A Fully-Consistent 1D Radiative-Convective Equilibrium Model for Planetary Atmospheres

Benjamin Drummond
Pascal Tremblin, Isabelle Baraffe, Nathan Mayne, David Skålid Amundsen

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Outline

• ATMO
  – a new 1D model for sub-stellar atmospheres

• Fully-consistent non-equilibrium chemistry
  – feedback of chemistry onto background atmosphere
  – application to hot exoplanet atmospheres

• Chemistry and GCMs
Exoplanet Atmospheres

HD 209458b
Deming et al., 2013

GJ 436b
Knutson et al., 2014
1D Photochemical Models

Moses et al., 2011
Venot et al., 2012
Zahnle et al., 2009

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**1D Photochemical Models**

**INPUT:** Temperature, Elemental Abundance

**OUTPUT:** Chemical Abundances

- Calculate chemical abundances based on input temperature structure
- Simple Constructions e.g. isothermal
- 1D Radiative-Convective Codes
- Averaged from 3D GCM simulations
**1D Atmosphere Model**

- **Pressure Temperature Profiles**
- **Synthetic Observations**
- **Equilibrium and Non-equilibrium Chemistry**

Tremblin et al., 2015, *ApJL*

Drummond et al., 2015, *ApJL, submitted*

Evans et al., 2015, *MNRAS*
• **1D Atmosphere Model**
  - Hydrostatic Equilibrium
    \[
    \frac{dP_{gas}}{dz} - \rho g = 0
    \]
  - Energy Balance
    \[
    F_{\text{star}} + F_{\text{rad}} + F_{\text{conv}} = F_{\text{int}}
    \]
• **1D Atmosphere Model**
  – Equilibrium Chemistry
    • Gibbs Energy Minimisation
    • Including formation of condensates
  – Non-Equilibrium Chemistry
    • High-temperature chemical network of Venot et al., 2012, *A&A*
      – *See next talk*
    • Including vertical mixing and photodissociations
  – Radiative Transfer
    • Opacities binned using correlated-k method
    • Including scattering
Photochemical Modeling

1D column of atmosphere

Pressure

Temperature

Chemical Abundance

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Photochemical Modeling

But how does non-equilibrium chemistry effect the temperature of atmosphere?
Method

1. Calculate equilibrium chemistry
2. Solve for hydrostatic equilibrium
3. Solve equations of radiative transfer
4. Switch to non-eq chemistry
5. Reconverging PT profile throughout
### Test Case Planets

<table>
<thead>
<tr>
<th></th>
<th>HD 209458b</th>
<th>GJ 436b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass $M_J$</td>
<td>0.71</td>
<td>0.078</td>
</tr>
<tr>
<td>Radius $R_J$</td>
<td>1.38</td>
<td>0.37</td>
</tr>
<tr>
<td>Semi-major axis AU</td>
<td>0.047</td>
<td>0.030</td>
</tr>
<tr>
<td>Gravity (log g)</td>
<td>3.03</td>
<td>3.17</td>
</tr>
<tr>
<td>Host Spectral Type</td>
<td>G0 V</td>
<td>M2.5</td>
</tr>
</tbody>
</table>

- Short orbital periods of ~ few days or less
- Highly irradiated
- Tidally-locked – strong horizontal gradients
- **Hot Jupiters** ~ Jupiter mass planets
- **Hot Neptunes** ~ Neptune mass planets
HD 209458b

Chemistry

PRELIMINARY RESULTS

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PT Profiles

HD 209458b
PT Profiles

GJ 436b
Alkali Chemistry

- Important detections

Important detections which can affect the PT profile.

Important absorbers
Alkali Chemistry

- **Alkali Chemical Kinetics**
  - Chemical network of Glarborg and Marshall, 2005
  - High temperature kinetics for gas phase Na and K species
    - Na, NaCl, NaOH, NaO, NaH
    - K, KCl, KOH, KO, KH
    - 47 reactions
  - Also include reactions of chlorine species (Lavvas et al., 2014)
    - $\text{HCl} + h\nu \rightarrow \text{H} + \text{Cl}$
    - $\text{HCl} + \text{OH} \leftrightarrow \text{H}_2\text{O} + \text{Cl}$
    - $\text{H} + \text{HCl} \leftrightarrow \text{H}_2 + \text{Cl}$
    - $\text{HCl} + \text{M} \leftrightarrow \text{H} + \text{Cl} + \text{M}$
  - For hot atmospheres (e.g. HD 209458b), atomic Na and K dominate (e.g. Lavvas et al., 2014)
  - For cooler atmospheres (e.g. GJ 436b), molecular forms can become important (e.g. NaCl, NaOH, ...)

- Na + OH + M $\leftrightarrow$ NaOH + M
- Na + HCl $\leftrightarrow$ NaCl + H
- e.g.
Alkali Chemistry

GJ 436b

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PRELIMINARY RESULTS
Alkali Chemistry

Preliminary Results

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PT Profiles
Summary

• **ATMO**
  – a new fully-consistent 1D radiative-convective equilibrium model

• **Fully-consistent non-equilibrium chemistry**
  – gas phase non-equilibrium chemistry can have a (small, ~1%) effect on the temperature profile
  – formation of photochemical haze or condensation of clouds likely has more influence
  – missing chemical/opacity data for important absorbing species?

• **What Next?**
  – couple non-equilibrium chemistry with the UM
Chemistry and GCMs

• **The Unified Model (UM)**
  - A non-hydrostatic, deep atmosphere general circulation model (GCM)
  - Developed by the UK Meteorological Office for global climate predictions and local weather forecasting
  - Applications of dynamical core to hot exoplanet atmospheres (Mayne et al., 2014a, 2014b)
  - Adapted radiation scheme to high temperatures $10^3$ K (Amundsen et al., 2014)
Chemistry and GCMs

- **The Unified Model (UM)**

**HD 189733b**

**Zonal Mean Zonal Wind**

**Temperature at 30 mbar**
Chemistry and GCMs

- The Unified Model (UM)

GJ 436b

Zonal Mean Zonal Wind

Temperature at 30 mbar
Chemistry and GCMs

- The Unified Model (UM)
  - Next stage: Couple chemical kinetics to track 3D advection of important chemical species
Summary

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HD 209458b

Model Spectra

Preliminary Results

Wavelength $\mu$m

$F_p/F_s$
Model Spectra

GJ 436b

PRELIMINARY RESULTS

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Model Spectra

![Graph showing Model Spectra for GJ 436b]