Properties of Exoplanetary Systems: A Spitzer Portrait Gallery

Heather Knutson
UC Berkeley
Two Commonly Used Methods for Finding & Characterizing Exoplanets

- **Doppler Method**
  - Determine Planet Mass

- **Transit Method**
  - Determine Planet Diameter

Calculated Planet Density and Infer Composition:
- Gas giant (Jupiter), Ice giant (Neptune), or Rocky planet (Earth)
Ongoing Surveys Have Discovered 400+ Planets So Far...
...56 of Those Planets Are Transiting.

Some planets appear to be inflated

Massive planets on highly eccentric orbits

Ice/Rock Planets
Hot Jupiters are **good test cases** for exoplanet characterization (big, hot, lots available). Current challenge is to explain diversity in observed properties.

Kepler will soon enable the first studies of **smaller** and/or **cooler** transiting planets.
Two Exoplanets: A Comparison

HD 209458b
- G0V primary, $m_k = 6.3$
- Mass: $0.66 \, M_{\text{Jup}}$
- Radius: $1.32 \, R_{\text{Jup}}$
- $P = 3.525 \, \text{days}$
- $T_{\text{equil}} = 1450 \, \text{K}$

HD 189733b
- K0V primary, $m_k = 5.5$
- Mass: $1.15 \, M_{\text{Jup}}$
- Radius: $1.15 \, R_{\text{Jup}}$
- $P = 2.218 \, \text{days}$
- $T_{\text{equil}} = 1200 \, \text{K}$

Equilibrium temperature assumes planet absorbs all incident flux and re-radiates as a blackbody.

These are the two **brightest** transiting planet systems known today. Also by far the **best-studied**.
Transiting Planets as a Tool for Studying 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
See cyclical variations in brightness of planet

*Spitzer* has provided some of the best examples of these two phenomena in the infrared to date.
2005: First Detection of Light From An Extrasolar Planet

Can measure the planet’s emitted flux without the need to spatially resolve the planet’s light separate from that of the star.

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

<table>
<thead>
<tr>
<th>Orbital Phase</th>
<th>Relative Flux</th>
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<tbody>
<tr>
<td>0.46</td>
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<tr>
<td>0.48</td>
<td>1.000</td>
</tr>
<tr>
<td>0.50</td>
<td>0.995</td>
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<tr>
<td>0.52</td>
<td>1.000</td>
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HD 209458, 24 μm
Deming et al. (2005)

<table>
<thead>
<tr>
<th>Time From Eclipse Center (days)</th>
<th>Relative Flux</th>
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<tbody>
<tr>
<td>-0.10</td>
<td>0.995</td>
</tr>
<tr>
<td>-0.05</td>
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<tr>
<td>0.00</td>
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</table>

TrES-1, 4.5 & 8.0 μm (pictured)
Charbonneau et al. (2005)
2007: First Spectrum for an Extrasolar Planet

IRS observations of two planets during secondary eclipse:

HD 209458b
Richardson et al. (2007)

HD 189733b
Grillmair et al. (2007)
State-of-the-Art Spitzer Observations of HD 189733b

Grillmair et al. (2009)
Data from this work and Knutson et al. (2008).
Models described in Burrows et al. (2007)
HD 209458b: Evidence for Two Classes of Hot Jupiter Atmospheres

Why would two hot Jupiters with similar masses, radii, compositions, and temperatures have such different pressure-temperature profiles?

Requires a model with a temperature inversion and water features in emission instead of absorption.

Data from Knutson et al. (2008), models from Burrows et al. (2007)
Can gas-phase TiO explain temperature inversions?

Problem: inversions do not appear to correlate with temperature

One alternative: sulfur photochemistry (Zahnle et al. 2009)

As described in Hubeny et al. (2003), Burrows et al. (2007, 2008), and Fortney et al. (2008)

Figure from Fortney et al. (2008)
Do Temperature Inversions Correlate With Any Other Properties of These Systems?

Unpublished + upcoming observations

Inversion
No Inversion
Some Challenges for 1D Atmosphere Models

1. Are we getting the chemistry right?

**HD 209458b:**
Best-fit mixing ratios for common IR absorbers

\[
\begin{align*}
\text{H}_2\text{O}: & \quad < 10^{-8} - 10^{-5} \\
\text{CH}_4: & \quad 4 \times 10^{-8} - 0.03 \\
\text{CO}: & \quad > 4 \times 10^{-4} \\
\text{CO}_2: & \quad 4 \times 10^{-9} - 7 \times 10^{-8}
\end{align*}
\]

Madhusudhan & Seager (2009)

2. What about the P-T profiles?

Circulation, clouds, and additional high-altitude absorbers can all alter the shape of the default P-T profile.

3. Where/how is energy transported to the night side?

Circulation model for HD 209458b from Showman et al. (2008)
What does the atmospheric circulation look like?

Close-in exoplanets should be **tidally locked**, may have large day-night temperature differences.

Planet’s slow rotation means that the circulation is **global in scale** (few broad jets, large vortices).
Mapping the Day-Night Circulation With Phase Curves

The HD 189733 system to scale

-orbital period = 2.21 d
-transit duration = 1.9 hr
-9.3 stellar radii

Size of observed variation depends on efficiency of day/night circulation

Efficient

Inefficient

Relative Flux

Time (hours)

Image courtesy G. Laughlin
First Longitudinal Temperature Profile for an Exoplanet: HD 189733b’s Warm Night Side

Spitzer 8 μm observations of HD 189733b (Knutson et al. 2007b, Nature 447, 183).
Evidence for a Diversity of Day-Night Circulation Patterns

Large day-night brightness gradient
HAT-P-7 / Kepler

Small day-night brightness gradient
HD 189733b / Spitzer

Large gradients:
υ And b* (Harrington et al. 2007)
HD 179949* (Cowan et al. 2008)
HAT-P-7 (Borucki et al. 2009)

Intermediate gradients:
HD 149026 (Knutson et al. 2009)

Small gradients:
HD 189733b (Knutson et al. 2007)
HD 209458 (Knutson et al., in prep.)

* non-transiting planet, brightness/temperature gradient degenerate with unknown orbital inclination and planet radius
Future Steps: More Systems, Multiple Wavelengths

Will have full-orbit phase curves for five planets spanning 3.6-24 μm (up to four bands per planet, 1138 hours, PI H. Knutson) by end of two-year warm mission.
Future Steps: More Systems, Multiple Wavelengths

Warm Spitzer: 3.6 and 4.5 μm

These light curves can also tell us more about the planet’s energy budget (closer to flux peak), horizontal extent of temperature inversions.

Will have full-orbit phase curves for five planets spanning 3.6-24 μm (up to four bands per planet, 1138 hours, PI H. Knutson) by end of two-year warm mission.
Spitzer will obtain phase curves for several more eccentric planets (HAT-P-2, HD 17156, XO-3) during the warm mission.
Beyond Hot Jupiters: The Age of Kepler

Kepler will find many new systems for Spitzer to study...

Can combine visible light Kepler phase curves with Spitzer observations in IR

Ex: HAT-P-7
What Can Spitzer do with Kepler Targets?

1. Rejection of Astrophysical False Positives (40 candidates)
   - Good planet candidate but...

2. Secondary eclipse observations of select Kepler targets (20 planets)
   - Transit depth is color dependent

Study previously inaccessible classes of exoplanets, namely cool Jupiters, hot Neptunes and superhot Super-Earths.

Exploration Science Program, 800 hours, PI D. Charbonneau

O’Donovan, Charbonneau, et al. 2006
The next few years will see two major changes:
1. Studies of hot Jupiters will move from an exploration phase to a survey phase with the goal of explaining the observed diversity in their properties.
2. These same techniques will be applied to a much wider range of planet types, including eccentric planets, cool(er) Jupiters, hot Neptunes, and superhot Super-Earths.

Warm Spitzer will be at the forefront of both areas! >2600 total hours of exoplanet observing time