Exoplanet Atmospheres

• Motivation (brown dwarfs, observations, etc.)

• equilibrium and non-equilibrium chemistry

• radiative transfer, opacities, and spectra

• simplified model atmosphere problems

• retrieval techniques
**Atmosphere:** Hydrogen & Helium, or other stuff.

**Interior:** solid (rock, ice) or convective fluid (Hydrogen, Helium)

**Bottom Layer:** abrupt solid/liquid surface or deep continuous transition region.
Atmosphere [noun]:
“a transition region between the stellar interior and the interstellar medium” (Grey 1992)
Atmosphere [noun]:
    a transition region between the planet interior
    and the interplanetary medium
We will focus first on giants
The atmospheres we can study are generally warm to hot
Lessons Learned from Brown Dwarfs
(~ 500K < $T_{\text{eff}}$ < 2500K)

- $M/M_{\text{Jup}} > 80$ (Star)
- $13 < M/M_{\text{Jup}} < 80$ (Brown Dwarf)
- $M/M_{\text{Jup}} < 13$ (planet)
Lessons Learned from Brown Dwarfs
(~ 500K < Teff < 2500K)

• observable atmosphere:
  Tgas ~ 1000K, Pgas ~ 0.1 to 1 bar.

• relatively thin atmospheres (Hp ~ 12 km)

• Major sources of opacity: Water, CIA, “dust”, Alkali (Na, K) doublets
Giant Planet / Brown Dwarf overlap:

- mass: \( \sim 1 \) to \(< 80 \times M_{\text{Jupiter}} \)
- radius: \( \sim 1 \) to \(< 5 \, R_{\text{Jupiter}} \)
- ages: \( \sim \) millions to billions of years old
- gravity: \( \sim 2 \) orders of magnitude
- effective temperature: \( \sim 100K \) to \( 2500K \)
- clouds: broad range of grains, ices (complex mixtures)
- non-equilibrium chemistry
- dynamics and “weather”
- BUT: different formation ... (composition & early evolution)
“Solar Abundances” (Asplund et al. 2009)

- solar abundances defines our baseline elemental composition
- solar C,N,O are often debated values (check the reference!)
- starting point for equilibrium chemistry calculations
- the relative values are “initial conditions” of atmosphere models (and usually conserved quantities).
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<tr>
<th>Chemical</th>
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<td>Mg&lt;sub&gt;2&lt;/sub&gt;SiO&lt;sub&gt;4&lt;/sub&gt;(cr)</td>
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The text includes a list of various compounds with their corresponding formulas. The highlighted compounds are Al<sub>2</sub>O<sub>3</sub>, CaTiO<sub>3</sub>, Mg<sub>2</sub>SiO<sub>4</sub>, and MgSiO<sub>3</sub>.
Chemical Equilibrium (in a box)

- independent of time
- independent of box history
- all fluctuations are damped out
- independent of position in box
- \( p_i = f(T, P, a_j) \) (partial pressure)

\[
p_i = \left( \frac{n_i}{n_{tot}} \right) P_{gas} = x_i P_{gas}
\]

\( x_i \) = mole fraction

Important references:
Fegley & Lodders (1994)
Burrows & Sharp (1999)
Equilibrium Chemistry (in a nutshell) More on this later ...

- Simplified example: Iron in Jupiter’s atmosphere

- mass balance: \[ \sum \text{Fe} = P_{\text{Fe}} + P_{\text{Fe(OH)}_2} + 2P_{\text{Fe}_2\text{Cl}_4} \]

- Expressed in terms of thermodynamic quantities:
  \[ \sum \text{Fe} = a_{\text{Fe}} \left[ K_{\text{Fe}} + K_{\text{Fe(OH)}_2}(f_{\text{H}_2})(f_{\text{O}_2}) + 2a_{\text{Fe}}K_{\text{Fe}_2\text{Cl}_4}(f_{\text{Cl}_2})^2 \right] \]

- System of equations for each element (each equation can be very long, e.g., hydrogen can have 100s of terms)

- solved for f, numerically, with some initial guesses and fixed element abundances. Equivalent to minimizing the Gibbs potential

- Alternative methods used (examples discussed later)
Temperature Structures of sub-stellar mass objects:

Results of model atmosphere calculations (See also Allard et al. 2001)

- chemical equilibrium
- hydrostatic equilibrium
- radiative+convective equilibrium
- one-dimension (radial)
- time-independent
- fixed abundances (e.g. “solar”)
A quick introduction to *spectral types* of brown dwarfs

2500K

~ 700K
A quick introduction to *spectral types* of brown dwarfs

![Normalized flux (F_\lambda) + constant vs Wavelength (\mu m)]

- 2500K
- ~ 700K
Jupiter

HD189733

\[ Y \quad T \quad L \quad M \]

chemical eq.
(at 1 bar)
Results of model atmosphere calculations
(See also Allard et al. 2001)

- chemical equilibrium
- hydrostatic equilibrium
- radiative+convective equilibrium
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**Temperature Structures** of sub-stellar mass objects:

Burrows & Sharp (1996)
A single object evolves through the Spectral Type (SpT(Teff)) also not exactly a unique function at low T)
This is actually $\text{cm}^2 / \text{molecule}$

major molecular absorbers
(NOT “continuous” -- 100s of billions of lines)
The basic model atmosphere recipe:
Major distinction between most brown dwarfs and giant planets -- incident stellar flux.
“Synthetic” Exoplanet Spectra

1 M_J, 5 Gyr planet orbiting a G2V star

$log_{10}(F_{\text{planet}} / F_{\text{star}})$

Wavelength [microns]
HD209458b

Line et al. (2016)
Fortney et al. (2008)
temperature inversions

TrES–4

HD209458b

HD189733b

$F_\lambda$ (mJy)

wavelength (µm)

$T$ [K]

log P [bars]
Phase-dependent Properties

Barman et al. 2005
latitude

longitude

1200K
1000K
750K
450K

1 mbar
30 mbar
1 bar

Showman et al. (2009)
eccentric planets

HD 17156b
\( e = 0.67 \)

HAT-2
\( e = 0.52 \)

XO-3
\( e = 0.26 \)
WASP-43b

Stevenson et al. (2017)
Exoplanet Atmospheres

- Secondary Eclipses (e.g., HD 209458b)
- Phase-curves (e.g., HD 189733b)
- Transit spectroscopy (e.g., HD 189733b)
- Spatially Resolved (“directly” imaged) (e.g., 2m1207b, HR 8799 bcde)
Transmission Spectrum (primary eclipse)
Shabram et al. (2011)
Shabram et al. (2011)

GJ 436 b

30xSolar

CH4/CO ~ 10^{-4}

CH4/CO ~ 10^{-3}
Kelt9-b, high-resolution transition spectroscopy

Balmer lines

Mg I

Ti II

Fe I

Cauley et al. (2018); Yan et al. 2018
Exoplanet Atmospheres

- Secondary Eclipses (e.g., HD 209458b)
- Phase-curves (e.g., HD 189733b)
- Transit spectroscopy (e.g., HD 189733b)
- Spatially Resolved (“directly” imaged) (e.g., 2m1207b, HR 8799 b, c, & d)
CO  H$_2$O  CH$_4$

$C = 8.21$  $O = 8.21$  [$C/O = 1.00$]

$C = 8.31$  $O = 8.50$  [$C/O = 0.64$]

$C = 8.49$  $O = 8.84$  [$C/O = 0.44$]

Konopacky, Barman, Macintosh & Marois (2013)
The importance of surface gravity:

M(Mjup)

104  94  83  73  62  52  41  31  20  10  8  6  4  2

T & Y dwarfs

M dwarfs

L dwarfs

Baraffe et al. 2003
Relative positions of photosphere and top of convection zone (cz). Vertical position indicates convective velocities at top of cz.
H-band (triangular shape)

Rice et al. (2010)

See also Allers et al. (2007) and refs for more examples.
H-band (triangular shape)

CIA:
lower gravity changes H and K bands, also makes spectrum redder

(see Borysow et al. 1997, Kirkpatrick et al. 2006)
“Weather” in a T-type brown dwarf:

Artigau et al. (2009)
disequilibrium chemistry (by mixing)

Zahnle & Marley (2014)
Hubeny & Burrows (2007);
Moses et al. (2011)
see Visshcer et al. (2010)
Direct Spectroscopy of planets: 2M1207b, HR 8799 b

Barman et al. (2011)
Patience et al. (2010)
HR8799 b

Barman et al. (2011)
2M1207b, 1000K and Methane-poor 
(non-eq CO/CH4 & clouds)

Barman et al. (2011)