The Interplay Between a Planet’s Atmosphere and its Global Evolution
what I’m not going to talk about:
• planet interior
• Solar System planets
• C/O ratio

Emily Rauscher
University of Michigan

The Interplay Between a Planet’s Atmosphere and its Global Evolution
Questions

- How does the atmosphere influence the evolution?
- How does the evolution influence the atmosphere?
- What are the observables?

Seager & Deming (2010)

credit: Keck Observatory
How does the atmosphere influence the evolution?

Evolution: cooling & shrinking

Miller et al. (2009)
How does the atmosphere influence the evolution?

The atmosphere is a boundary condition

A hot atmosphere slows cooling 

![Graph showing the effect of planet radius on age for different masses and semi-major axes.]

- **Semi-major axis (a) = 0.02 - 0.06 AU (G2V primary)**
- **Solar metallicity, no core**

**0.02 AU – 0.06 AU**

Burrows et al. (2007)
How does the atmosphere influence the evolution?

The atmosphere is a boundary condition

A hot atmosphere slows cooling ➣
A higher atmospheric opacity slows cooling ➤

Age (Gyrs)

Planet radius ($R_J$)

Semi-major axis (a) = 0.02 - 0.06 AU (G2V primary)
Solar metallicity, no core

0.02 AU – 0.06 AU

Burrows et al. (2007)
How does the atmosphere influence the evolution?

The radiative-convective boundary (RCB) is a bottleneck.
How does the atmosphere influence the evolution?

The radiative-convective boundary (RCB) is a bottleneck

For a RCB at higher pressure:
- higher opacity
- slower cooling

Guillot & Showman (2002); Arras & Bildsten (2006); Budaj et al. (2012); Spiegel & Burrows (2013)
How does the atmosphere influence the evolution?

The radiative-convective boundary (RCB) is a bottleneck

For a RCB at higher pressure:
- higher opacity
- slower cooling

Strong day-night difference in heating, but not seen at depth

Fortney et al. (2007)

Guillot & Showman (2002); Arras & Bildsten (2006); Budaj et al. (2012); Spiegel & Burrows (2013)
How does the atmosphere influence the evolution?

The radiative-convective boundary (RCB) is a bottleneck

The 2D global cooling rate could be up to 40% higher than the 1D rate

Rauscher & Showman (2014)
How does the atmosphere influence the evolution?

Hot Jupiters with Surprisingly Large Radii

Guillot & Gautier (2014)
How does the atmosphere influence the evolution?

Hot Jupiters with Surprisingly Large Radii

The amount of heating needed to explain inflated radii depends on where in the planet it is deposited.

- Tidal heating?
- Increased opacity?
- Downward waves?
- Ohmic dissipation?
- Mechanical greenhouse?
- Thermal tides?

1% of stellar flux at:
- interior
- 20 bar
- 10 bar

without any extra heating

Guillot & Gautier (2014)

Guillot & Showman (2002)
How does the atmosphere influence the evolution?

**Ohmic dissipation as a possible heating source**

The Basic Idea:

Thermal ionization + km/s winds + planetary B field = currents, which experience ohmic dissipation → heating

first set of references: Batygin & Stevenson (2010); Perna, Menou, & Rauscher (2010b); Batygin et al. (2011); Wu & Lithwick (2012); Huang & Cumming (2012)
How does the atmosphere influence the evolution?

Ohmic dissipation as a possible heating source

Rauscher & Menou (2013)
How does the atmosphere influence the evolution?

Ohmic dissipation as a possible heating source

Requires including a 3D effect, with feedback, in a 1D model

Rauscher & Menou (2013)

Batygin et al. (2013)

Temperature (K)

Rogers & Komacek (2014)

log (magnetic timescale)
Questions

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How does the evolution influence the atmosphere?

“Age” of interior is unimportant (for hot Jupiters)

High entropy interior
\(T_{\text{int}} = 500 \text{ K}\)

Low entropy interior
\(T_{\text{int}} = 0 \text{ K}\)

Rauscher & Menou (2012)
How does the evolution influence the atmosphere?

“Age” of interior is unimportant (for hot Jupiters)
... except for when it comes to magnetic effects

Electrical resistivity

Rauscher & Menou (2013)
How does the evolution influence the atmosphere?

Evolution of a different type: rotation rate

Hot Jupiters are expected to have synchronous rotation ... but what do we know?

Rauscher & Kempton (2014)
How does the evolution influence the atmosphere?

Evolution of a different type: rotation rate

Emitted light, as seen throughout one orbit

Slow
Synch.
Fast

see also: Showman et al. (2009)

Rauscher & Kempton (2014)
How does the evolution influence the atmosphere?

Evolution of a different type: rotation rate

Atmospheric Doppler shift, due to winds & rotation

Rauscher & Kempton (2014)
Questions

- How does the atmosphere influence the evolution?
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Seager & Deming (2010)

Credit: Keck Observatory
What are the observables?

What do we actually measure? (for transiting planets)

- Radius ($R_p/R_\star$), mass ($M_p/M_\star$), age (?)
- Stellar flux ($F_\star$)
- Temperature of dayside ($F_p/F_\star$ during secondary eclipse)
- Composition of the atmosphere (absorption lines during transit)

- Circulation of the atmosphere (orbital phase curves: $\Delta F$ day-night, shifted hot spot)

- Magnetic effects? (compare: radius, circulation, evaporation, star-planet interaction)
- Wind speed & rotation rate? (Doppler-shifted atmospheric lines)
What are the observables?

**What do we actually measure?** (for transiting planets)

- Radius \((R_p/R_\star)\), mass \((M_p/M_\star)\), age (?)
- Stellar flux \((F_\star)\)
- Temperature of dayside \((F_p/F_\star\) during secondary eclipse)
- Composition of the atmosphere (absorption lines during transit)

**Easy**

- Temperature of dayside \((F_p/F_\star\) during secondary eclipse)
- Composition of the atmosphere (absorption lines during transit)

**Moderate**

- Circulation of the atmosphere (orbital phase curves: \(\Delta F\) day-night, shifted hot spot)

**Wishful**

- Magnetic effects? (compare: radius, circulation, evaporation, star-planet interaction)
- Wind speed & rotation rate? (Doppler-shifted atmospheric lines)

atmosphere
What are the observables?

**What do we actually measure?** *(for transiting planets)*

- **Radius** ($R_p/R_*$), **mass** ($M_p/M_*$), **age** (?)
- **Stellar flux** ($F_*$)
- **Temperature of dayside** ($F_p/F_*$ during secondary eclipse)
- **Composition of the atmosphere** (absorption lines during transit)

**Easy**

- **Circulation of the atmosphere** (orbital phase curves: $\Delta F$ day-night, shifted hot spot)

**Moderate**

- **Magnetic effects?** *(compare: radius, circulation, evaporation, star-planet interaction)*
- **Wind speed & rotation rate?** *(Doppler-shifted atmospheric lines)*
Directly imaged planets

The physical properties of directly imaged planets are “measured” by comparison to evolutionary and atmospheric models.

First measured rotation of a planet: \( \beta \) Pic b

Rotational broadening: 25 km/s

Marois et al. (2008)

Snellen et al. (2014)
Questions

- How does the atmosphere influence the evolution? a lot, in many ways
- How does the evolution influence the atmosphere? not obvious
- What are the observables? multiple, and growing