T_{\text{eff}} = \sim 1200 \) K
- Previously claimed to be hazy (muted H\(_2\)O feature, large scattering slope in the visible)
### Results

**HD 209458b:**
- R=1.38 R<sub>j</sub>
- M=0.69 M<sub>j</sub>
- T<sub>eff</sub> =~1400 K
- Previously claimed to be cloudy (muted features)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Barstow17</th>
<th>Pinhas19</th>
<th>Fisher18</th>
<th>Tsiaras18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log(H&lt;sub&gt;2&lt;/sub&gt;O VMR)</td>
<td>-4.89</td>
<td>-4.95</td>
<td>-5.11</td>
<td>-5.02</td>
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<tr>
<td>Log(nadir optical depth)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Scattering index</td>
<td>3.69</td>
<td>8.79</td>
<td>5.08</td>
<td>N/A</td>
</tr>
<tr>
<td>Log(top pressure (bar))</td>
<td>-0.65</td>
<td>-0.61</td>
<td>N/A</td>
<td>-0.79</td>
</tr>
<tr>
<td>ΔLn evidence</td>
<td>-3.6</td>
<td>-2.1</td>
<td>0.0</td>
<td>-1.7</td>
</tr>
</tbody>
</table>

**HD 189733b:**
- R=1.138 R<sub>j</sub>
- M=1.162 M<sub>j</sub>
- T<sub>eff</sub> =~1200 K
- Previously claimed to be hazy (muted H<sub>2</sub>O feature, large scattering slope in the visible)

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<tr>
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<td>-4.94</td>
<td>-4.98</td>
<td>-5.02</td>
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<tr>
<td>Log(nadir optical depth)</td>
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<td>4.35</td>
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<td>2.55</td>
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<tr>
<td>Scattering index</td>
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<td>6.47</td>
<td>6.37</td>
<td>N/A</td>
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<tr>
<td>Log(top pressure (bar))</td>
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<td>0.34</td>
<td>N/A</td>
<td>0.28</td>
</tr>
<tr>
<td>ΔLn evidence</td>
<td>-0.7</td>
<td>-0.2</td>
<td>0.0</td>
<td>-35.8</td>
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Conclusions: cloud modelling

All cloud parameterisations in the literature do a reasonable job of fitting the data

H₂O abundances are very robust to different cloud models.

Combination of fits with different models elucidates key points about the cloud:

• For HD 189733b: cloud with steep scattering slope is present at low pressures, no evidence for grey cloud
• For HD 209458b, no evidence for small particle haze but evidence for deep cloud deck.
Conclusions

• After 10 years of exoplanet atmospheres, quality of spectra has improved enormously but problem still degenerate. ARIEL represents a significant advance on what is currently possible.

• Model dependence is an inescapable fact – but we can use it

• No model is ‘right’ – but some may be wrong!

• 3D effects will become increasingly important, must be accounted for

• Comparative work using different codes/approaches helpful for getting close to ‘truth’