Portraits of Distant Worlds:
Mapping the Atmospheres of Hot Jupiters

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The Big Question: Atmospheric Circulation?

- Hot Jupiters receive ~20,000 times more radiation than Jupiter
- What happens to this energy?
  - Hot day side, cool night side
  - Strong winds -> equal temperatures
- Answer depends on properties of atmosphere (radiative vs. advective timescales)
- Models predict a range of possibilities

Circulation model for HD 209458b from Cooper & Showman 2005.
Methods for Studying Hot Jupiters

**Transits**
- Mass-radius relation
- Transmission spectroscopy
- Transit timing

**Phase Curves**
- Day-night temperature contrast
- Atmospheric dynamics
  
  Most difficult type of observation, but also most informative!

**Secondary Eclipses**
- Emission Spectrum (IR)
- Albedo (visible light)
- Eccentricity
What is phase variation?

Hot Jupiters should be tidally locked, so 1 orbit = 1 rotation of planet
Initial Observations

Observations of the non-transiting system $\upsilon$ And b at 24 $\mu$m (Harrington et al. 2006) seem to indicate large day-night contrast . . .

. . . but similar observations of HD 209458b at 8 $\mu$m (Cowan et al. 2007) point to smaller day-night variations

-> Need better-constrained data!

System Geometry

What We Observe

Grey line: Efficient redistribution of heat from the dayside to the nightside

Black: Inefficient heat redistribution, large day-night temperature difference

33 hours of continuous observations at 8 µm using Spitzer/IRAC

Image courtesy of Greg Laughlin (www.oklo.org)
Complications: Star Spots and Detector Effects

HD 189733 is a relatively active K1 star . . .

Project variation from spots observed by Winn et al. (2007) forward 3 months in time, scale amplitude for 8 µm observations

Conclusion: spots could cause linear increase in flux with amplitude ~0.1%

Measured flux in individual pixels increases over time, with shape of ramp determined by illumination level for pixel

Solution: Derive set of functions describing shape of ramp as a function of illumination and correct individual pixels accordingly
HD 189733b: A (Very) Windy Planet

- Observed for 33 hours continuously at 8 µm using Spitzer/IRAC
  - Correct for detector ramp
  - Aperture photometry, radius of 3.5 pixels

- Small size of observed phase variation indicates relatively efficient circulation between day/night sides
  - \( T_{\text{day}} = 1212 \pm 11 \text{ K}, \ T_{\text{night}} = 973 \pm 33 \text{ K} \)
  - Requires winds on the order of ~several km/s

- Shifted locations of peak and minima also point to strong winds
  - Peak occurs 16±6° before opposition

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“Whoa, whoa, whoa! They used a kajillion dollar instrument to find out the side near the sun is hotter than the rest?“

--anonymous Slashdot user

Eclipse Photometry

- **Transit**
  - $R_P = 1.137 \pm 0.006$ $(\pm 0.020) R_{\text{Jup}}$
  - 6 s. error on best-fit transit time

- **Secondary Eclipse**
  - Depth is $0.3381 \pm 0.0055\%$
  - Secondary eclipse occurs 120 ±24 s later than predicted
    - Eccentric orbit? $e \cos(\omega) = 0.0010 \pm 0.0002$
Mapping the Day-Night Contrast

(a) Spherical model of the Earth

(b) Graph showing relative brightness of a slice as a function of longitude from the substellar point
Filling in the Picture: HD 189733b in Emission

Fluxes are reasonably consistent with predictions from Barman model . . . also MOST upper limit on albedo coming soon.
The Next Steps: Mapping at Two Wavelengths

- Why is day-night contrast so large for υ And b and so small for HD 189733b?
  - Different opacities at 8 vs 24 μm or different types of atmospheres?
- Different wavelengths should probe different depths in atmosphere
- Time awarded in Cycle 4 to map HD 189733b at 24 μm, will allow for direct comparisons between planets

Cooper and Showman (2005) model for HD 209458b
The Next Steps: Comparative Exoplanetology

- HD 209458b and υ And b: two of a kind?
  - HD 209458b has longer period/slower rotation, day side receives 60% more radiation than HD 189733b
  - υ And b has properties intermediate between these two planets
- Will map HD 209458b at 8 and 24 μm, data set will allow for direct comparisons to HD 189733b at two wavelengths

Charbonneau et al. (2007)
The Next Steps: Eccentric Planets

HAT-P-2b, $e = 0.507$

HD 80606, $e = 0.9321$

Figures from Langton & Laughlin (2007, submitted)
Conclusions

• For tidally-locked hot Jupiters, models of atmospheric circulation predict a range of possible outcomes

• Observations of phase variation constrain the temperature differences between day and night sides
  – With high signal-to-noise observations, can create a map of temperature as a function of longitude

• Transiting planet systems are preferred targets for these observations
  – Knowledge of planet’s radius and the flux from the dayside needed to accurately interpret relative changes in flux over orbit

• Future observations will look at other wavelengths, compare results for different planets, and extend observations to highly eccentric systems