Characterization of Transiting Planet Atmospheres

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Limited information available for individual planets—goal is to identify patterns in exoplanet population that constrain formation, migration, and mass loss models.
A Mass-Radius Diagram for Exoplanets

Do smaller planets accrete less hydrogen?

Mass loss?

Super-Earths (1-10 M_⊕)

Figure courtesy Leslie Rogers
Composition as a Clue to Origin of Close-in Super-Earths

Premise: small planets grow by accreting solids, so bulk composition reflects that of the solids in the disk at the formation location.
Determining Super-Earth Compositions

Caveat: the presence of thick atmospheres makes it difficult to uniquely constrain bulk compositions from mass and radius alone.

Water world (migrated from beyond ice line) or rocky with a H/He envelope (in situ formation)?
Observations of Eclipsing Systems Allow Us to Characterize Exoplanet Atmospheres

- **Transit**
  - See radiation from star transmitted through the planet’s atmosphere

- **Secondary Eclipse**
  - See thermal radiation and reflected light from planet disappear and reappear

- **Orbital Phase Variations**
  - Changes in reflected/emitted light spectrum as function of orbital phase.
Absorption During Transit (%): 

Secondary Eclipse Depth (IR):

Orbital Phase Variations:

Always less than secondary eclipse depth.

Three ways to decrease signal: smaller planet, lower temperature, heavier atmosphere.

Scaling Laws for Transiting Planets

\[
\frac{10R_p}{R_*^2} \left( \frac{kT_p}{\mu g} \right) \\
\left( \frac{R_p}{R_*} \right)^2 \left( \frac{T_p}{T_*} \right)
\]

M stars preferred!
Transmission Spectroscopy Measures Mean Molecular Weight of Atmosphere

Compositions:
- solar
- 30x solar
- 50x solar

H₂O (steam)
50/50 H₂O, CO₂
CO₂ (Venus)

Scale Height

\[ H = \frac{kT}{g\mu} \]

Miller-Ricci & Fortney (2010)
Characterizing the Warm Transiting Neptune GJ 436b

GJ 436A: 
0.5 $M_{\text{Sun}}$, 3600 K

GJ 436b: 
23 $M_{\text{Earth}}$, 2.6 day orbital period, 
~800 K

Estimated H/He mass fraction between 3-22%, comparable to Neptune (Nettelmann et al. 2010).
Characterizing Atmospheres With Transmission Spectroscopy

A good understanding of *limb-darkening* is needed in order to determine the planet’s wavelength-dependent radius.

HST STIS transits of HD 209458b from 290-1030 nm (Knutson et al. 2007a)
Super-Earth GJ 1214b also has similar clouds (Kreidberg et al. 2014)
What Might Form Clouds on GJ 436b and GJ 1214b?

Condensate clouds like the Earth?

- Zinc sulfide or potassium chloride (Morley et al. 2013)

Photochemical hazes like Titan?

- Photochemistry converts methane to “soot” (long hydrocarbon chains)
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Constraints on GJ 436b’s Dayside Emission Spectrum from *Spitzer*

Stevenson et al. (2010, 2012)

Observe the decrease in light as the planet disappears behind the star and then reappears.
Comparison to Models

Stellar Atmosphere Model

Flux (erg s\(^{-1}\) cm\(^{-2}\) cm\(^2\))

Wavelength (\(\mu\)m)

Planet Atmosphere Models

Metal-rich model

Metal-poor model

\[
\text{depth}(\%) = \frac{F_{\text{planet}}}{F_{\text{star}} + F_{\text{planet}}} \approx \frac{F_{\text{planet}}}{F_{\text{star}}}
\]
GJ 436b: A Warm Neptune With a Metal-Rich Atmosphere

Can explain data if atmosphere has a metallicity of 300-2000x solar (Moses et al. 2013).

1000x solar atmosphere is only 40% H₂ by number!

Data from Lanotte et al.

Models courtesy M. Line & J. Fortney
Observations of Eclipsing Systems Allow Us to Characterize Exoplanet Atmospheres

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Study Weather Patterns on Tidally Locked Planets

Close-in exoplanets should be **tidally locked**, may have large temperature gradients between the two hemispheres.

Planet’s slow rotation means that the circulation should be **global in scale** (few broad jets, large vortices).

Image credit: ESA/C. Carreau
Constraints on Atmospheric Circulation from Phase Curve Observations

Phase curve for hot Jupiter HD 189733b observed at 8 µm with Spitzer (Knutson et al. 2007)
Constraints on Atmospheric Circulation from Phase Curve Observations

Relative Flux vs Orbital Phase

Observer's View of Planet
Phase Curves Allow Us to Map Atmospheric Circulation Patterns for Tidally Locked Planets

Balmy night side

Blazing hot day side

Strong winds

Knutson et al. (2007)
Multi-Wavelength Observations Map Thermal + Chemical Gradients in Atmosphere

Stevenson et al. (2014)
Conclusions: What Can We Learn from Atmosphere Studies?

- Gas Giants
  - Cloud compositions?
  - Does atmospheric metallicity increase with decreasing mass?

- Super-Earths
  - Can we pick cloud-free planets to study?

- Habitable Zone Earths
  - Effect of tidal locking on planet climate?

- Formation in situ or inward migration?

Planets drawn to scale.