Planetary Atmospheres: Models and Observations

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Atmospheres

Why?
Structure
Energetics
Clouds
Spectra

Focus on processes more than results
Why Study Atmospheres?

- Mediate all information (even transit radii)
- Regulate thermal evolution and radii
- Gravity, composition diagnostics
  - Mass is not trivial for directly imaged planets
  - Composition traces formation mechanism
Radius: IR + Visible

\[ L = 4\pi R^2 \sigma T_{\text{eff}}^4 = (1 - \Lambda) \pi R^2 (\pi F_*) + L_{\text{int}} \]
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$\Rightarrow \delta \, L/L = 60\%$

also will depend on composition
Constraining $R$

\[ L = 4\pi R^2 \sigma T_{\text{eff}}^4 = (1 - \Lambda)\pi R^2 (\pi F_\star) + L_{\text{int}} \]

\[ \frac{\delta R}{R} > \frac{1}{2} \frac{\delta L_{\text{int}}}{L} \]

easily 30% or more
Need gravity diagnostics! (spectra)
Signature of planethood?
But...

Requiring composition information turns most of the “Known Exoplanets” into “Known Exoplanet Candidates”

Known Exoplanets:
- HD149026b
- Gl 436b
Need composition diagnostics! (spectra)
Need Models!
Composition
Chemistry
Opacities
Condensates
+ Dynamics
Thermal Structure & Spectrum
Composition
Chemistry
Opacities
Condensates
+ Dynamics

Metallicity, C/O, ...

Thermal Structure & Spectrum
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Thermal Structure & Spectrum

Metallicity, C/O, ...
Sedimentation
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Metallicity, C/O, ...
Sedimentation
High $T$ CH$_4$

Thermal Structure & Spectrum
Composition
Composition
Chemistry
Chemistry
Opacities
Opacities
Condensates
Condensates

+ Dynamics
+ Dynamics

Metallicity, C/O, ...
Sedimentation
High $T$ CH$_4$
Cloud Physics

Thermal Structure & Spectrum
Composition
Chemistry
Opacities
Condensates + Dynamics
Thermal Structure & Spectrum

Metallicity, C/O, ...
Sedimentation
High $T$ CH$_4$
Cloud Physics
Circulation, $f$
Basics of Atmospheres

- Hydrostatic equilibrium
- Energy balance
- Breezing over details, see a basic atmospheric science text for derivations
Hydrostatic Equilibrium

- Static atmosphere -> no net forces
- Weight of slab = $\rho g$
- Balanced by pressure differential = $dP/dz$
- $dP/dz + \rho g = 0$
- $dP/dz = -\rho g$
- Combine with ideal gas law
  $$P = nkT = \left(\frac{\rho}{m}\right)kT$$
Consequences

\[ P = P_0 \, e^{-z/H} \]

Scale Height: \( H = kT/mg \)

- \( m \) is mean molecular weight

9 km on Earth; scale for a hot Jupiter....

Column number density \( N = nH = P/(mg) \)

- \( n \) is local number density

Note scaling with \( g \) (low \( g \) requires more molecules to compress air to given \( P \))
Optical Depth

Recall $N (\text{cm}^{-2}) = n \, H$

Each species has a wavelength dependent cross section for interacting with a photon, $\sigma_\nu \,(\text{cm}^2)$

Optical depth above a given pressure level

$$\tau = \sigma_\nu N$$

Transmission from or to a given pressure level

$$I = I_0 \, e^{-\tau}$$
SPECTRAL ENERGY PER UNIT TIME AND AREA ($10^2 \text{ W m}^{-2} \text{ m}^{-1}$)

Solar Radiation

Top of atmosphere
Top of troposphere

WAVELENGTH (µm)
Thermal Emission

- At each wavelength, see flux from $\tau \sim 1$

- If $T(P)$ monotonic, strong absorption features are dark because the gas is cold, so viewing a fainter blackbody

- $T_{brt} \neq T_{eq}$
Thermal Emission

At each wavelength, see flux from $\tau \sim 1$

If $T(P)$ monotonic, strong absorption features are dark because the gas is cold, so viewing a fainter blackbody

$T_{\text{brt}} \neq T_{\text{eq}}$
Probing an Atmosphere

- $T_{\text{min}} \sim 500$ K, $P_{\text{min}} \sim 0.1$ bar
- $T_{\text{max}} \sim 1600$ K, $P_{\text{max}} \sim 19$ bar
- 5 scale heights!
Energy Transport

- Deposited incident light heats atmosphere
- Atmosphere must transport upward all of the energy deposited below that point
  - convection
  - radiation
  - conduction
- Plus internal heat flux
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How to Deposit Incident Light?

\[ I = f \left( \frac{I_0}{\mu} \right) e^{-\tau/\mu} \]

- **stellar school:** \( f = \frac{1}{4} \)
  \( \mu = 1 \)

- **planetary school:** \( f = \frac{1}{2} \)
  \( \mu = \frac{1}{2} \)

- **Hot Jupiter school:** \( 0 < f < 1 \)
  \( \mu = ? \)
How to Deposit Incident Light?

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Ultimately Need a GCM
Uranus

Marley & McKay (1999)
Uranus

Marley & McKay (1999)
Brown dwarfs
\[ f = 1 \]

\[ f = 1/2 \]
Clouds
Jupiter  Cloudless  Hot Jupiter

Lodders (2005)
Marley et al. (1999)
Clouds

- No definitive detection yet in EGPs
- Very difficult to model, but play a crucial role in the spectra
- Phase variation as a function of wavelength can reveal sizes and vertical distribution
Photochemistry

Jupiter at 1 AU

- 25x higher UV flux
- H, C, O, N, S, P chemistry
- Many pathways to hazes
- But...Liang et al. (2004) find no hazes in hot Jupiters
Haze Production

$CH_4 + UV$

- $C_2H_2$
  - $C_6H_6$
  - Soot

- $C_2H_6$
  - $C_3H_8$
  - parafin

New Paradigm?  Old School
Haze Production

\[ \text{CH}_4 + \text{UV} \]

\[ \text{C}_2\text{H}_2 \rightarrow \text{C}_6\text{H}_6 \rightarrow \text{Soot} \]

\[ \text{C}_2\text{H}_6 \rightarrow \text{C}_3\text{H}_8 \rightarrow \text{parafin} \]

New Paradigm?                      Old School

Substantially alter spectra and colors of canonical haze-free models
At Low Spectral Resolution

- Clouds trump
- Hazes are a concern
- Metallicity
- C/O
- Non-equilibrium chemistry
Stratospheres
Net Absorbed Flux

$P = 0.1 \text{ mbar}$

$P = 1 \text{ mbar}$

$\lambda \ (\mu\text{m})$
Net Emitted Flux

$\nu$ (\(\mu\)m)

$T = 123K$ $P = 0.1$ mbar

$T = 86K$ $P = 1$ mbar
Net Emitted Flux

\[ \nu (\mu m) \]

- For \( T = 123 \, \text{K} \) and \( P = 0.1 \, \text{mbar} \):
  - The net emitted flux is shown in the graph.

- For \( T = 86 \, \text{K} \) and \( P = 1 \, \text{mbar} \):
  - The net emitted flux is shown in the graph.
TiO Stratospheres
TiO Stratospheres

Harrington et al. (2007), for HD 149026b
Planetary Atmospheres

- Structure and spectra dependent on interplay of chemistry, radiative transfer, cloud and molecular opacities, photochemistry, dynamics...
- Solar system planets are complex
- Beware simplistic analyses
- Planetary spectra are highly non-Planckian
Hot Jupiter Observations

- Models grossly validated
- Many indications that global dynamics are important (day/night contrasts, maps)
- Prediction and detection of hot TiO stratospheres
- Transit spectroscopy
- Much more to come from Spitzer & JWST