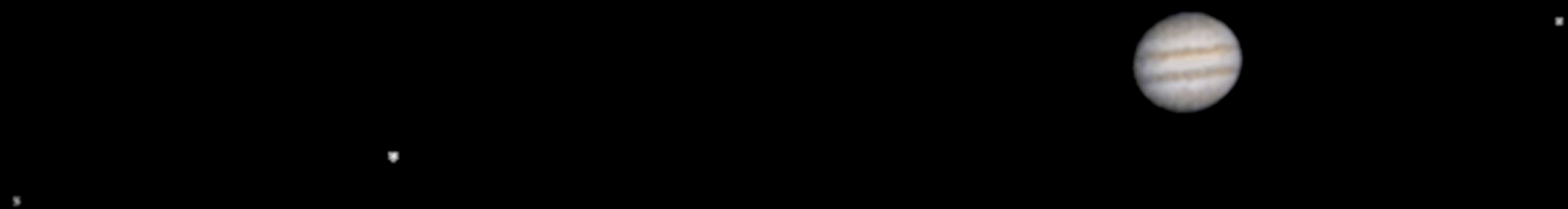
Portraits of Distant Worlds:

Mapping the Atmospheres of Hot Jupiters



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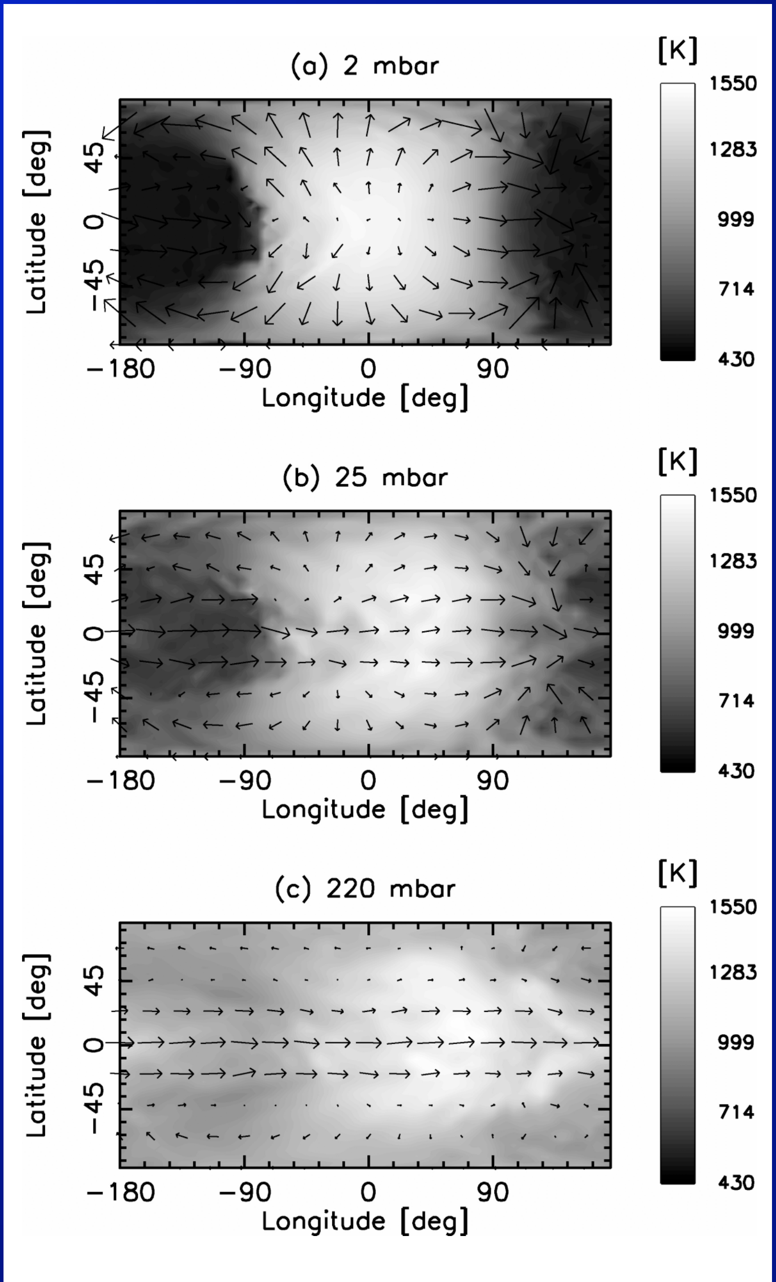
The Big Question: Atmospheric Circulation?

- 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
  - Showman & Guillot 2002, Cho et al. 2003, Burkert et al. 2005, Cooper & Showman 2005, 2006, Langton & Laughlin 2007, Dobbs-Dixon & Lin 2007

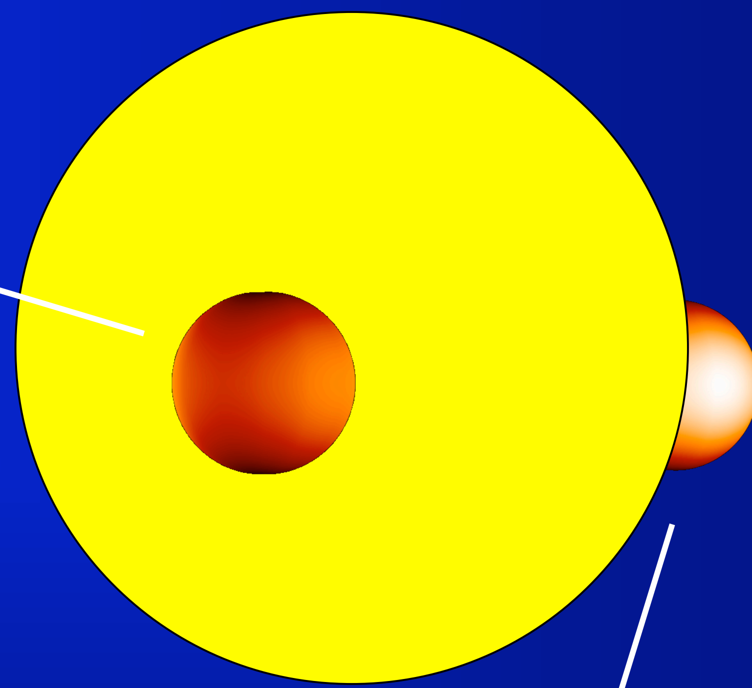


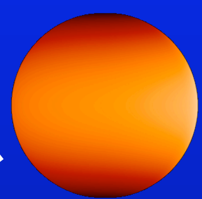
Circulation model for HD 209458b from Cooper & Showman 2005.

Methods for Studying Hot Jupiters

Transits

- Mass-radius relation
- Transmission spectroscopy
- Transit timing





Phase Curves

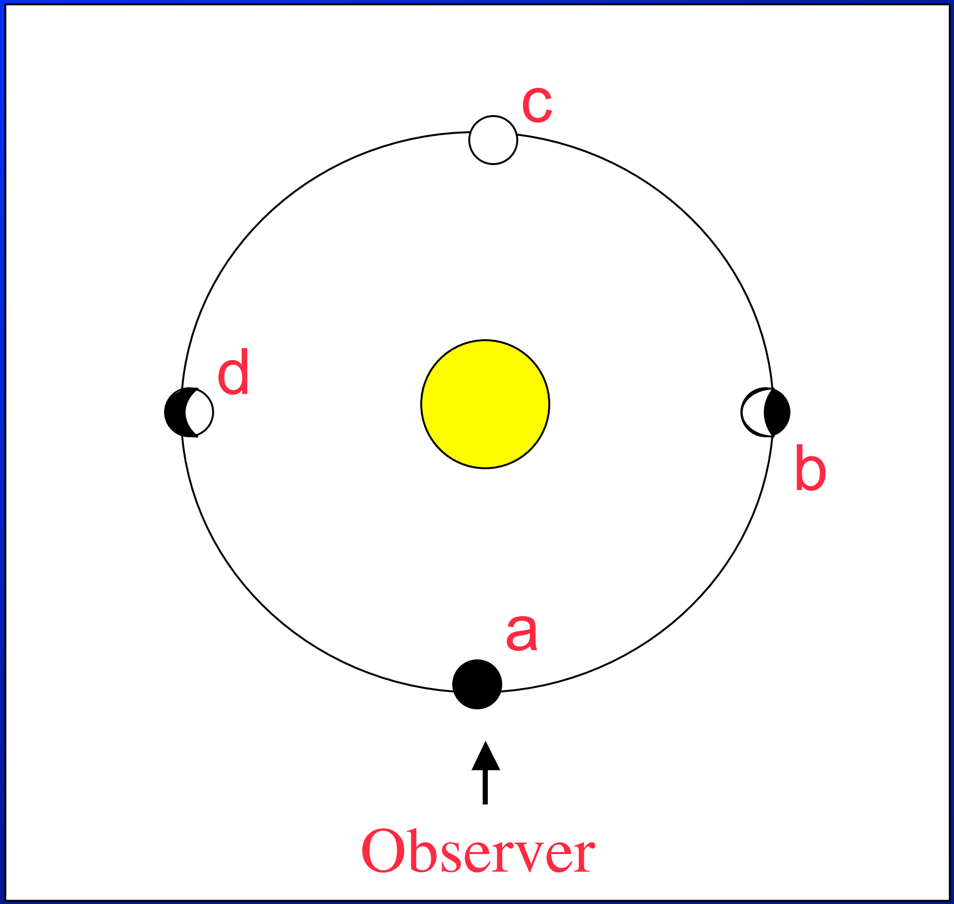
- Day-night temperature contrast
- Atmospheric dynamics

Most difficult type of observation, but also most informative!

Secondary Eclipses

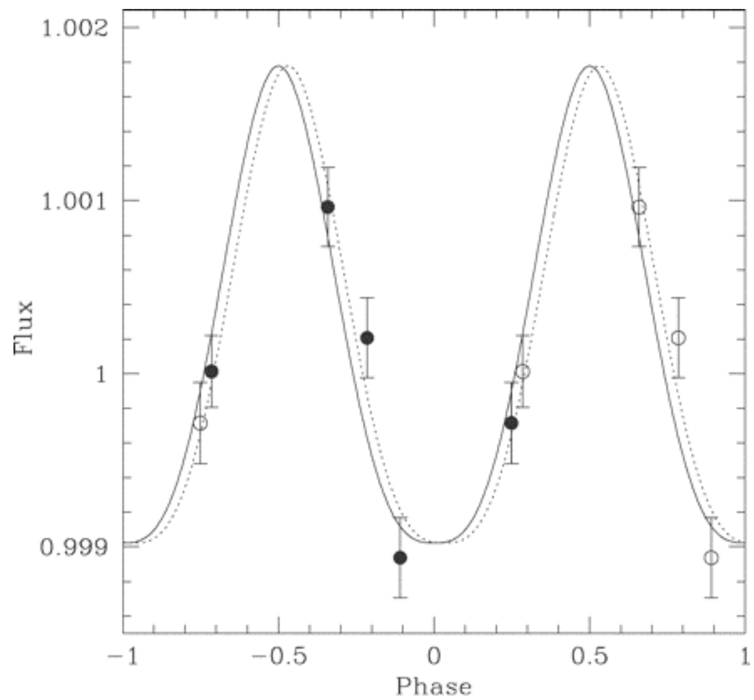
- Emission Spectrum (IR)
- Albedo (visible light)
- Eccentricity

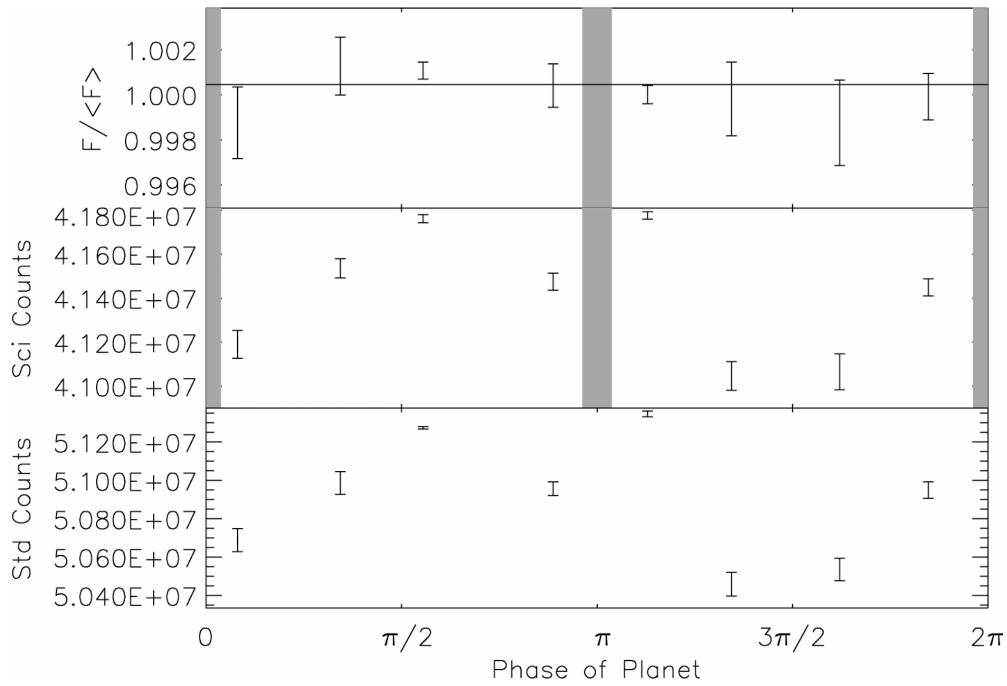
What is phase variation?



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

Initial Observations





Observations of the non-transiting system υ And b at 24 μm (Harrington et al. 2006) seem to indicate large day-night contrast . . .

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

-> Need better-constrained data!

HD 189733b: A More Detailed Look . . .

System Geometry

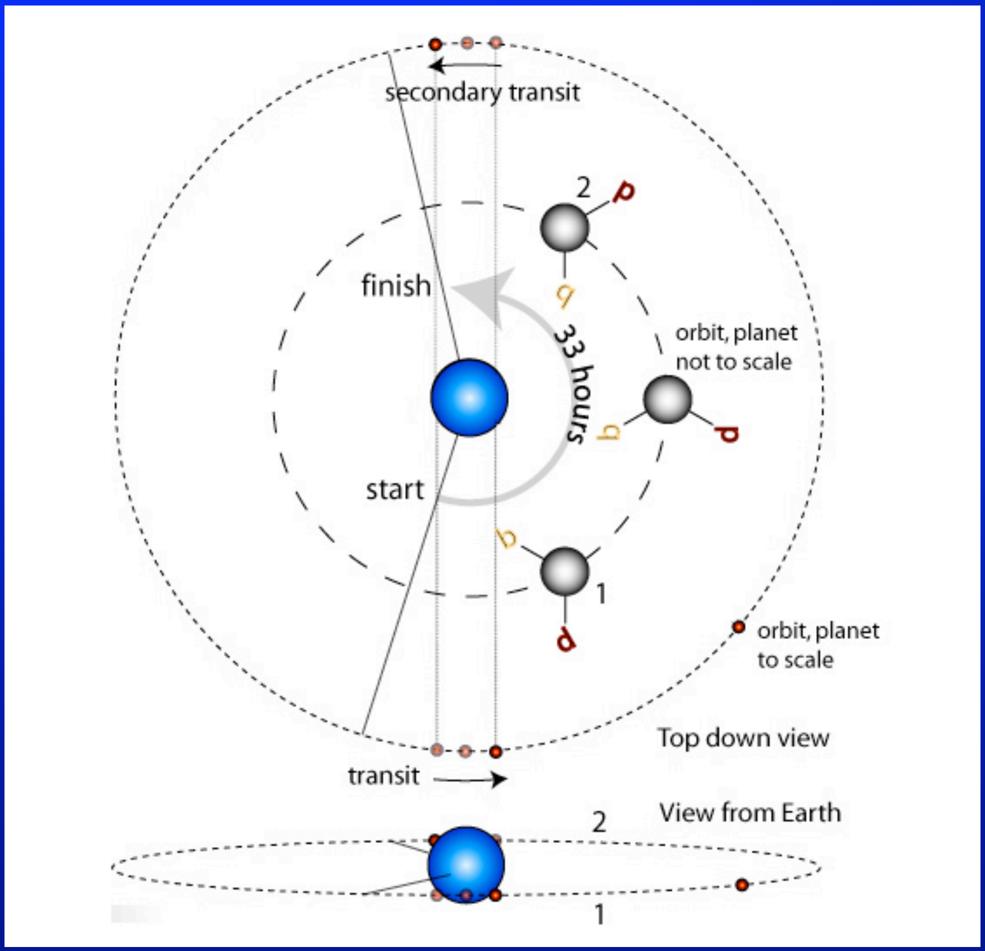
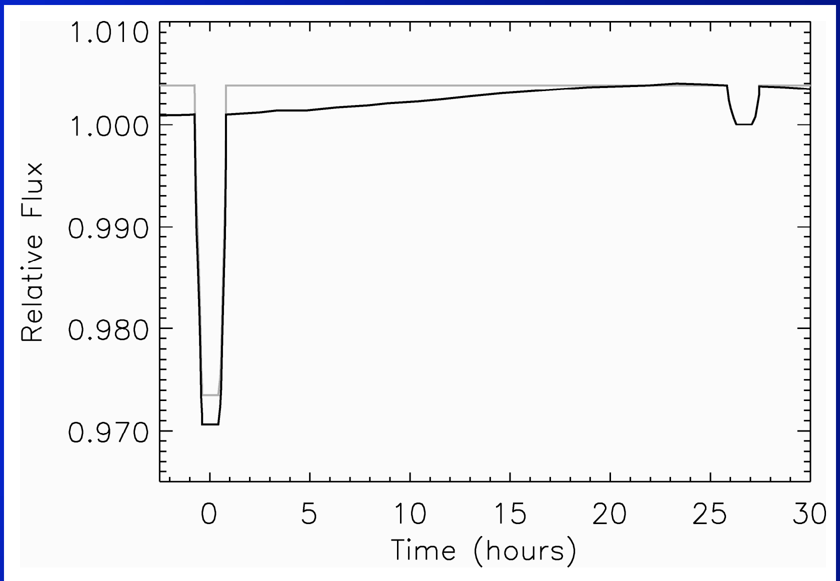


Image courtesy of Greg Laughlin (www.oklo.org)

What We Observe



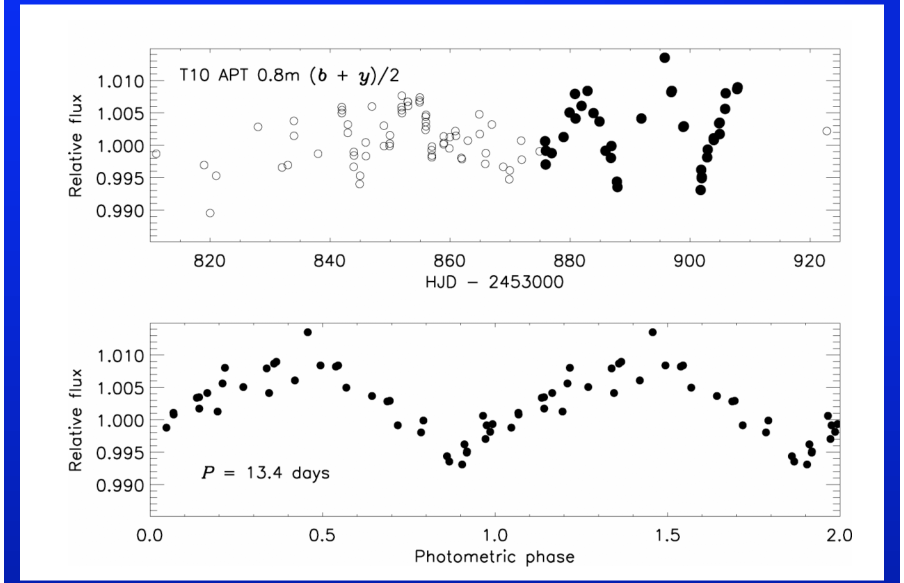
Grey line: Efficient redistribution of heat from the dayside to the nightside

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

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

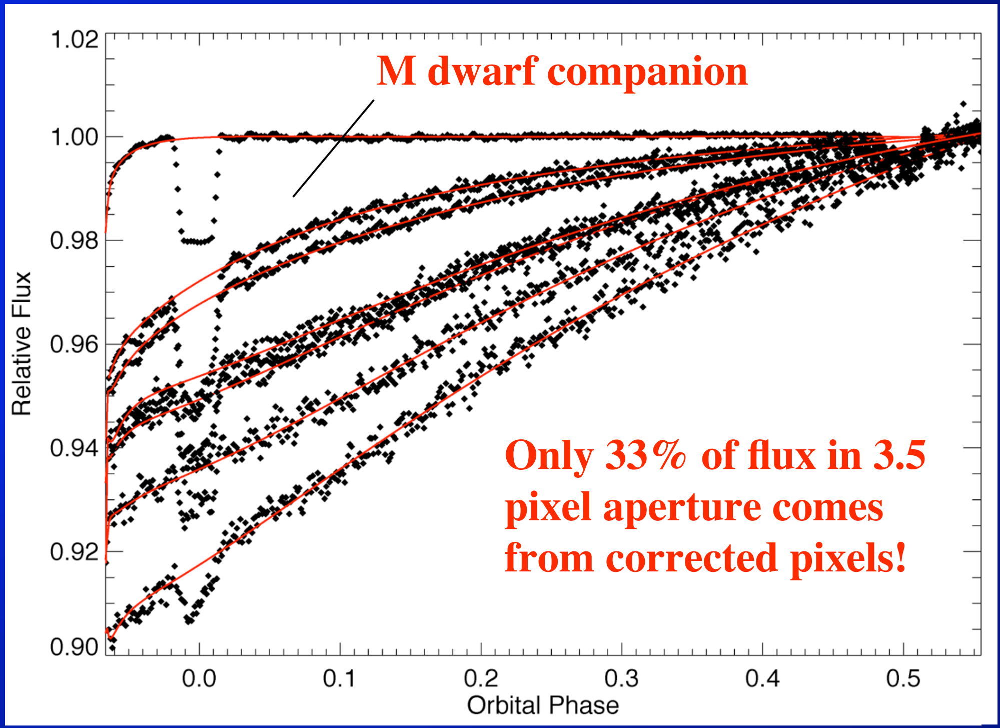
Complications: Star Spots and Detector Effects

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 c
  - Aperture ph pixels
- Small size o variation ind efficient circ day/night sic
  - T_{day}=1212±
  - 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

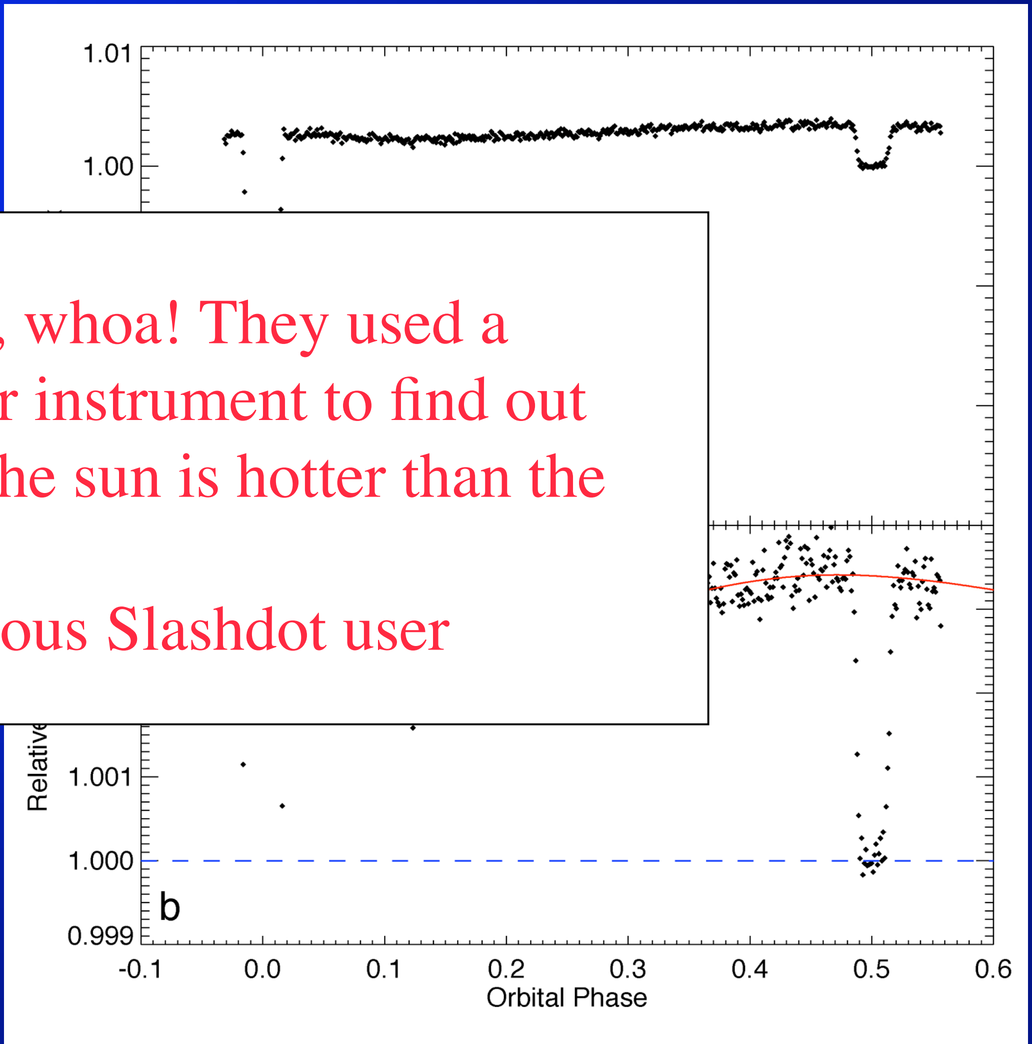


Figure from Knutson, H., Charbonneau, D., Allen, L., Fortney, J., Agol, E., Cowan, N., Showman, A., & Cooper, C. , *Nature* May 10 2007

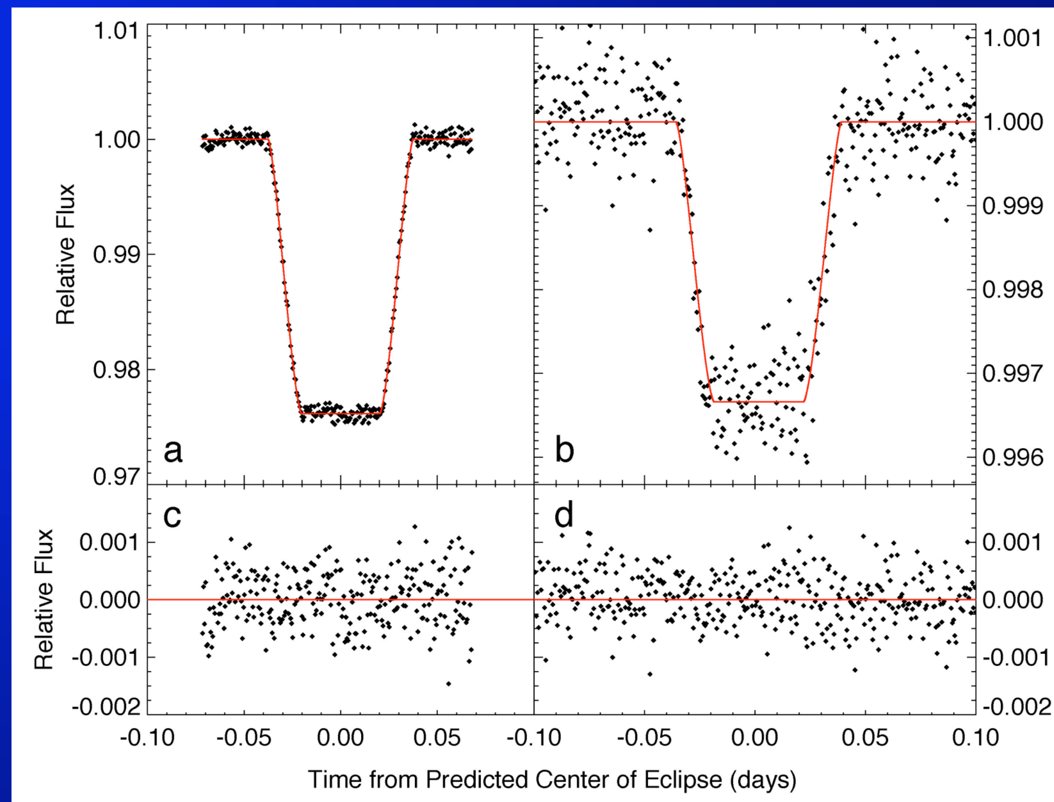
"Whoa, whoa, whoa! They used a kajillion dollar instrument to find out the side near the sun is hotter than the rest?"

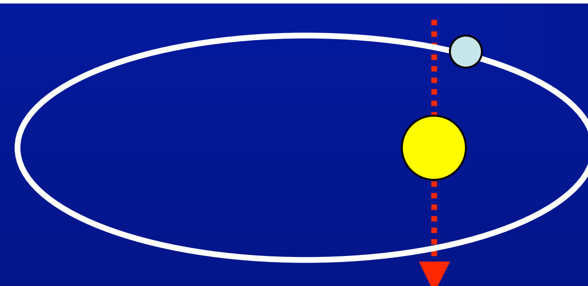
--anonymous Slashdot user

Eclipse Photometry

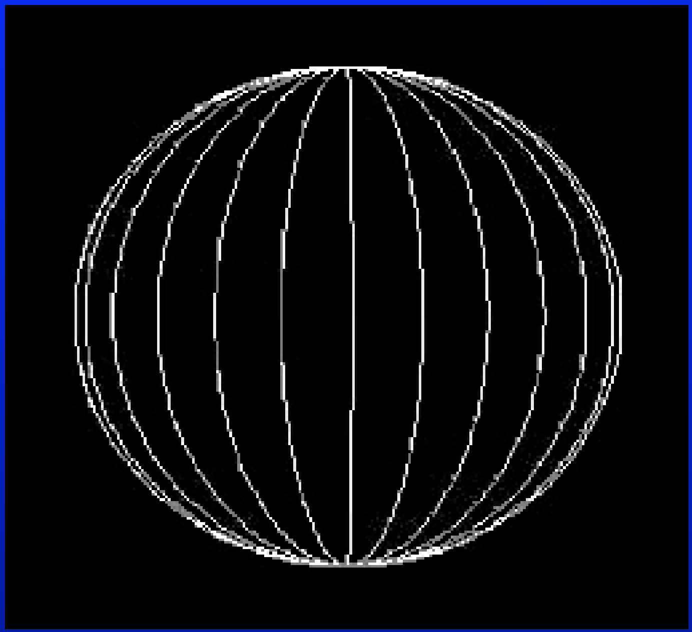
- Transit
  - $R_P = 1.137 \pm 0.006$ (± 0.020) R_{Jup}
  - 6 s. error on best-fit transit time
- Secondary Eclipse
  - Depth is 0.3381±0.0055%
  - Secondary eclipse occurs 120 ±24 s later than predicted
    - Eccentric orbit? $e*\cos(\varpi) = 0.0010 \pm 0.0002$

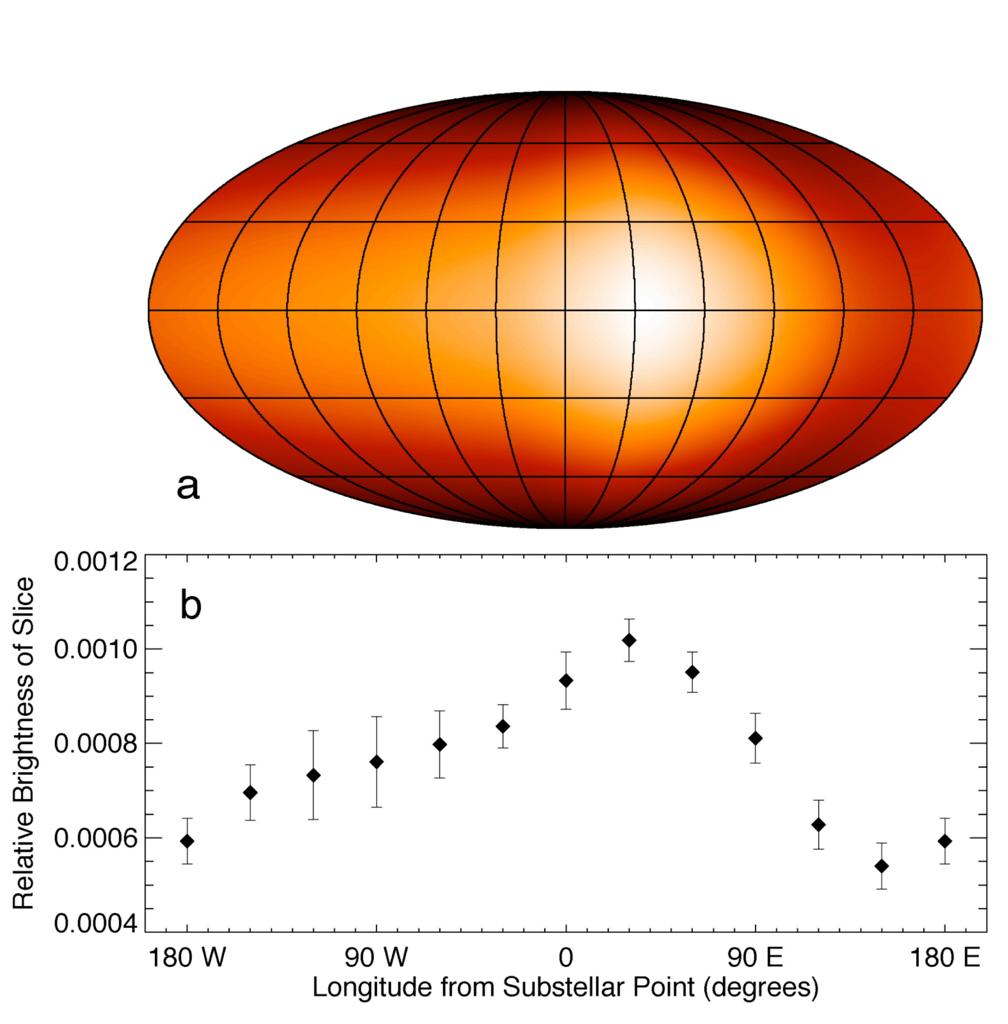
Transit Secondary Eclipse



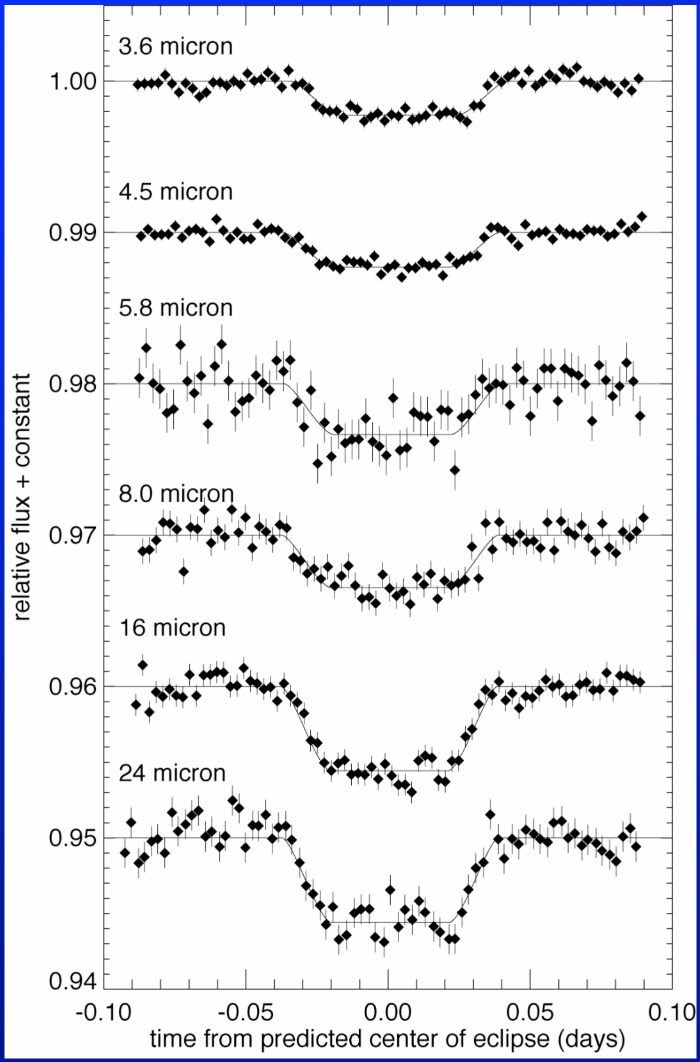


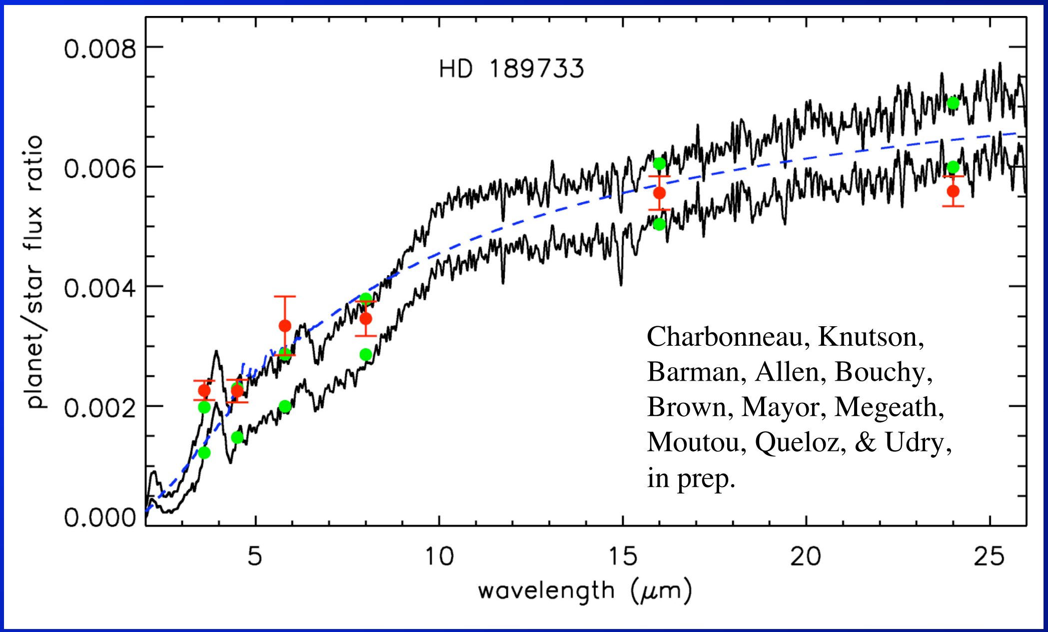
Mapping the Day-Night Contrast





Filling in the Picture: HD 189733b in Emission

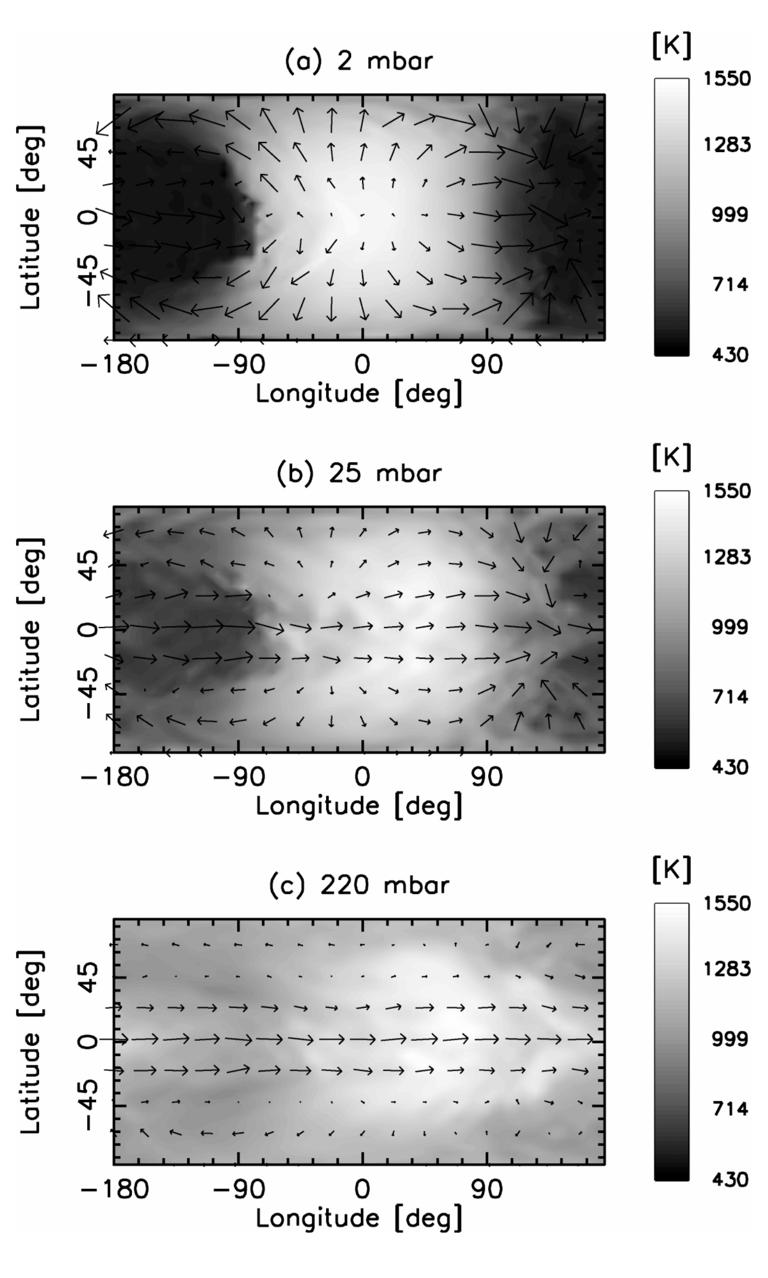




Fluxes are reasonably consistent with predictions from Barman model . . . also MOST upper limit on albedo coming soon.

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

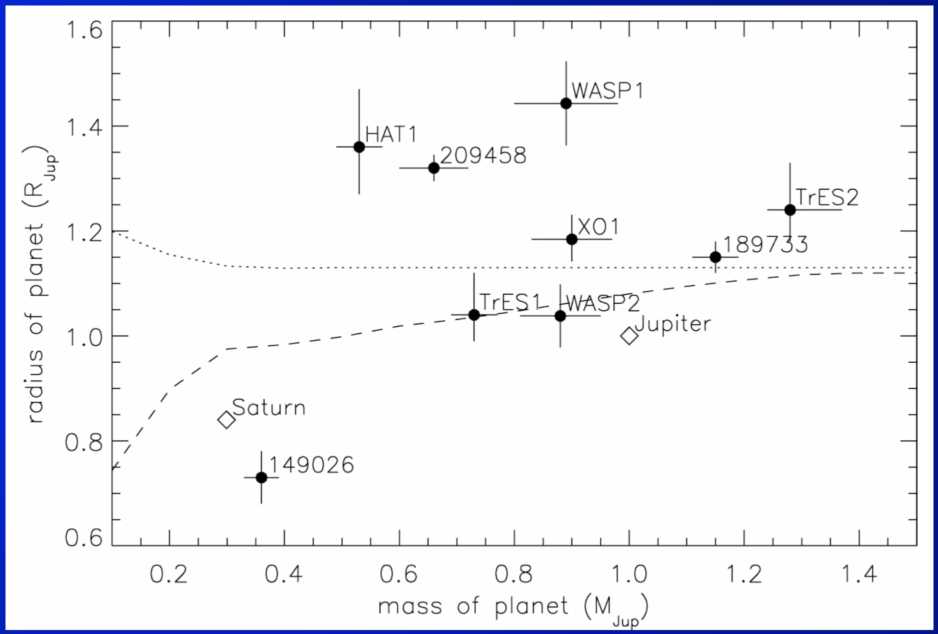


Cooper and Showman (2005) model for HD 209458b

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

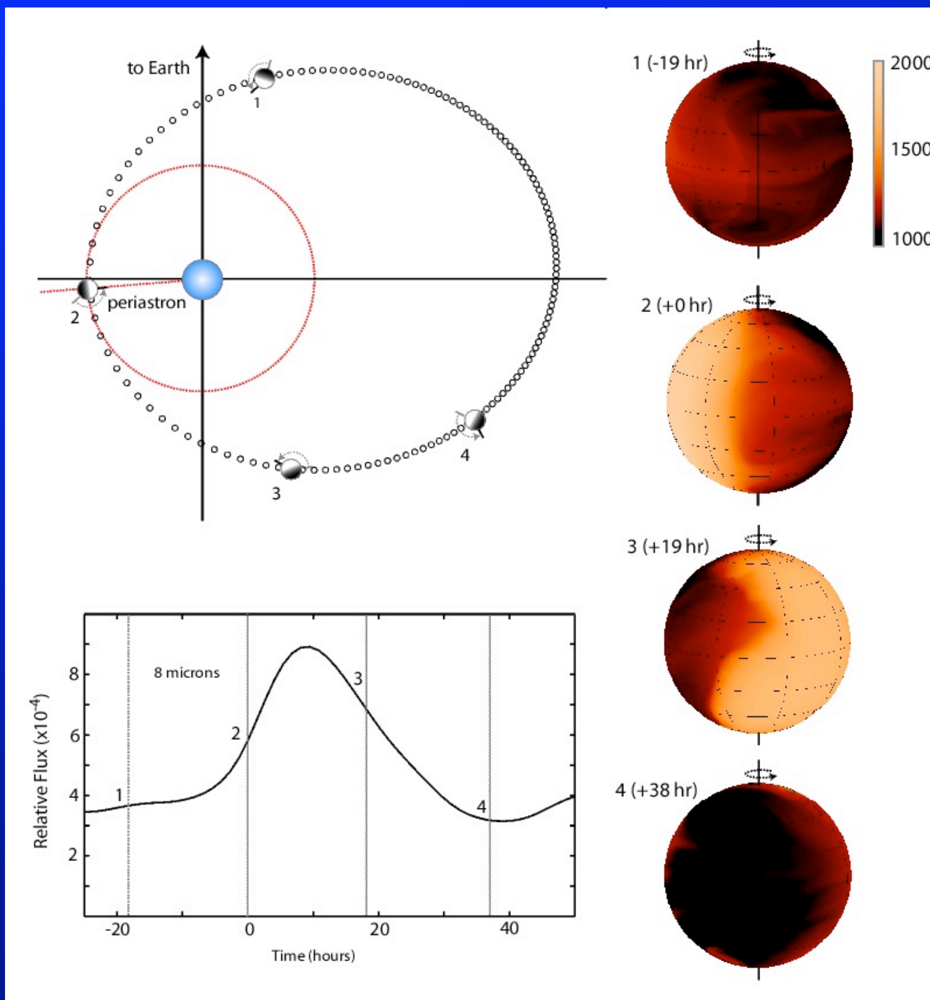
Clues to the Inflated Radius Problem?



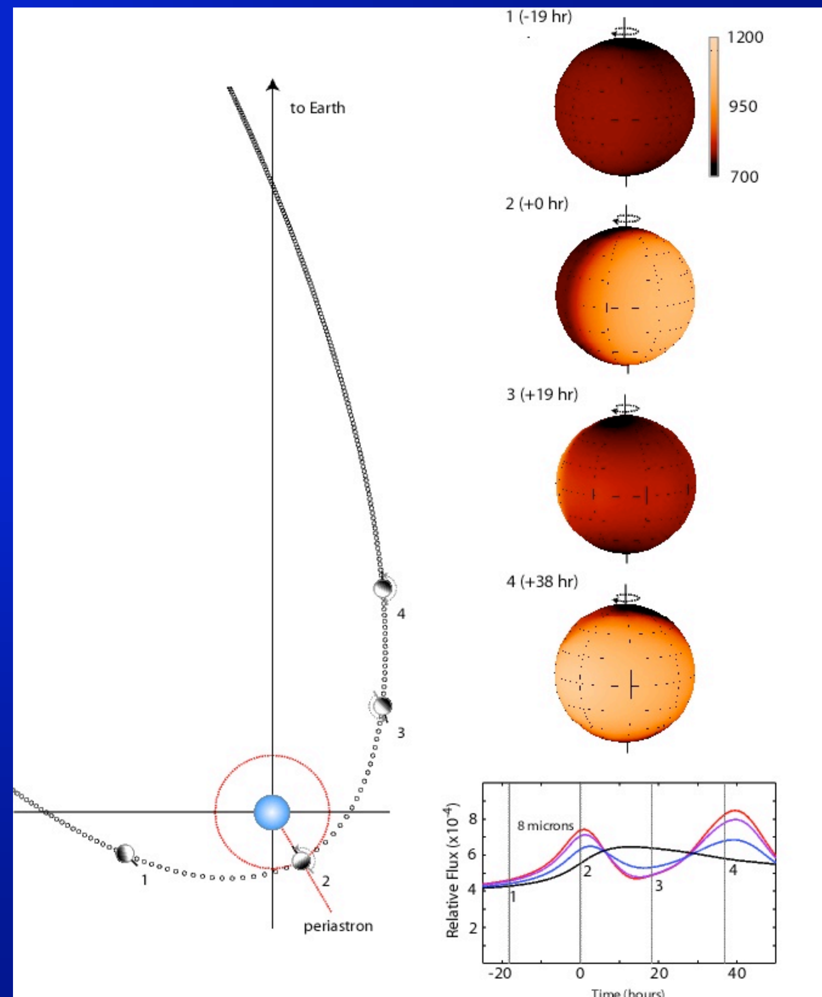
Charbonneau et al. (2007)

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