Atmospheres of Giant Planets

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de Wit+12, Majeau+12

credit: Keck Observatory
Atmospheres: the next step

**Detection:**
- orbital distance
- mass and/or radius
- age?
- companions?

**Characterization:**
- temperature
- composition
- spatial structure
- chemistry, clouds, etc.
- etc., etc., etc.

**Reviews:**
Basic question:

WHAT DEFINES THE ATMOSPHERE?
What if there’s no surface?

- **Molecular hydrogen**
  - Depth 100 km
  - Temperature 300 K
  - Pressure 10 atm

- Depth 20,000 km
  - Temperature 11,000 K
  - Pressure $3 \times 10^6$ atm

- Depth 60,000 km
  - Temperature 18,000 K
  - Pressure $4 \times 10^7$ atm

- **Icy/rocky core**
  - Depth 70,000 km
  - Temperature 25,000 K
  - Pressure $6 \times 10^7$ atm

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Defining the atmosphere

Jupiter  hot Jupiters

Distance from star in AU

Fortney et al. (2007)
Defining the atmosphere

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Atmospheres

stellar flux
absorbed

local radiative equilibrium:
\[ \frac{dF}{dP} = 0 \]

multi-\(\lambda\) radiative transfer:

\[ F (P, T, \kappa, F_{\uparrow}, F_{\downarrow}) \]

assuming hydrostatic equilibrium:

\[ \tau = \left( \frac{\kappa}{g} \right) P \]

\(\lambda\)-dependent opacities \((\kappa)\) are a function of temperature, pressure, and composition

adiabatic profile

intrinsic heat

Pressure-Temperature (P-T) Profiles

Fortney et al. (2007)
Defining the atmosphere

ATMOSPHERE:

the pressure range where
1) stellar light is absorbed
2) planet’s emission originates

\( \frac{dF}{dP} = 0 \)

mul-\( \lambda \) radiaHve transfer:
\[ F(P, T, \kappa, F_{\uparrow}, F_{\downarrow}) \]

assuming hydrostatic equilibrium:
\[ \tau = (\kappa/g)P \]

\( \rightarrow \) stellar flux
\( \rightarrow \) absorbed

\( \uparrow \) intrinsic heat

\( \downarrow \) adiabatic profile

\( \lambda \)-dependent opacities (\( \kappa \)) are a function of temperature, pressure, and composition

Pressure-Temperature (P-T) Profiles

Fortney et al. (2007)
For the observers:

WHAT DO WE MEASURE?

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Exoplanet atmospheric measurements

Seager & Deming (2010)

credit: Keck Observatory

Absorption

Emission

Reflection
Opacities depend on: $\lambda$, $T$, $P$, abundances

Shabram et al. (2011)
Interpreting data: $T(P)$ and composition

WASP-12b, $T \approx 3000$ K

Stevenson et al. (2014)
Interpreting data: \( T(P) \) and composition

WASP-12b, \( T \approx 3000 \) K

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Interpreting data: $T(P)$ and composition

WASP-12b, $T \approx 3000$ K

Stevenson et al. (2014)
Unavoidable complication: clouds

Clouds form where P-T profiles cross condensation curves

Clouds can reflect incoming radiation and absorb or emit thermal radiation
Observational impact: reflection

Cahoy et al. (2010)
Observational impact: emission

Marois et al. (2008)
more physics,

MORE COMPLICATIONS
Planets are not 1D

de Wit et al. (2012), Majeau et al. (2012)

adapted from Rauscher & Menou (2012)
Atmospheric Circulation

What drives the atmospheric circulation?

- Horizontal temperature and pressure contrasts
- Laterally varying radiative heating/cooling
- Deviation from radiative equilibrium
- Winds

from review by Showman, Cho, & Menou, in *Exoplanets* ed. Seager (2011)

from review by Heng & Showman (2014) for AREPS
P-T profiles are not always spatially uniform

Barman et al. (2005)

A planet’s spectrum may change because of viewing geometry, rotation, or atmospheric variability

see also: Fortney et al. (2006, 2010); Burrows, Rauscher et al. (2010)
We should **expect** disequilibrium (neither LRE, nor chemical equilibrium)

Moses et al. (2013)

Parmentier et al. (2013)
(time permitting)

BONUS MATERIAL
Measuring rotation

\( \beta \) Pic b

Rotational broadening of \( 25 \pm 3 \) km/s

The current & future ability of high-resolution spectroscopy

(related: brown dwarf variability)

Snellen et al. (2014)

Rauscher & Kempton (2014)

2 km/s shift between models with fast and synchronous rotation

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Connection to brown dwarf variability

Crossfield et al. (2014)
Signature of formation location?

The C/O ratio in protoplanetary disks should vary with radius because of condensation of molecular gases at snowlines.

The relative atmospheric abundances of molecules (as a function of T, P) depends on the C/O ratio.

Öberg et al. (2011)

Madhusudhan (2012)
Points to remember

- **Atmospheric characterization**: beyond detection, measuring physical properties
- **Simplest atmosphere**: 1D, $F_\star$, $F_{\text{int}}$, $\kappa(\lambda)$, $T(P)$
- **Observations**: emission & reflection
  **Tell us**: $T(P)$, composition/abundances, clouds
- **More detail**: non-uniformity, disequilibrium, variability and rotation, etc.