WASP-8b: Characterization of a Cool and Eccentric Exoplanet with Spitzer

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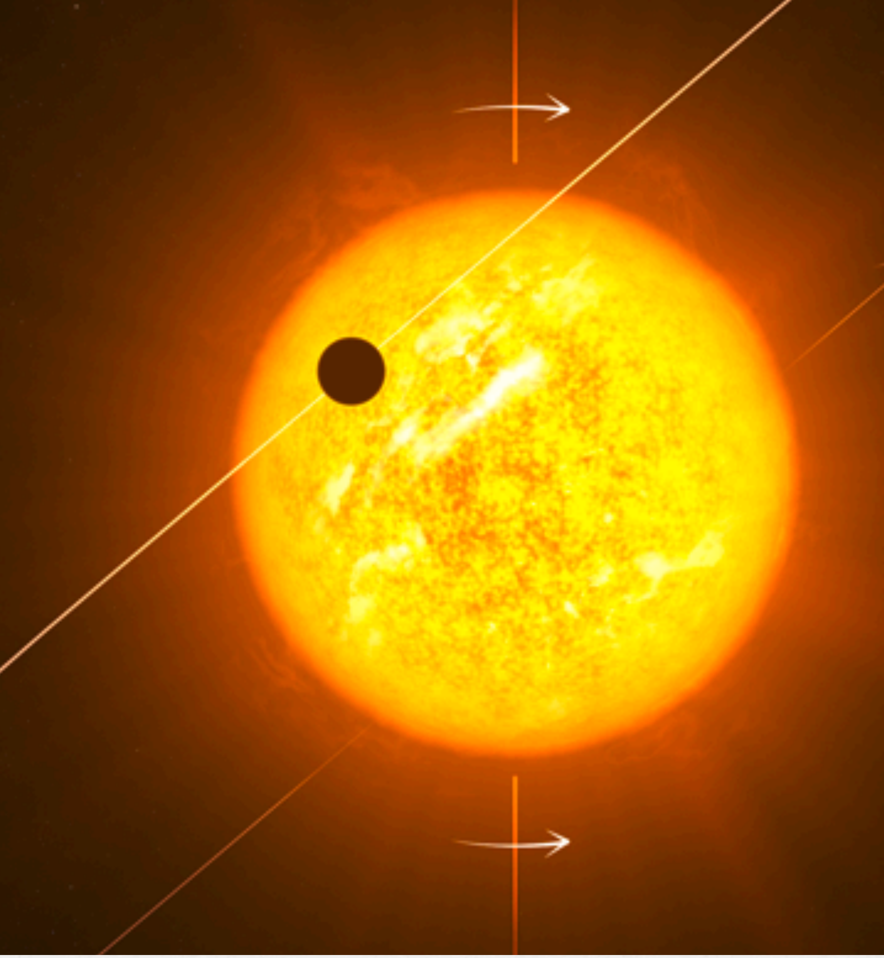

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SPITZER SPACE TELESCOPE

Committee members:
Joseph Harrington
Eduardo Mucciolo
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April 12th, 2012

Outline:

1.- Introduction to exoplanets

2.- Objectives

3.- Observations and data analysis

4.- Orbital dynamics analysis

5.- Atmospheric analysis

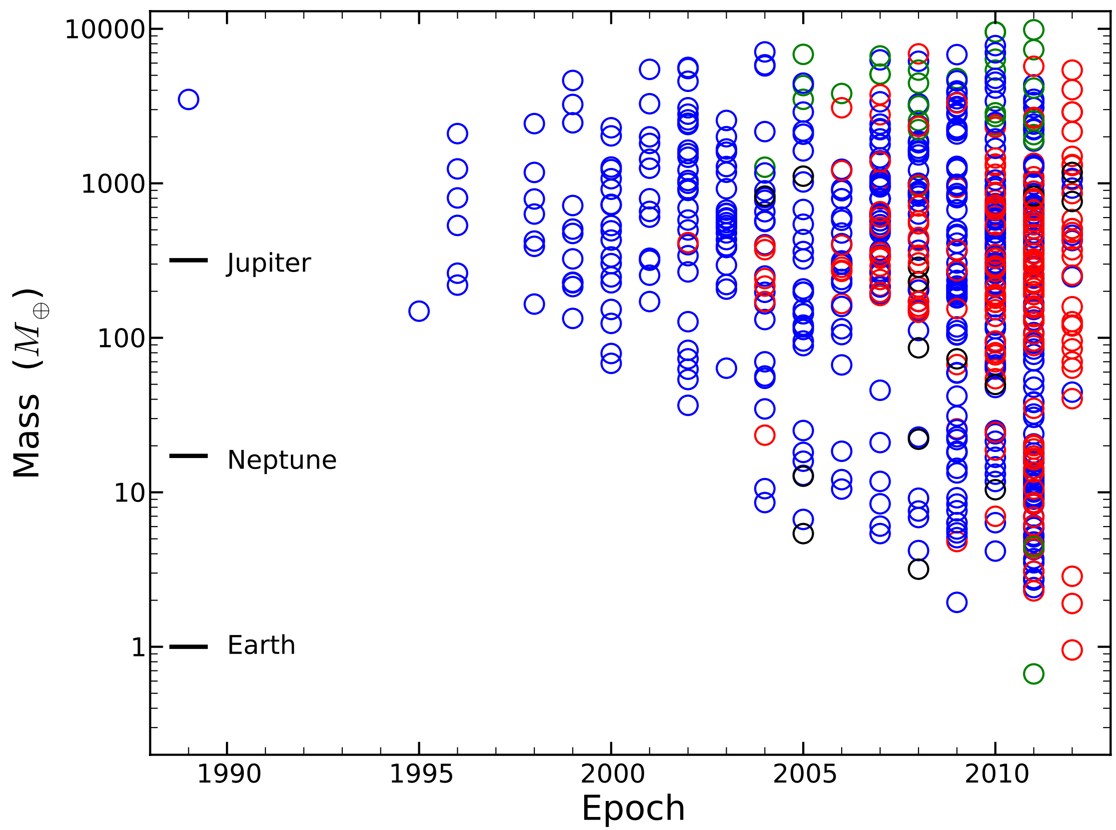
6.- Thermal variation analysis

7.- Conclusions

Extrasolar Planets:

- 17 years of history.
- 763 exoplanets detected to date.
- Increasing discovery rate.
- Improving detection limits.

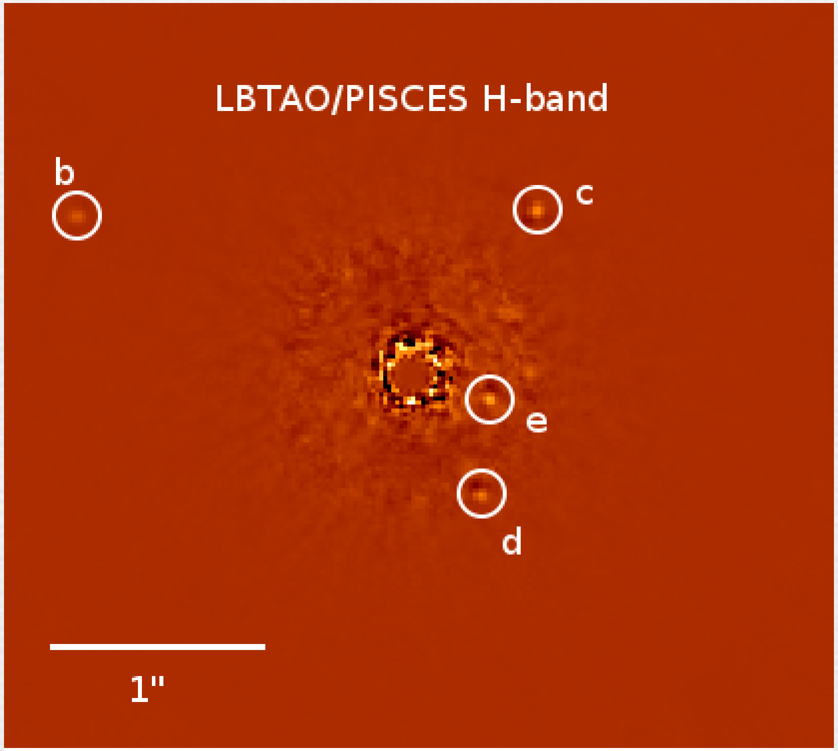
(data from exoplanet.eu)



Skemer et al. (2012)

Detection Methods:

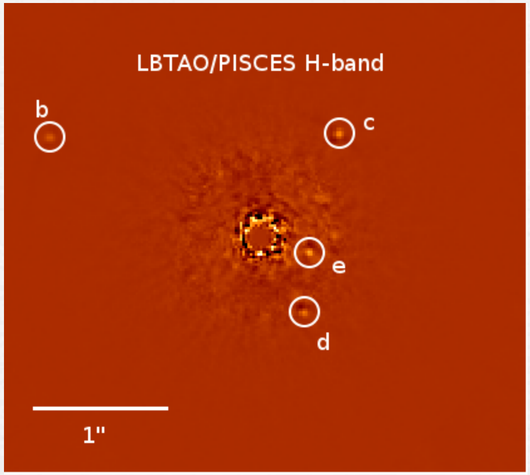
- Direct Imaging

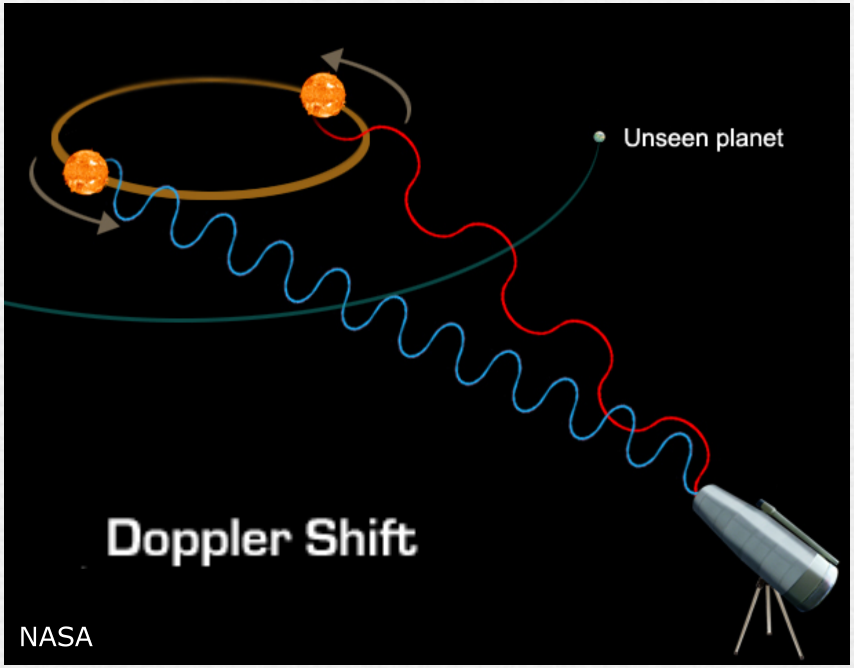


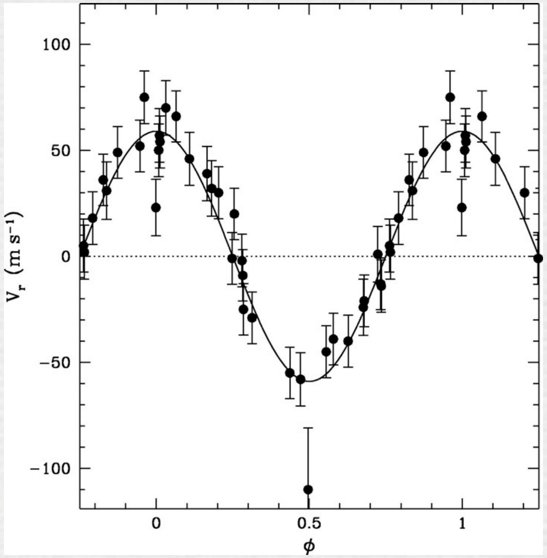
Skemer et al. (2012)

Detection Methods:

- Direct Imaging
- Radial Velocity (Doppler Shift)

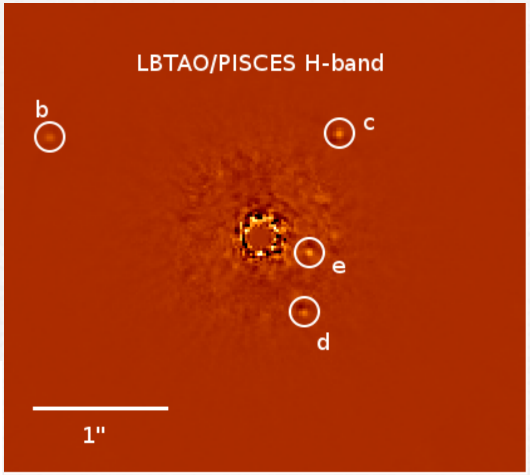






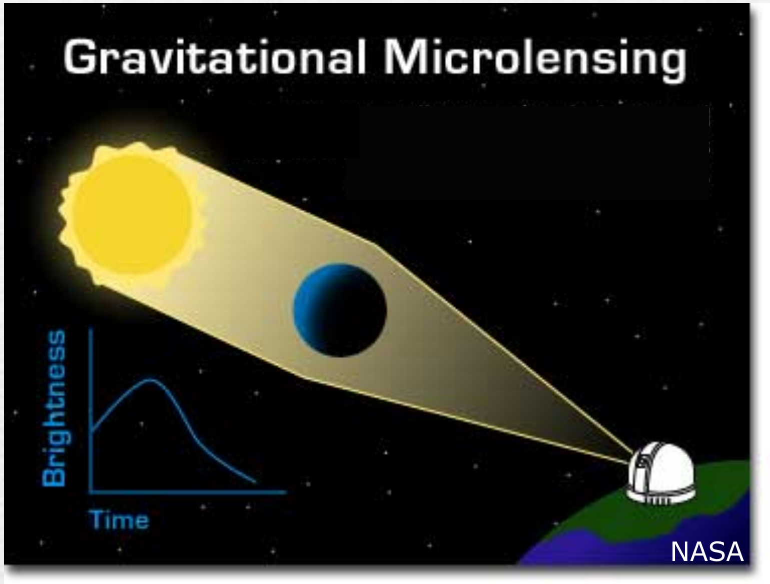
Mayor & Queloz (1995)

Skemer et al. (2012)

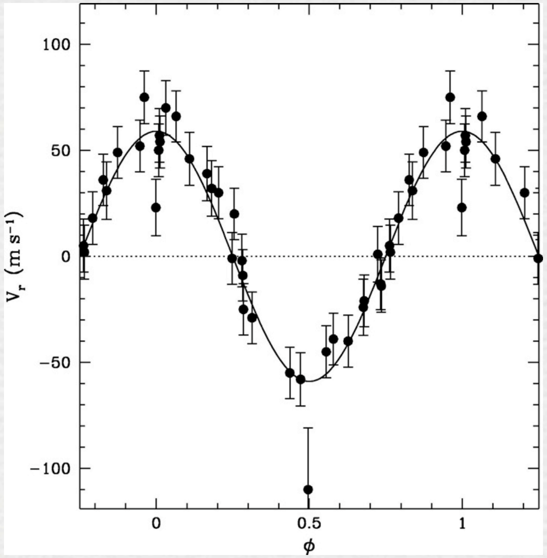


Detection Methods:

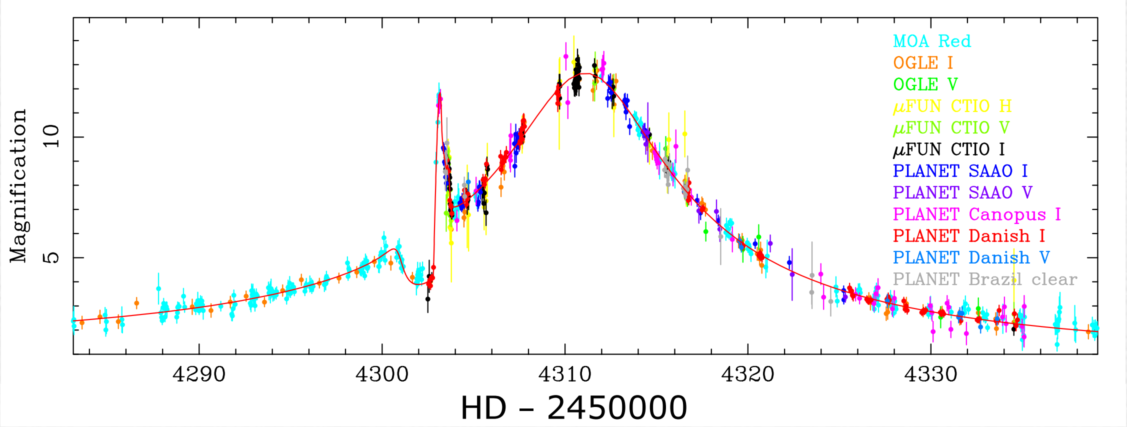
- Direct Imaging
- Radial Velocity (Doppler Shift)
- Gravitational Microlensing



Sumi et al. (2010)



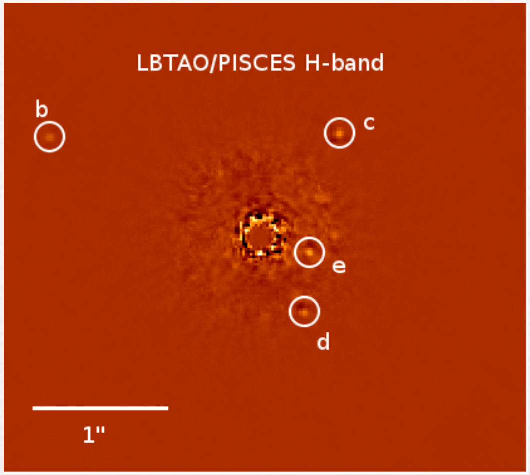
Mayor & Queloz (1995)

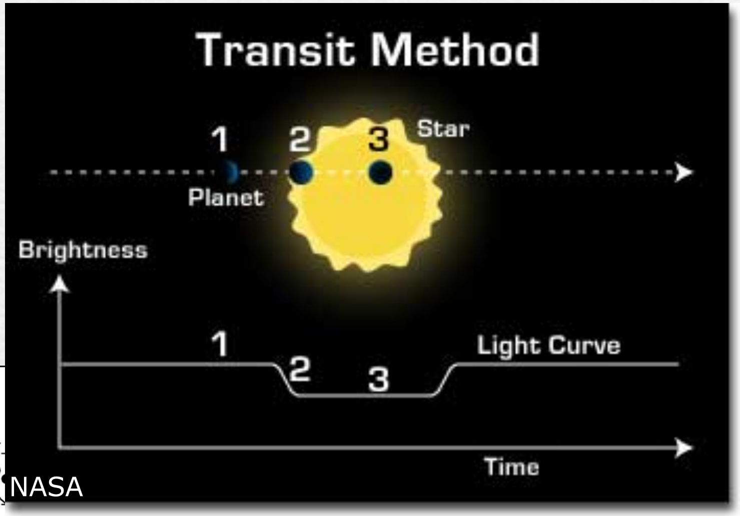


Detection Methods:

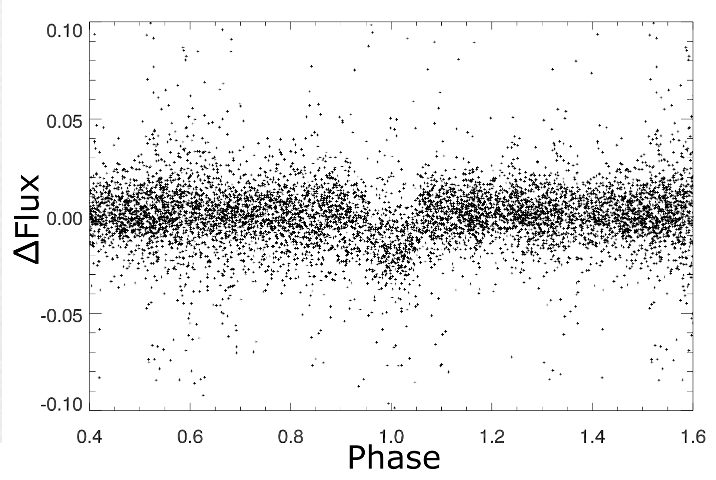
- Direct Imaging
- Radial Velocity (Doppler Shift)
- Gravitational Microlensing
- Transits

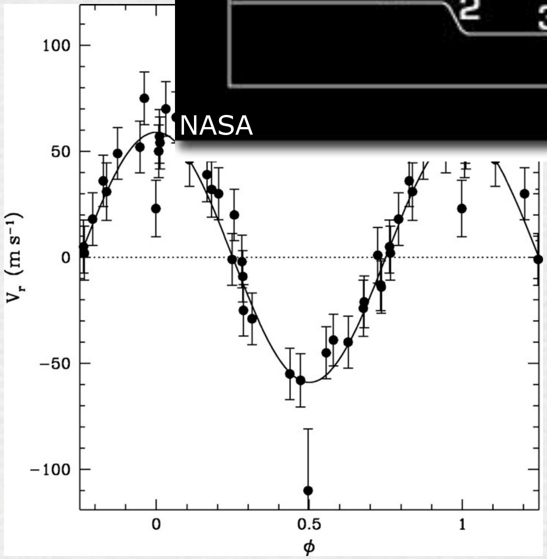
Skemer et al. (2012)





Hebb et al. (2009)





Mayor & Queloz (1995)

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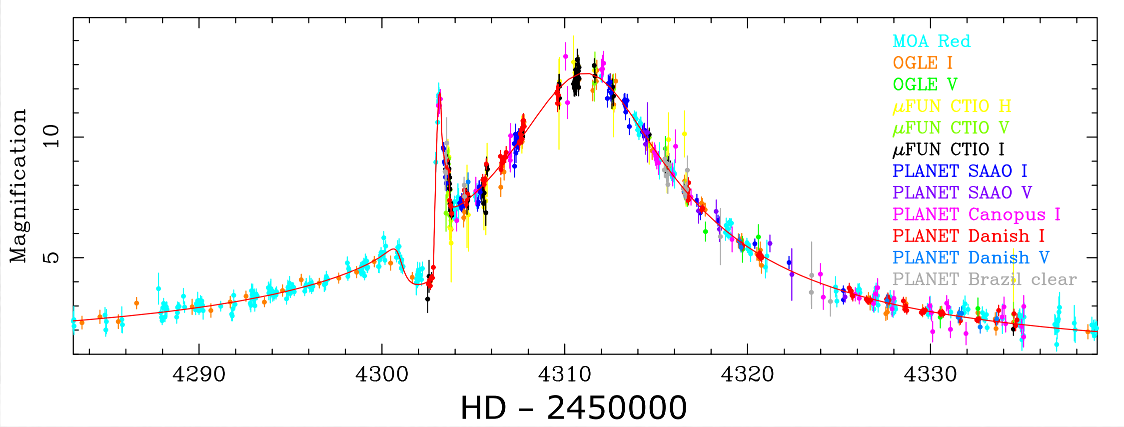
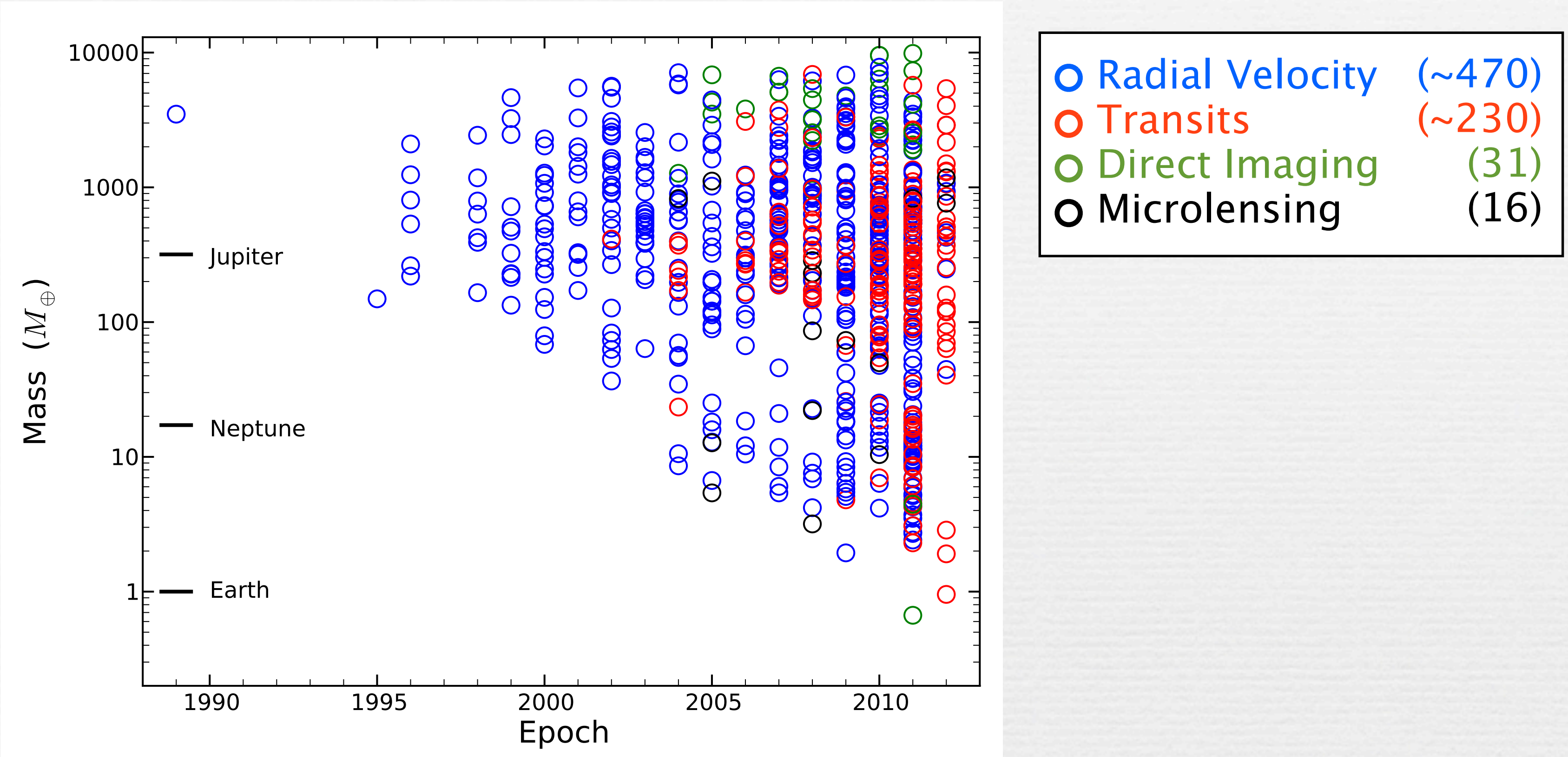


Extrasolar Planets:



"on average every star has 1.6 $(^{+0.7}_{-0.9})$ planets"

i.e., "every star in the Milky Way hosts one planet or more"

(Cassan et al. 2012)

"0.41 $(^{+0.5}_{-0.1})$ is the frequency of habitable planets orbiting M-dwarf stars"

(Bonfils et al. 2011)

Objectives:

Long term:

- Find evidence for life on other planets.

Shorter term:

- Determine the abundance and diversity of exoplanets.
- Study the physics and chemistry of exoplanetary atmospheres.

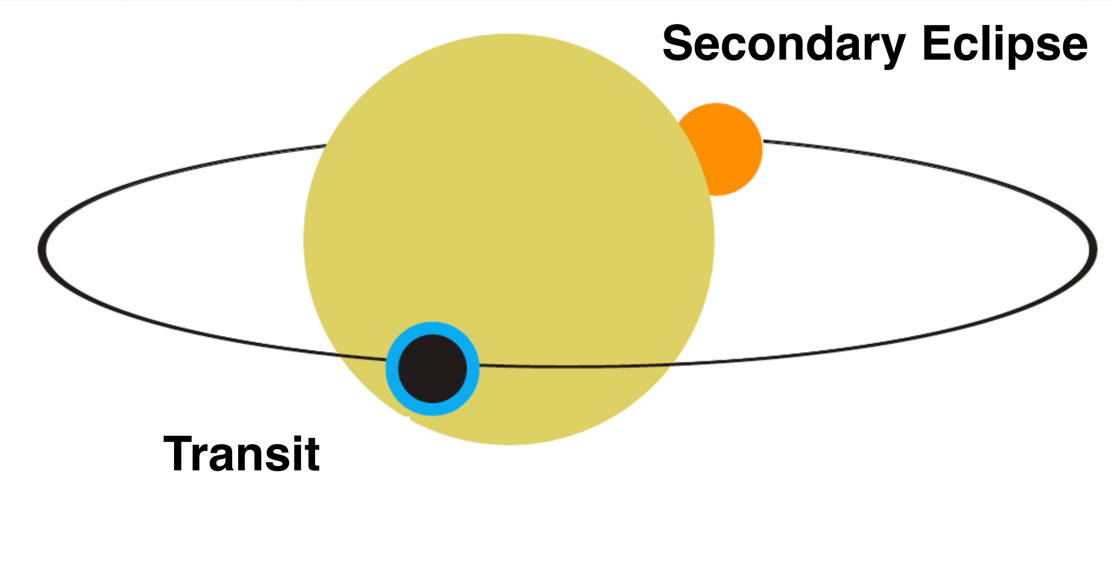
This work:

- Analyze secondary-eclipse light curves of WASP-8b.
- Determine broadband IR fluxes.
- Improve orbital solutions.
- Fit physical models to the IR fluxes to constrain the planet's atmospheric composition and thermal profile.

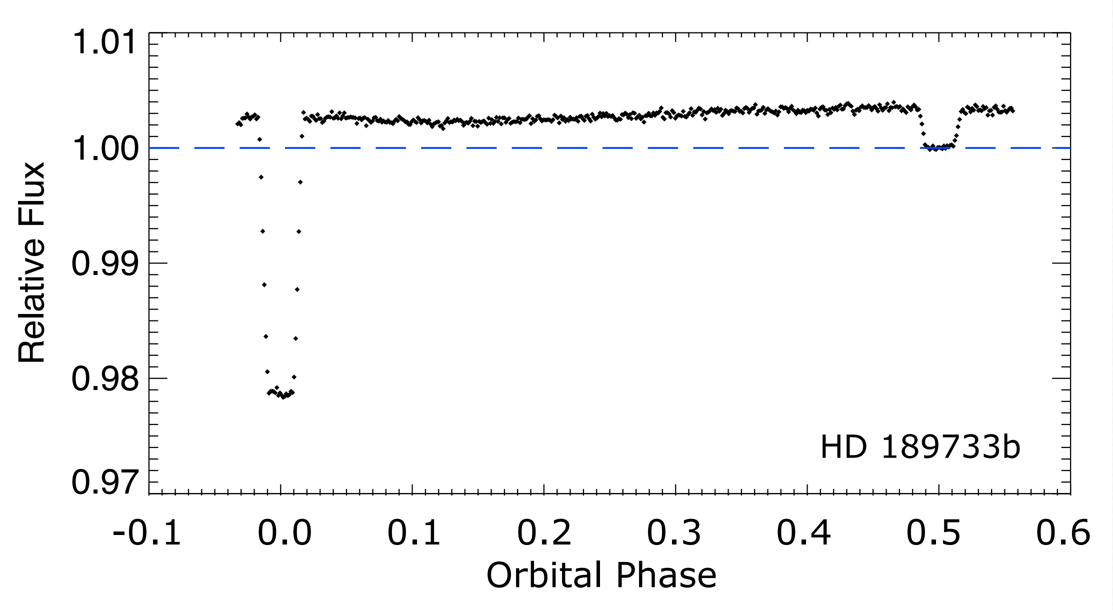
Transiting Exoplanets Observations:

In transiting exoplanets the planet is also eclipsed.

IR observations measure its thermal emission.



Seager & Deming al. (2010)



$$\text{Eclipse depth} = \frac{\Delta F}{F} \approx \frac{F_p}{F_s}$$

Knutson et al. (2009)

The WASP-8 System:

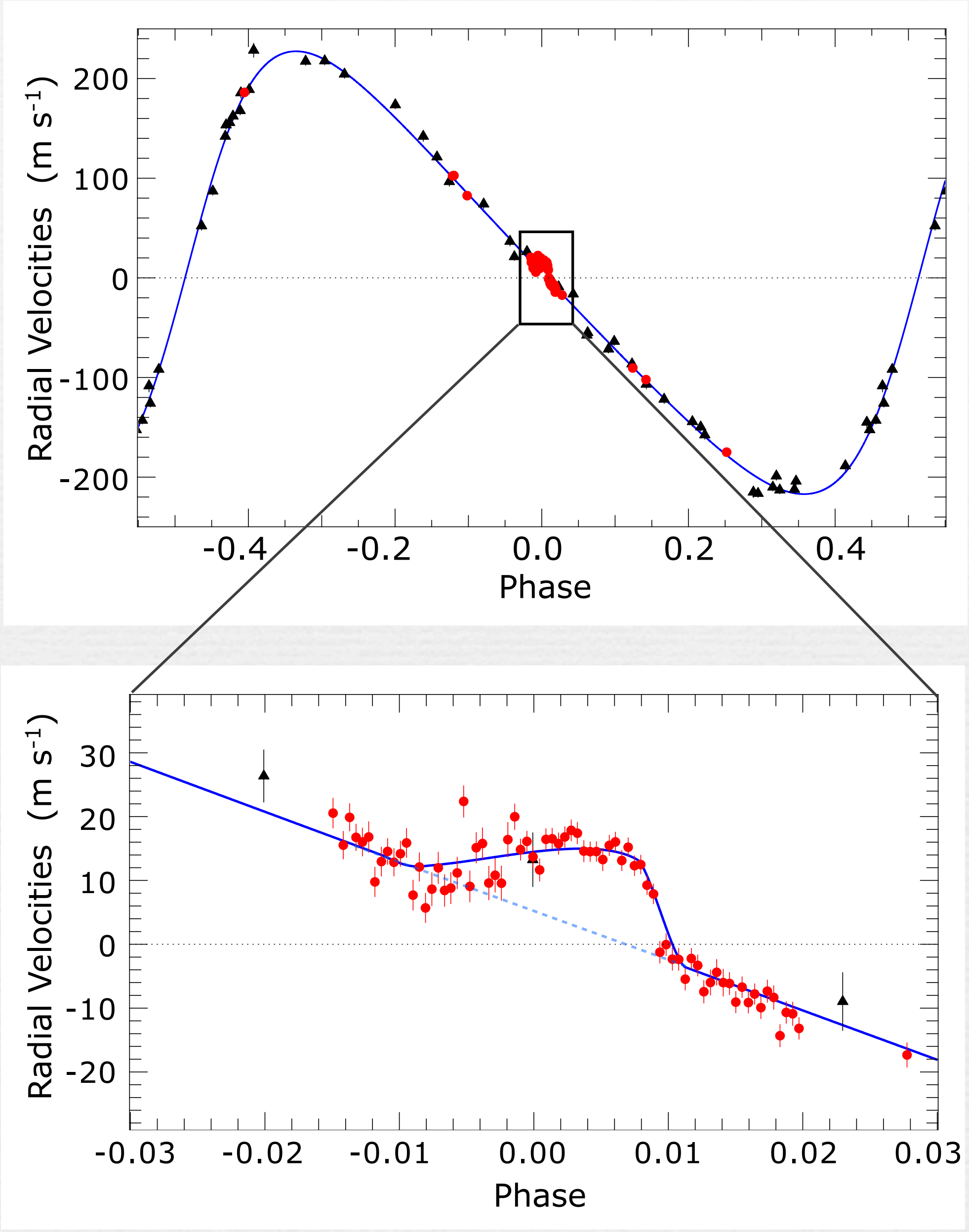
The planet WASP-8b orbits the primary star of a binary stellar system.

Eccentric (e=0.31), 8.1-day orbit.

Equilibrium temp.: 942 K

Rossiter-McLaughlin effect:

⇒ Retrograde orbit



Queloz et al. (2010)

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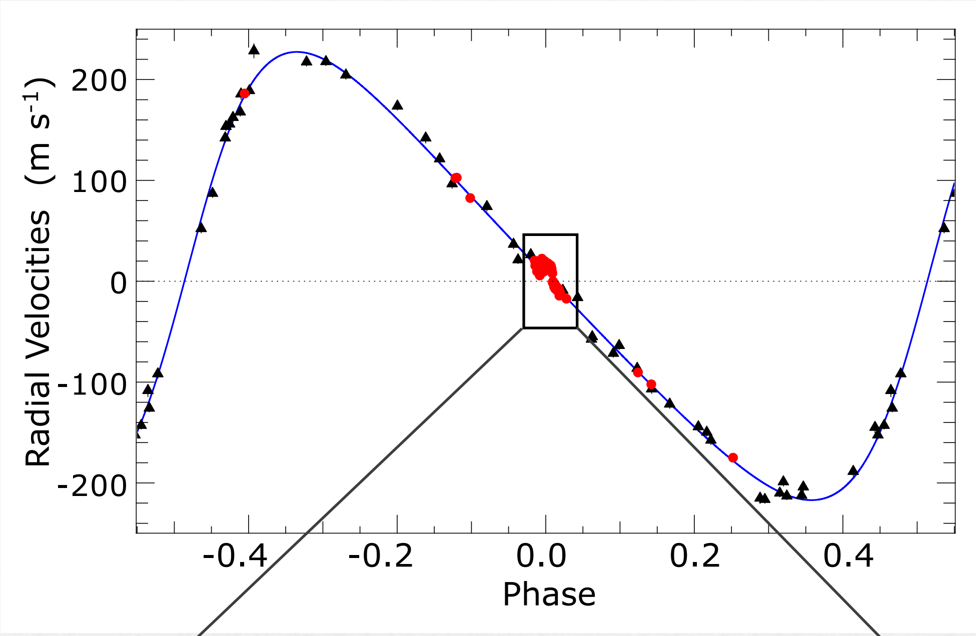
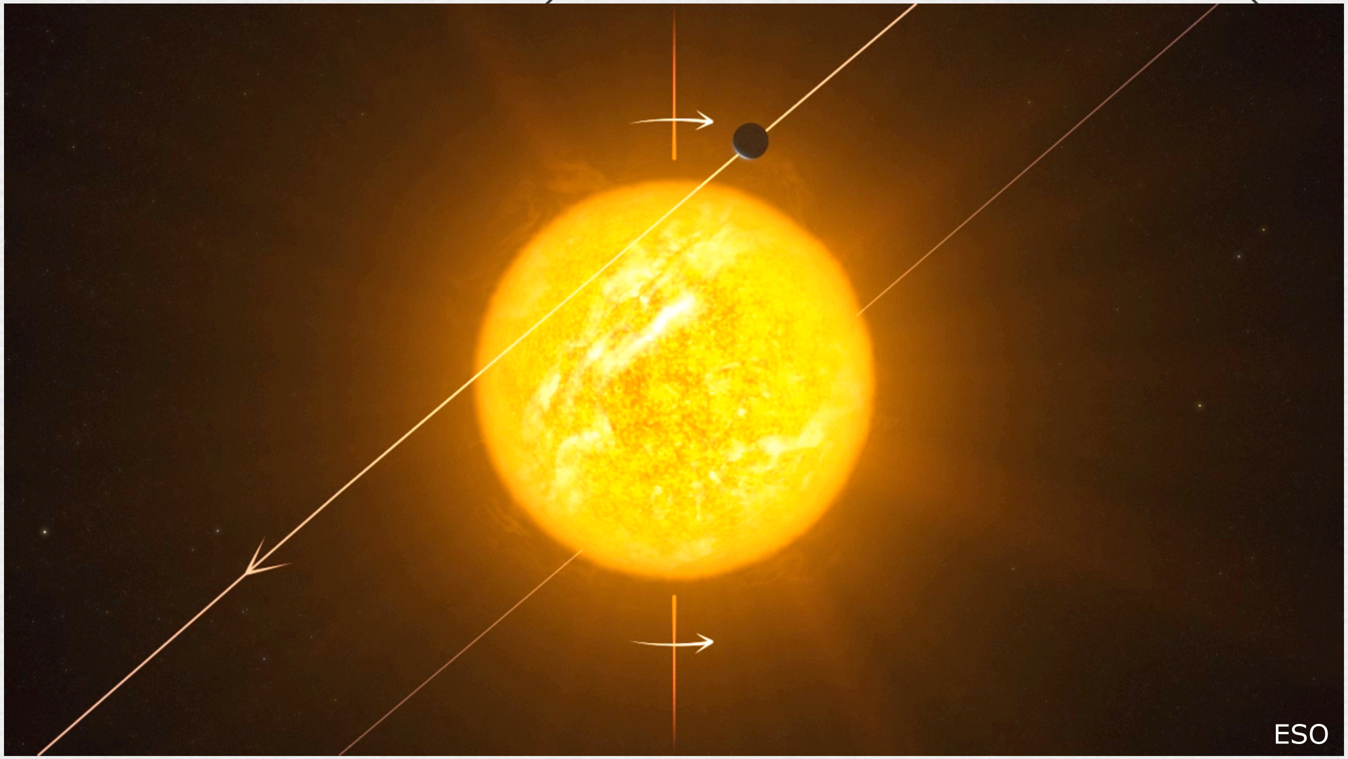




Observations:

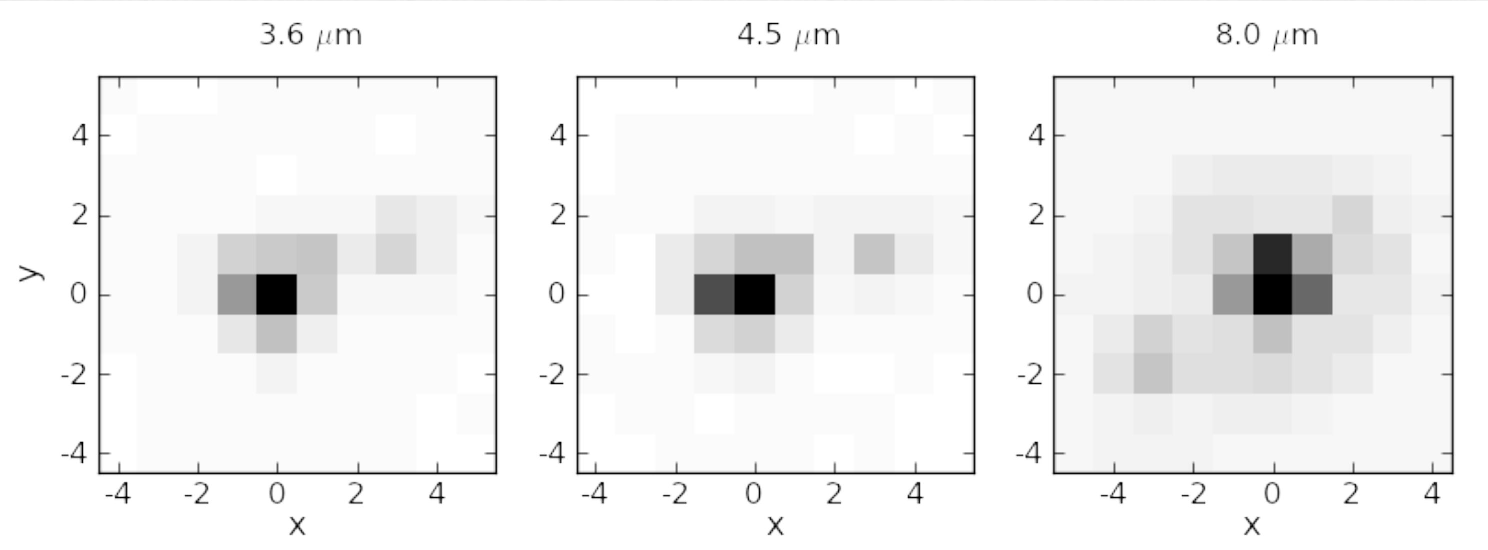
Spitzer Space Telescope broadband IR light curves:

	Dec. 13 2008	Dec. 21 2008	Jul. 23 2010	Jul. 31 2010
3.6 μm			✔	
4.5 μm	✔	✔		✔
8.0 μm	✔	✔		

WASP-8B:

– 3.7 pixels distant from the target (~440 AU).

$$\frac{\text{WASP-8B Flux}}{\text{WASP-8A Flux}} \approx \frac{1}{6}$$



POET: Photometry for Orbits, Eclipses, and Transits

Performs:
- Bad-pixel masking.
- Centering.
- Aperture photometry.
- Light-curve modeling.

POET: Centering

Implemented a double PSF fitting. (Crossfield et al. 2010)

– Fit $\{x_A, y_A, x_B, y_B, F_A, F_B, f_{sky}\}$

Created high resolution stars models (Tiny Tim software).

- Positions fitted by: shifting and binning to avoid interpolation.
- Fluxes are fitted with a χ^2 minimizer.

POET: Photometry

We need to remove the contribution from WASP-8B.

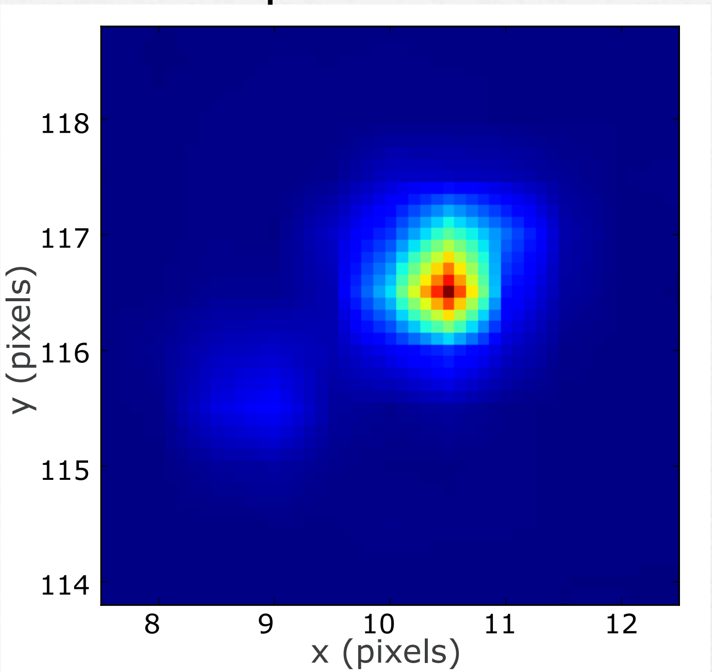
Implemented two methods:
1.- **B-Subtract** photometry:
Subtract WASP8-B model from data.

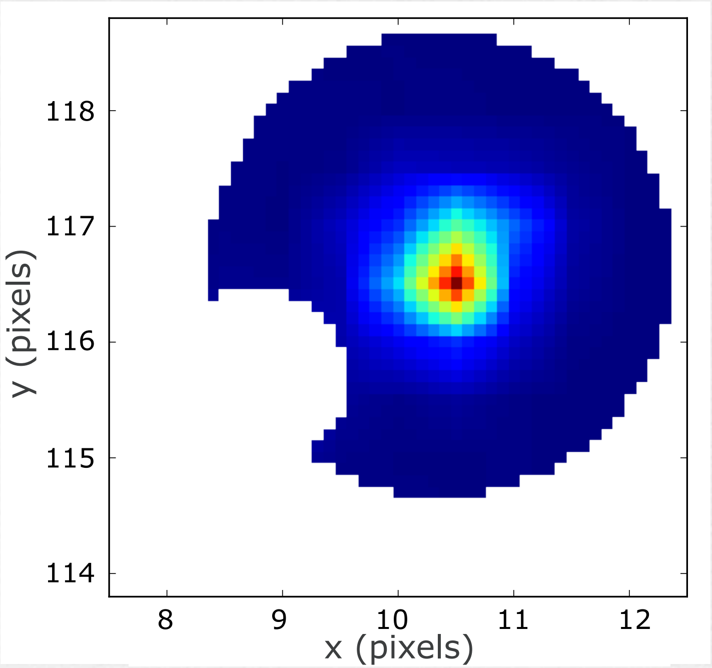
2.- **B-Mask** photometry:
Discard the pixels within a circular aperture around WASP-8B.
(masks radii: 1.6, 1.8, 2.0 pix.)

Performed 5X-interpolated aperture photometry (Harrington et al. 2007).

Methods x Apertures
(4) x (~7) = ~30 light curves.

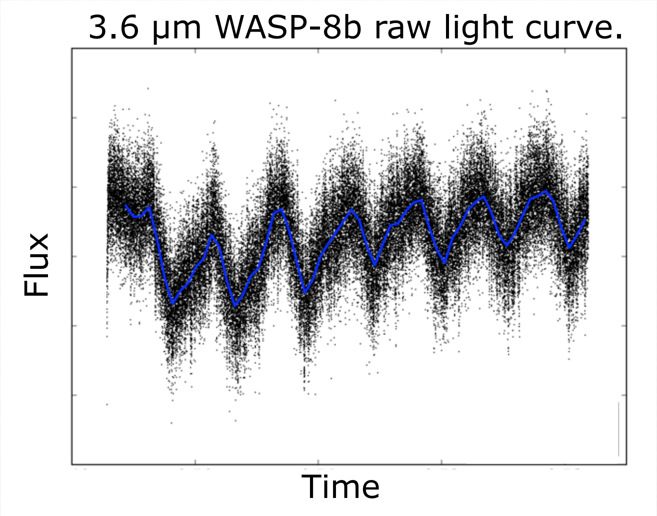
Interpolated data:

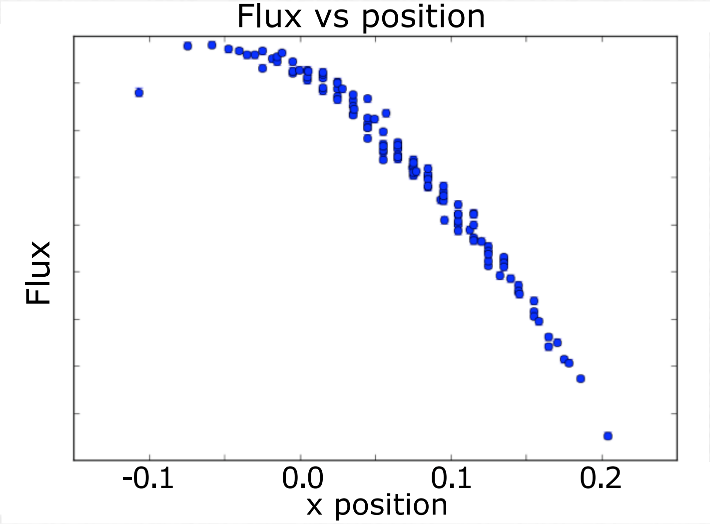




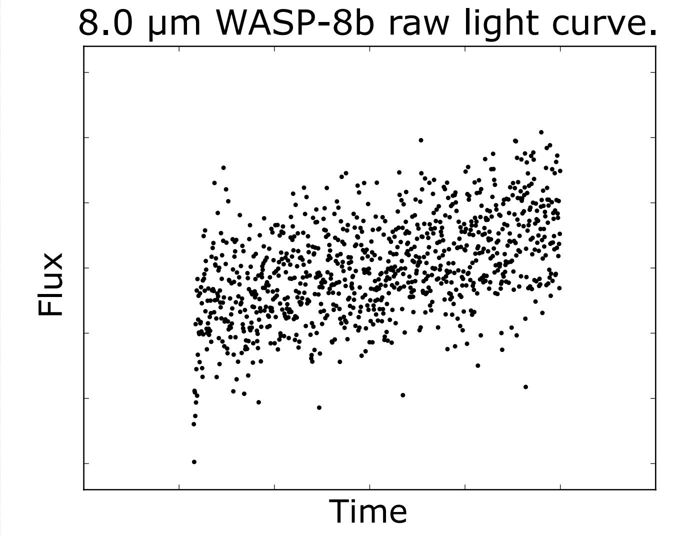
Spitzer Systematics:

1.- Position dependent flux variations ("Intra-pixel effect"). Charbonneau et al. (2005)





2.- Time-dependent pixel sensitivity ("Ramp"). Agol et al. (2010)



POET: Light Curve Modeling

Model the light curve as:

$$F(x,y,t) = F_s\, E(t)\, M(x,y)\, R(t)$$

F_s = System flux.

E(t) = Eclipse model.

Mandel & Agol (2002)

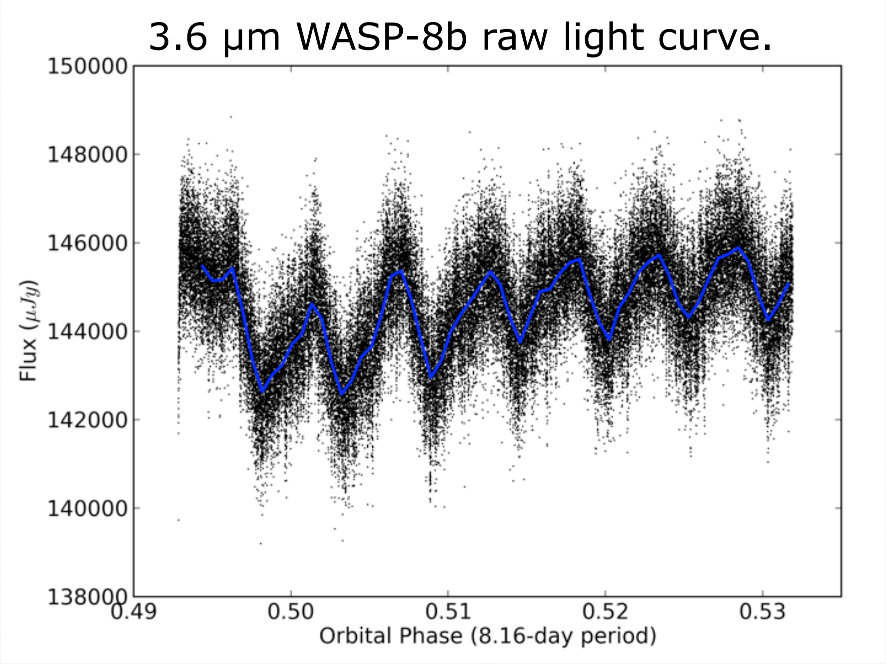
M(x,y) = Bi-linearly Interpolated subpixel sensitivity.

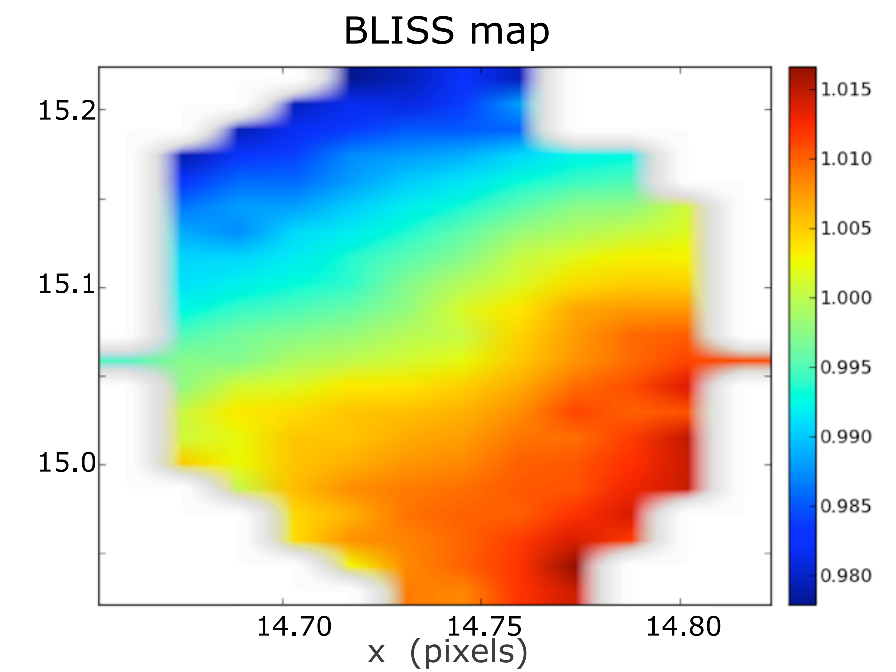
Stevenson et al. (2011)

R(t) = Ramp model.

Select among:

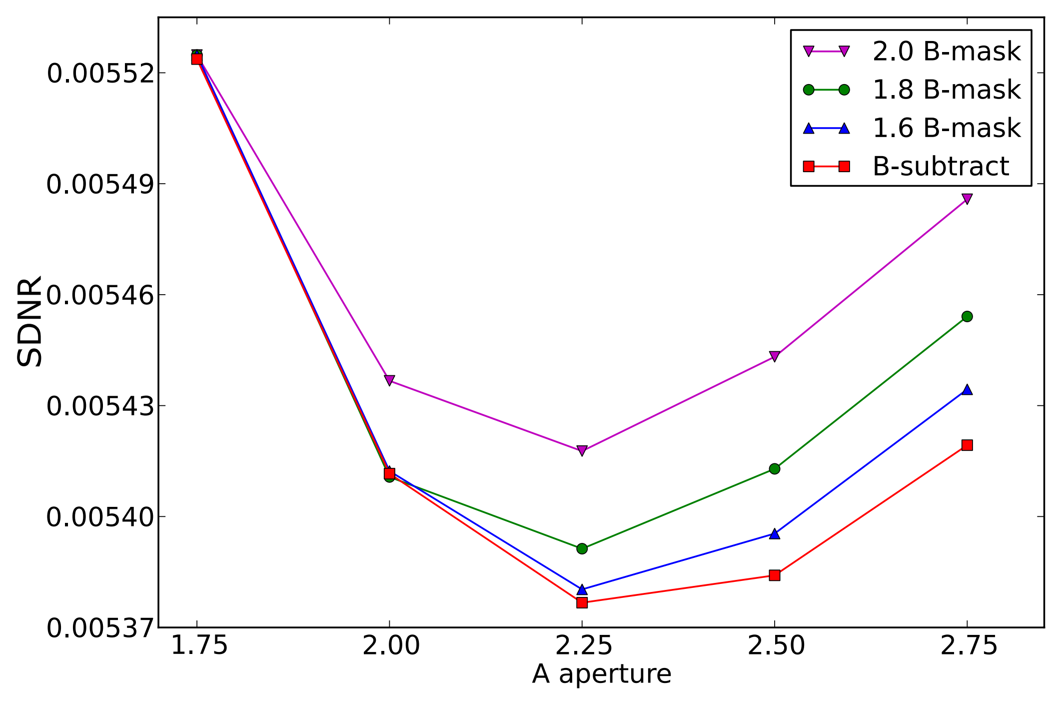
- Polinomial
- Logarithmic
- Exponential functions





POET: Light Curve Modeling

Select light curve:
- Minimizing the standard deviation of the normalized residuals (SDNR).

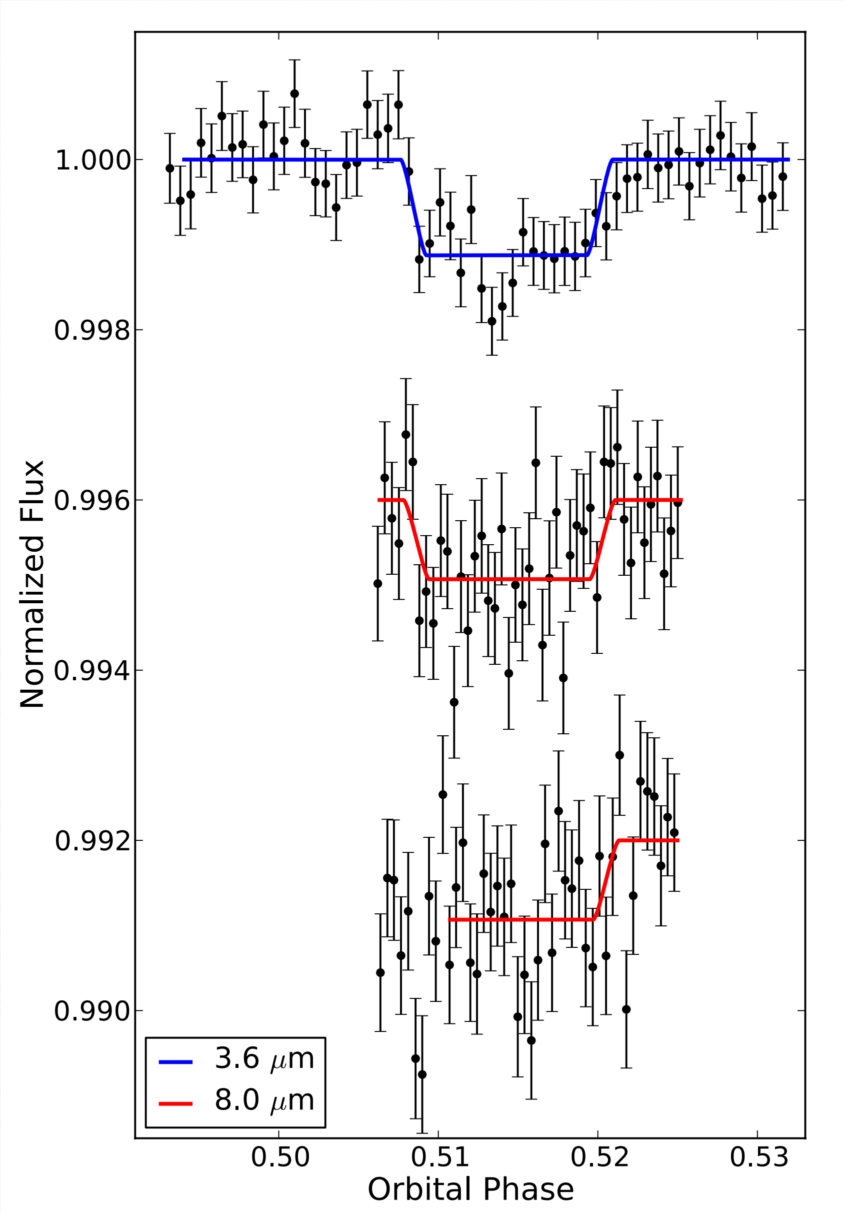


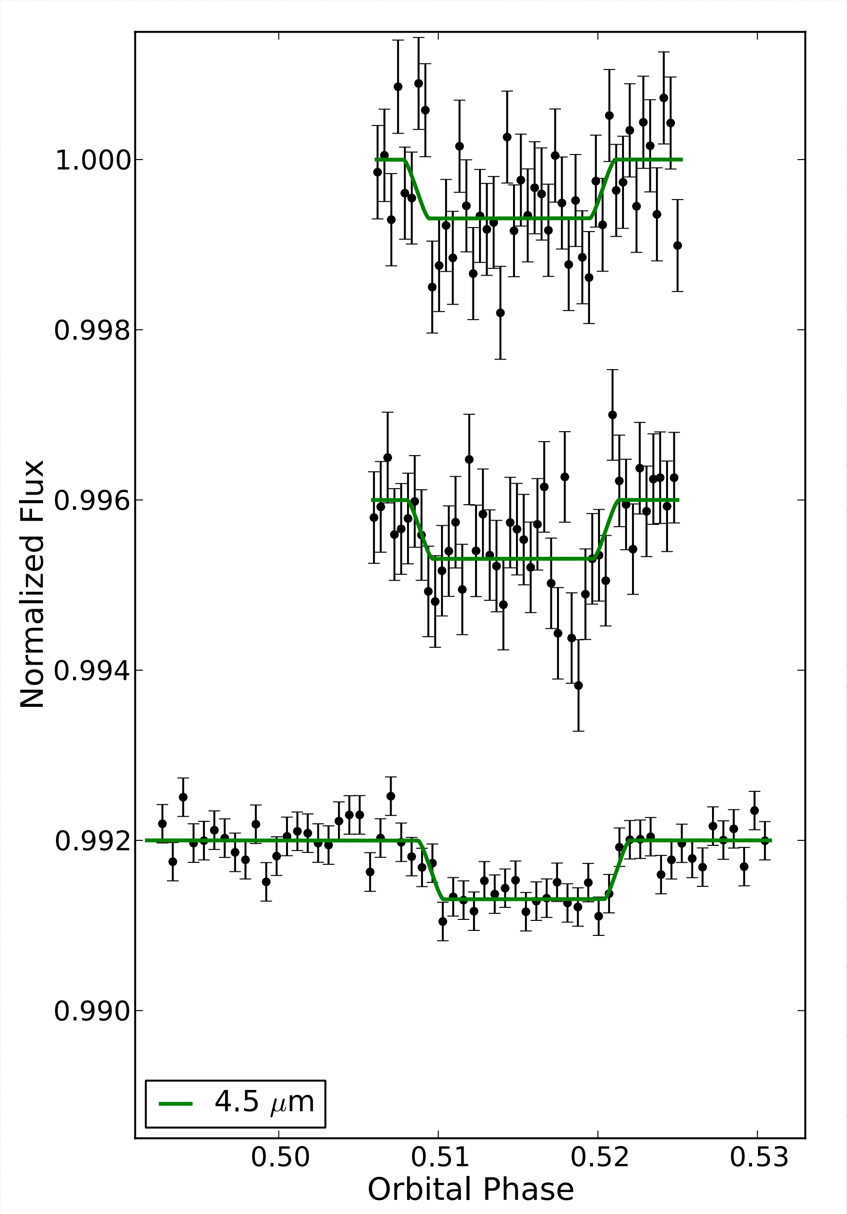
Select model:
- Minimizig the Bayesian information criterion:

$$BIC = \chi^2 + k \ln(N)$$

k: # free parameters
N: # data points

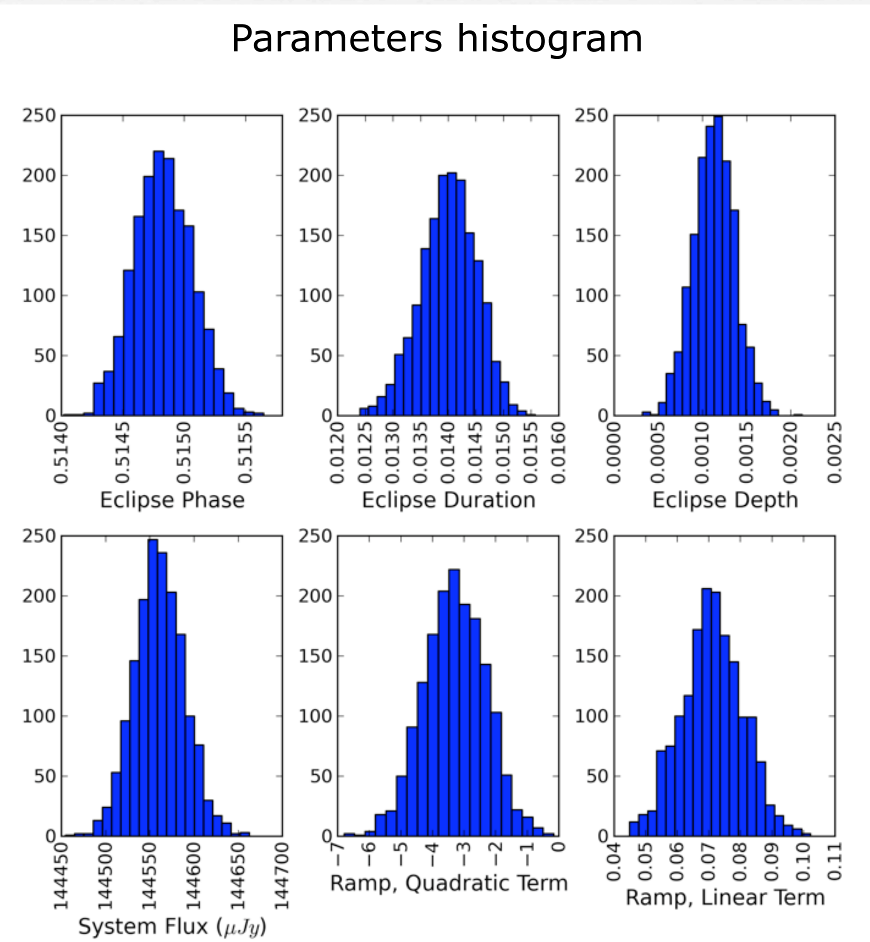
POET: Light Curve Modeling

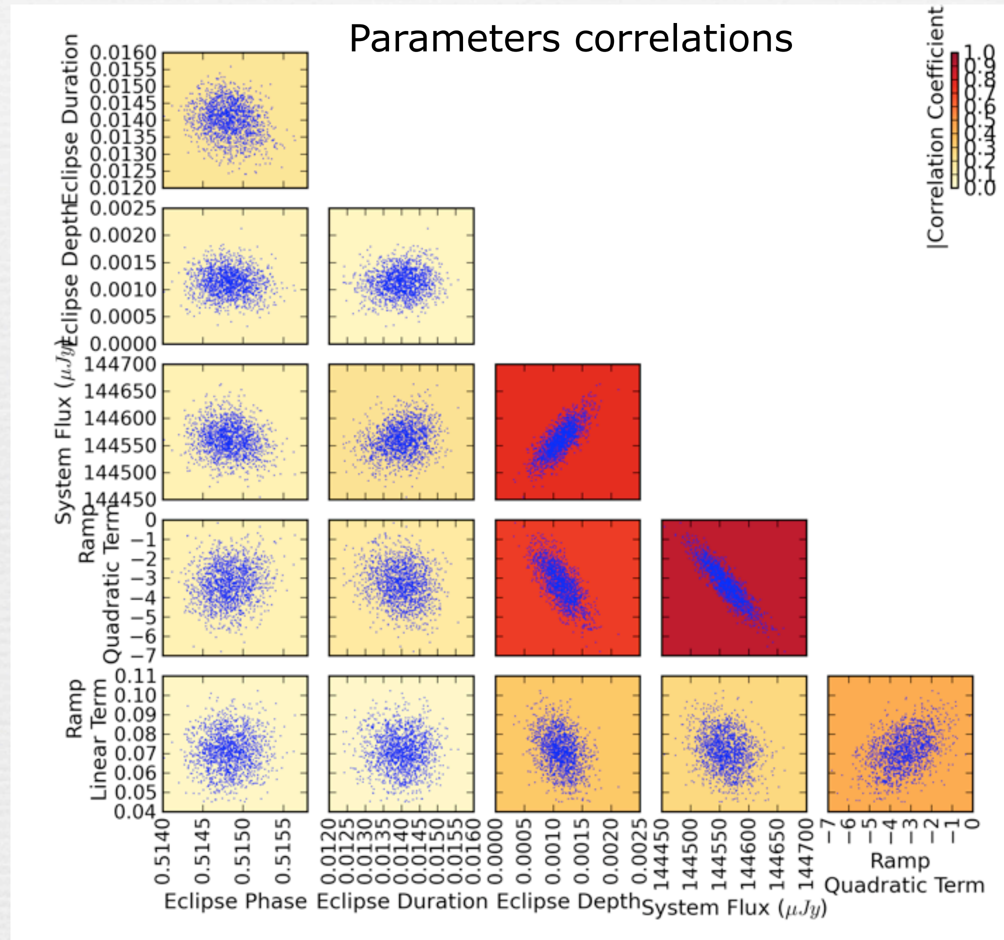




POET: Error Determination

Assessed uncertainties with a Markov-Chain Monte Carlo (MCMC) algorithm.





Orbital Dynamics:

We found, with respect to Queloz et al. (2010):

- One **eclipse phase** differs by 2.5σ.
- Significantly larger **radial velocity drift** (7.5σ).
- Marginal longer **period** (1.6σ).

- Radial velocity drift
- High eccentricity
- High obliquity
- Parameter variability

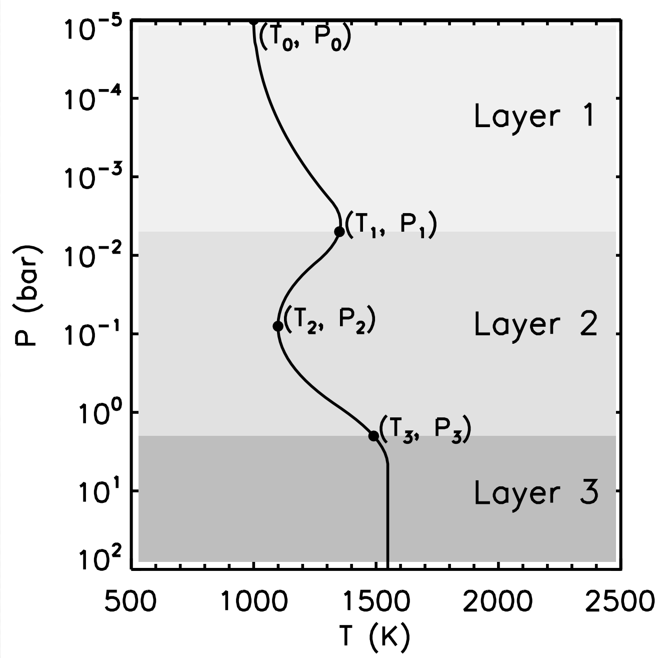
} WASP-8b is being perturbed.

Parameter variability within 3 yr period $\Rightarrow$ Unseen object rather than WASP-8B

Atmospheric Modeling:

Characterize the planetary atmosphere by fitting physical models to the eclipse depths.

Eclipse depths = F_{planet} / F_{star}.



(Madhusudhan & Seager 2009, 2010)

Parametrize:

- Pressure-temperature profile.
- Molecular abundances
  - water vapor (H_2O)
  - carbon monoxide (CO)
  - carbon dioxide (CO_2)
  - methane (CH_4)

1D radiative transfer

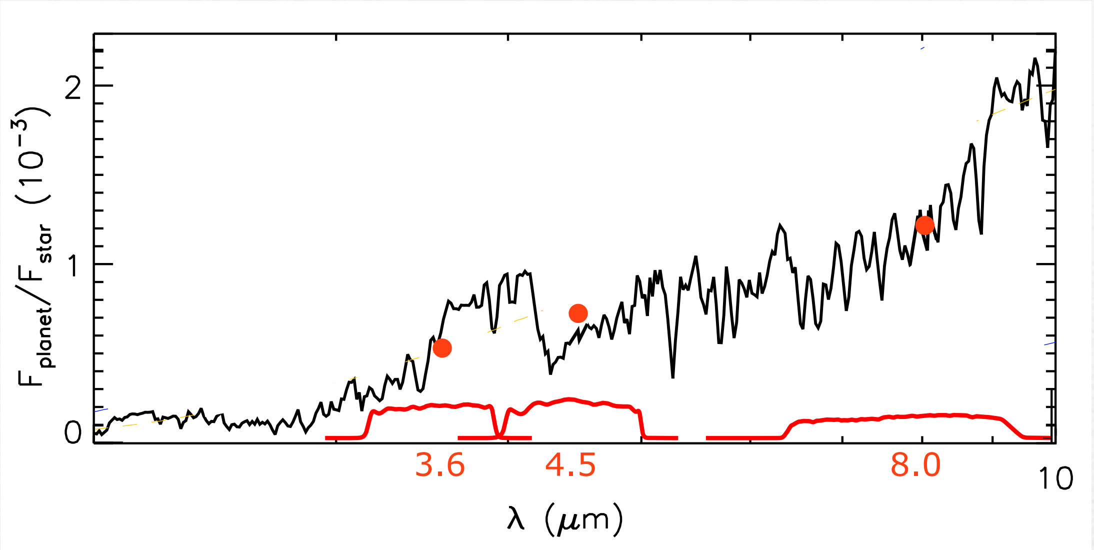
⇒

Planetary spectrum

Atmospheric Modeling:

Combine the planetary models with a stellar model.

Castelli & Kurucz (2004)



Integrate spectrum over the Spitzer wavebands.

- Compare through χ^2.
- MCMC samples the posterior distribution.

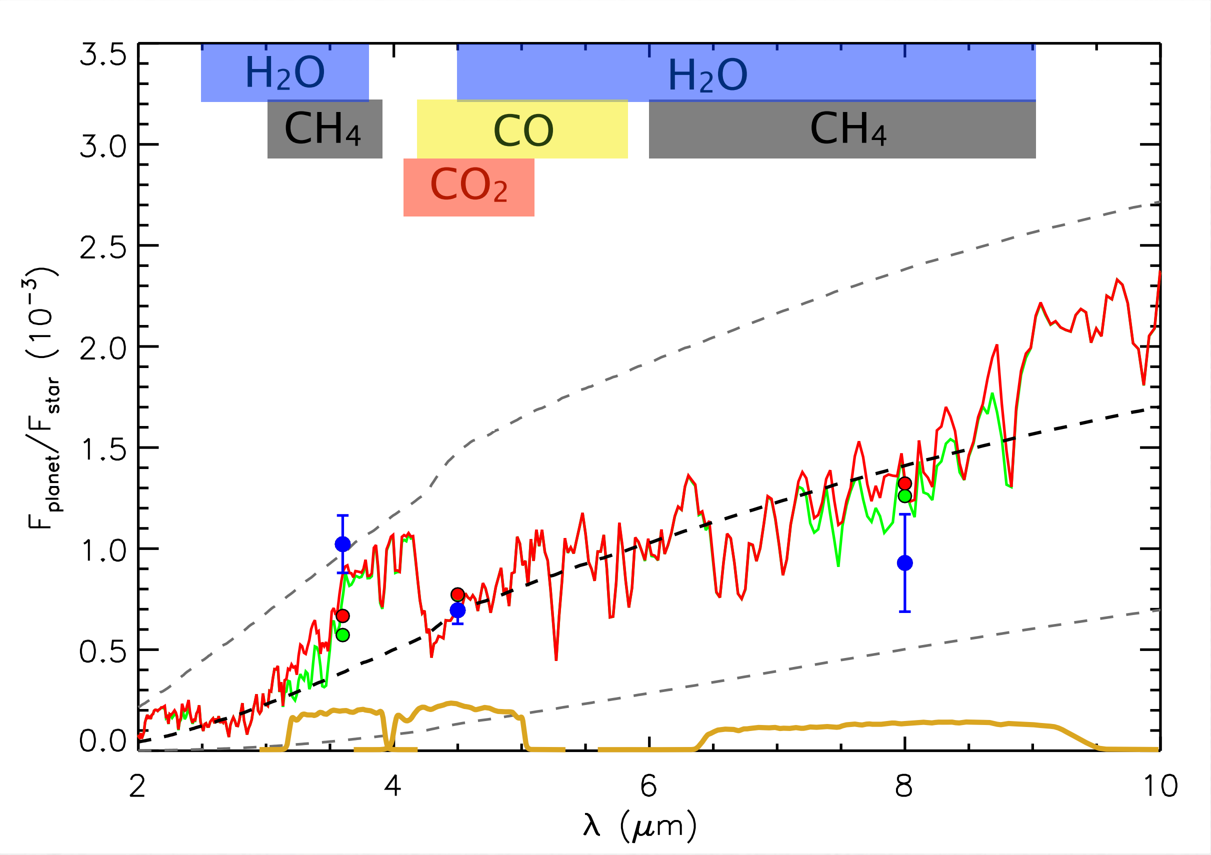
Waveband (μm)	Depth (%)	Brightness temp. (K)
3.6	0.113 +/– 0.018	1552
4.5	0.069 +/– 0.007	1131
8.0	0.093 +/– 0.023	938

(Equilibrium temperature ~ 950 K)

Atmospheric Modeling:

The molecular bands:

- Deviate spectrum from blackbody curve.
- Specific to certain wavelengths.
- Thermal profile determines: emission — absorption



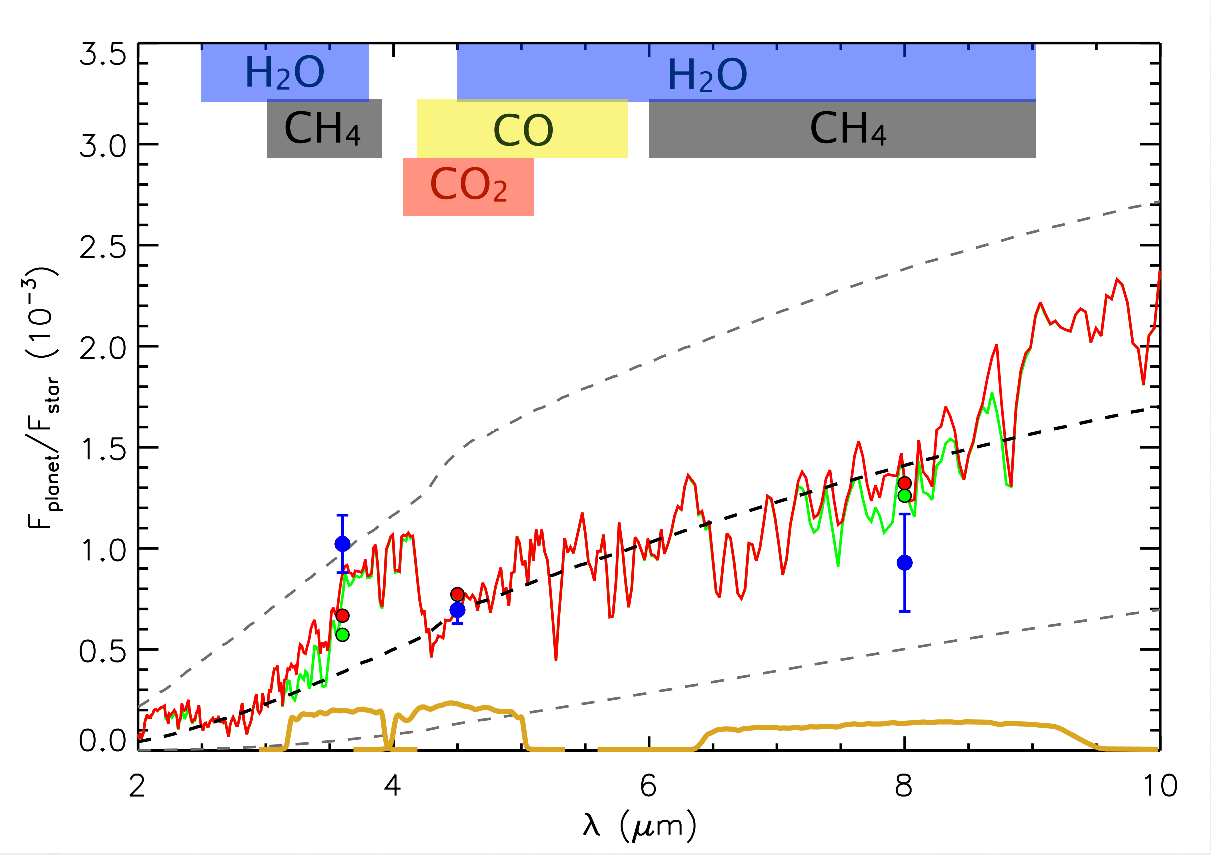
Atmospheric Modeling:

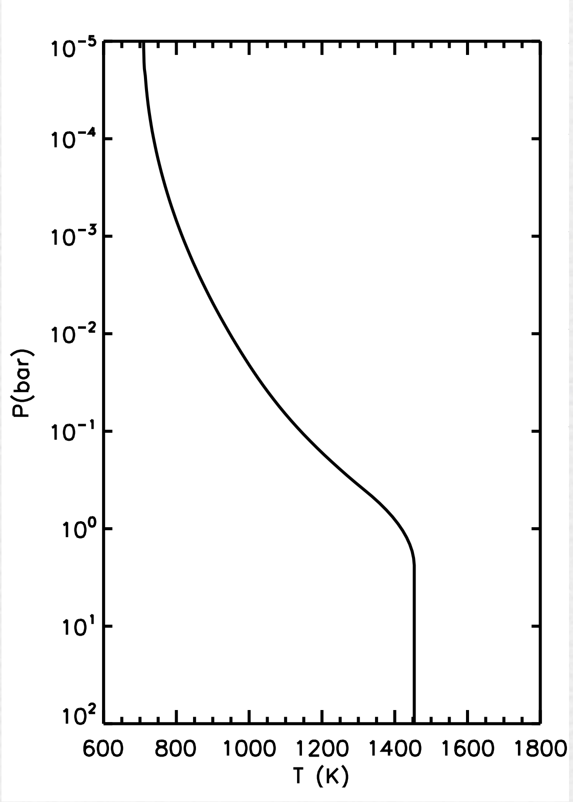
Depths: 3.6 μm > 4.5 μm
⇒
No thermal inversion

(Independent of composition)

Agrees with:

Fortney et al. (2008);
Burrows et al. (2008).

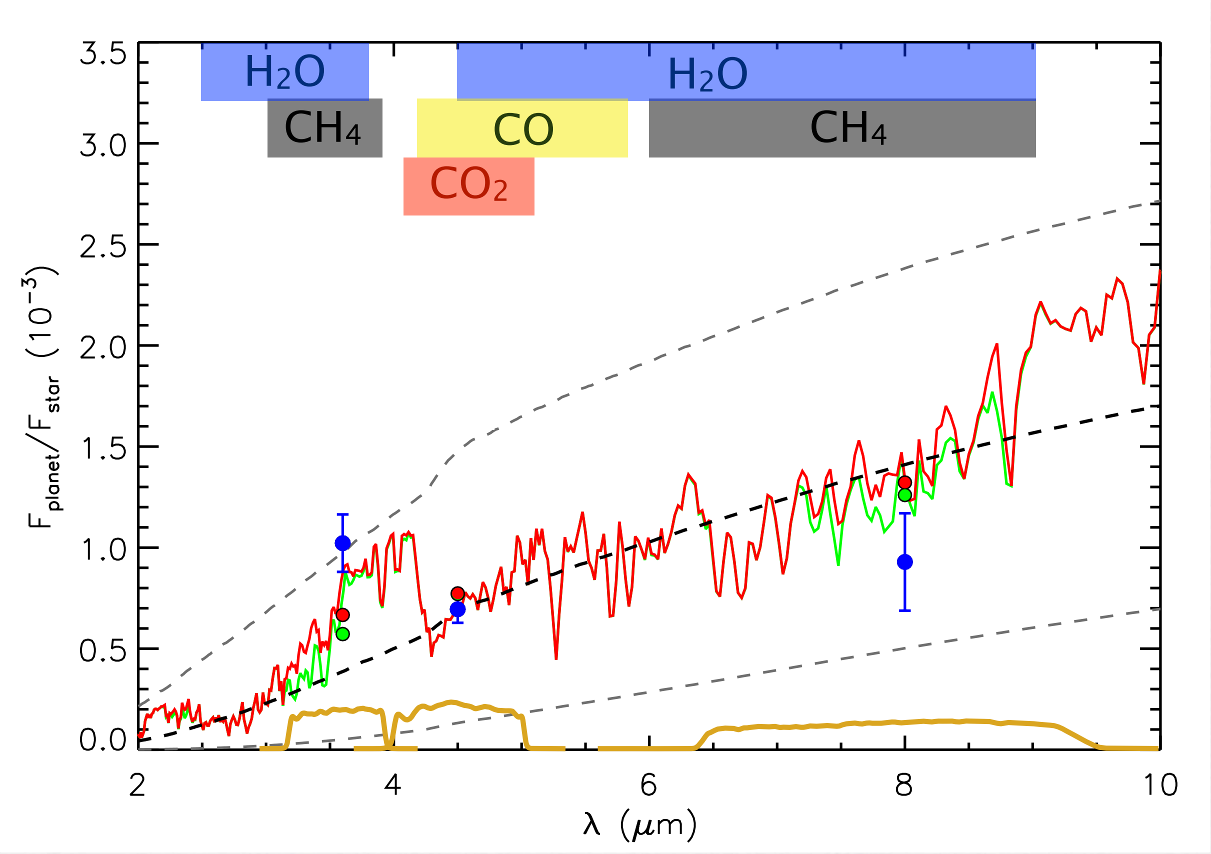




Atmospheric Modeling:

How to improve the 3.6 μm fit?

- Lower methane abundance, but worsens the 8.0 μm.
- Increase temperature, but misses fit at 4.5 and 8.0 μm.



Solar Composition.

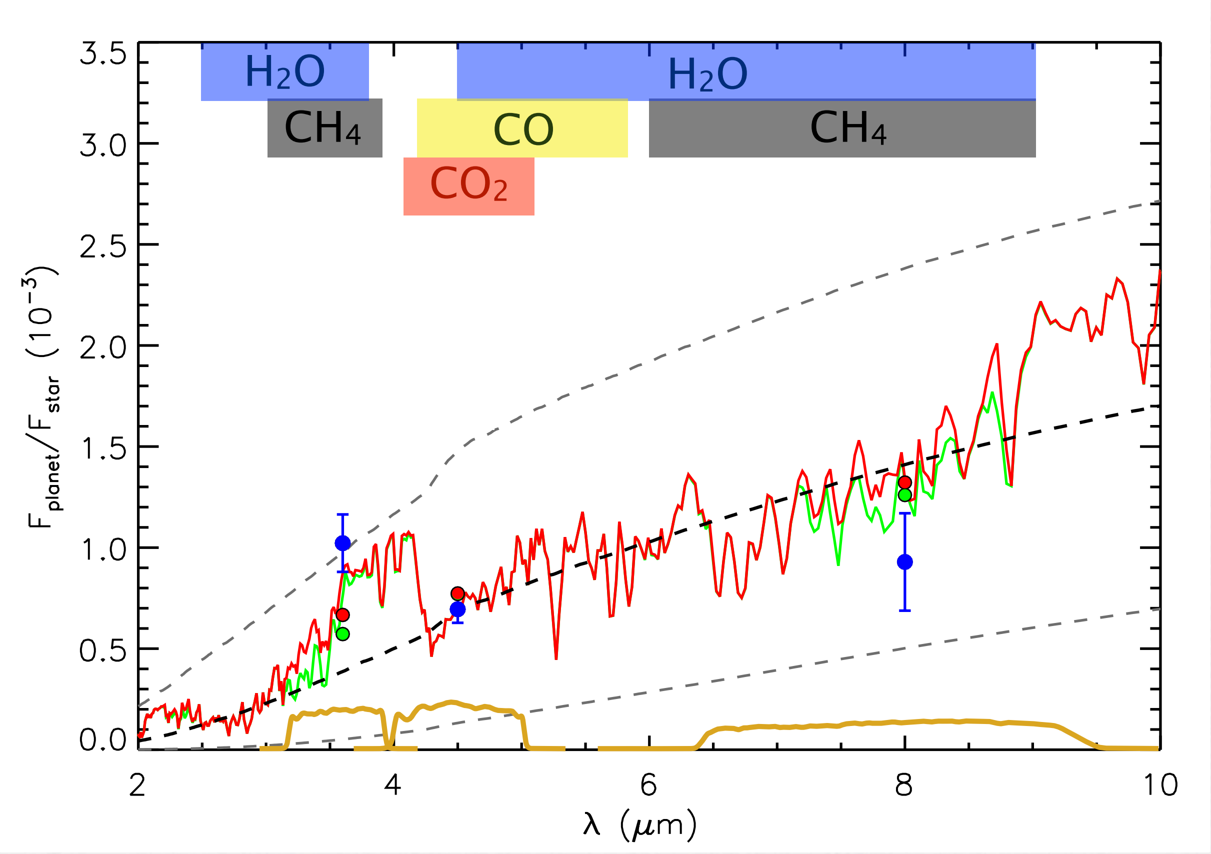
Low methane abundance.

Atmospheric Modeling:

- Near solar metallicity.
- The 3.6 μm depth is higher than expected.
- Very low energy redistribution.
- Very low albedo.

Waveband (μm)	Brightness temp. (K)
3.6	1552
4.5	1131
8.0	938

Equilibrium temp.: 942 K



Orbital Thermal Variation:

The incident irradiation varies in time.

We studied temperature variations: 1-D latitude-longitude grid model.

Energy change:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \left[\underbrace{(1-A)\sigma T_{\mathrm{eff}}^4 \left(\frac{R_*}{r(t)}\right)^2 \cos\psi(t)}_{\text{Incident flux}} - \underbrace{\sigma T^4}_{\text{Blackbody emission}} \right]$$

Geometrical factor:

$$\cos\psi(t) = \sin\theta \max\{\cos\Phi(t), 0\}$$

The sub-stellar longitude:

$$\frac{\mathrm{d}\Phi(t)}{\mathrm{d}t} = \omega_{\mathrm{rot}} - \omega_{\mathrm{orb}}(t)$$

Orbital Thermal Variation:

A few reasonable assumptions:

1.- The planet is in pseudo-synchronous rotation: (Hut 1981)

$$\omega_{\rm rot} = \{0.8,\ 1.0,\ 1.5\}\ \omega_{\rm orb,\ p}$$ (Hut 1981; Ivanov & Papaloizou 2007)

2.- The albedo is negligible: $A = 0$. (This work; Cowan & Agol 2011)

3.- Zero rotational obliquity. (Hut 1981, Peale 1999)

Temperature change is parametrized by $\tau_{\rm rad}$ and $\omega_{\rm rot}$:

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{T_0}{\tau_{\rm rad}}\left[\left(\frac{a(1-e)}{r(t)}\right)^2 \max(\cos\Phi(t), 0) - \left(\frac{T}{T_0}\right)^4\right]$$

Define: $\tau_{\rm rad}$ the radiative time,

T_0 the sub-stellar temperature at periastron.

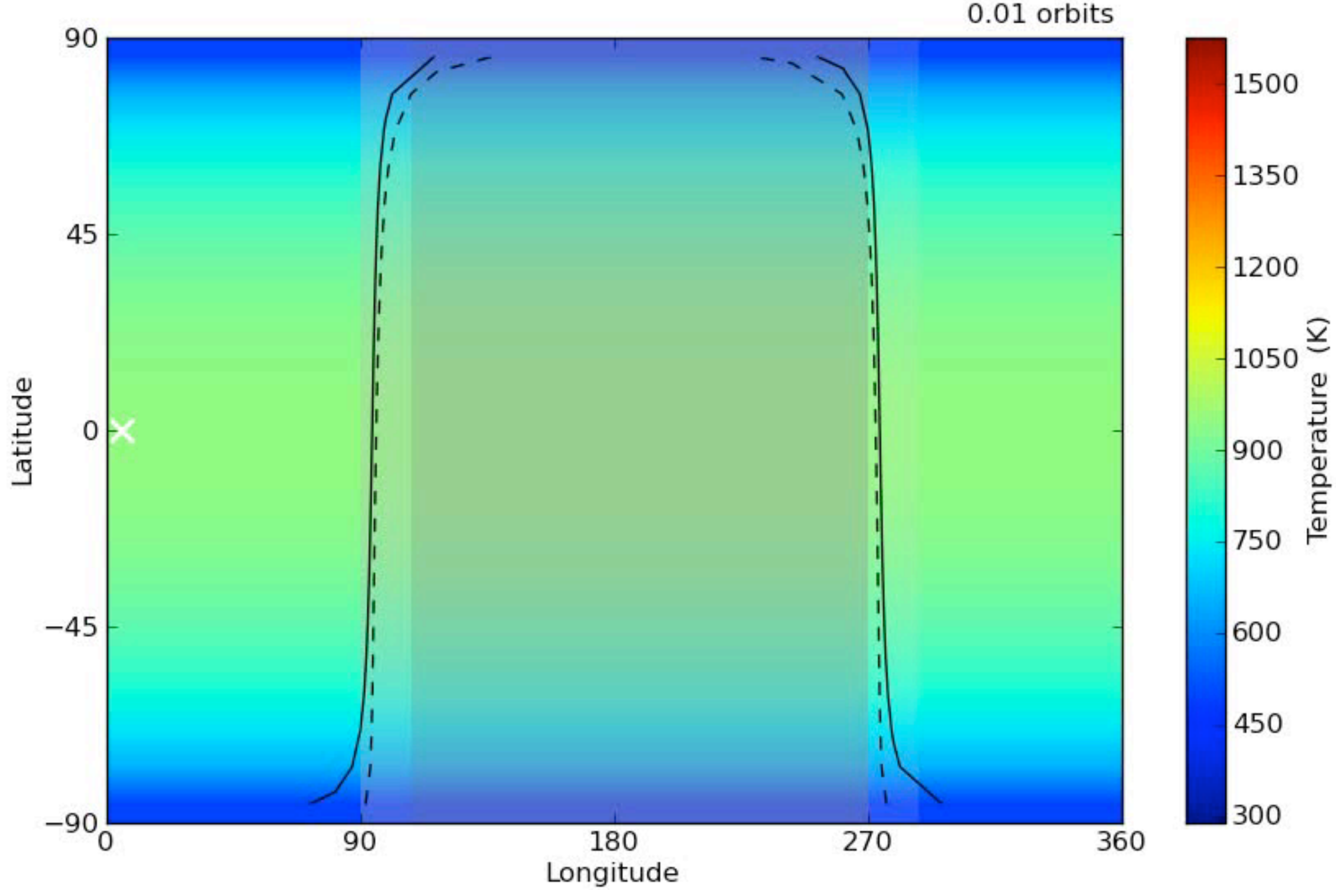
Orbital Thermal Variation:

Simulation with: $\tau_{rad} = 20$ hr

$\omega_{rot} = 1.0\ \omega_{orb,p}$

$$\omega_{\mathrm{orb,p}} = \frac{(1+e)^{1/2}}{(1-e)^{3/2}}\left(\frac{2\pi}{P}\right) = 1.99\left(\frac{2\pi}{P}\right)$$

(youtube.com/watch?v=VczcNlR5mH4)



Orbital Thermal Variation:

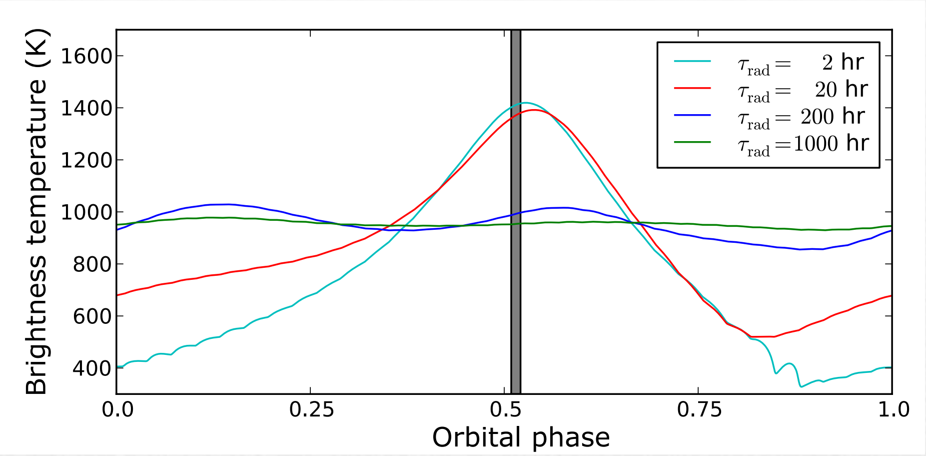
Calculated the brightness temperature as observed from Earth.

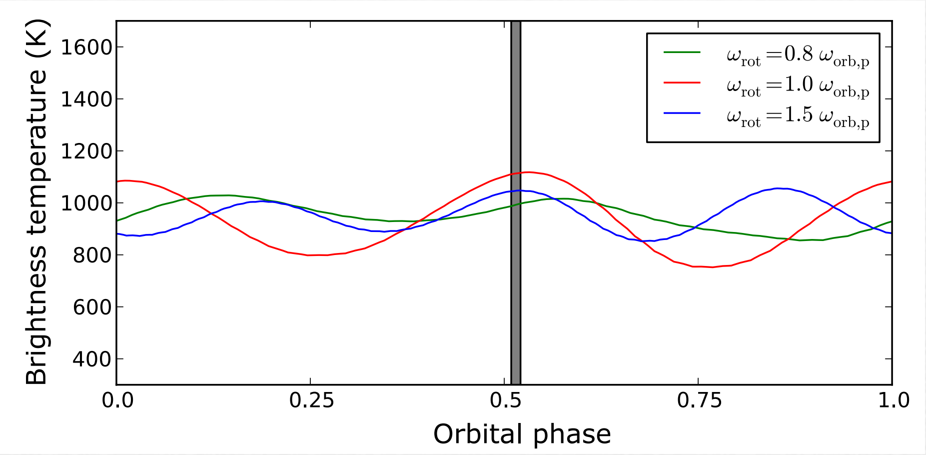
- Eclipse coincides with periapsis.
- Longer exposition time contributes.

We tested different τ_{rad}:

- $\tau_{rad} < 100$ hr reach 1400 K.

Change in ω_{rot} modifies mainly the shape.





Summary and Conclusions:

Contribution:

- POET: Re-wrote and upgraded a significant part of our pipeline.
- Developed centering and photometry routines to analyze a target in a stellar binary.
- Implemented orbital thermal evolution model.

Conclusions:

- Successfully analyzed the eclipse light curves of WASP-8b
- Determined eclipse depths
- Constrained orbital parameters
- Determined thermal profile

Thanks!