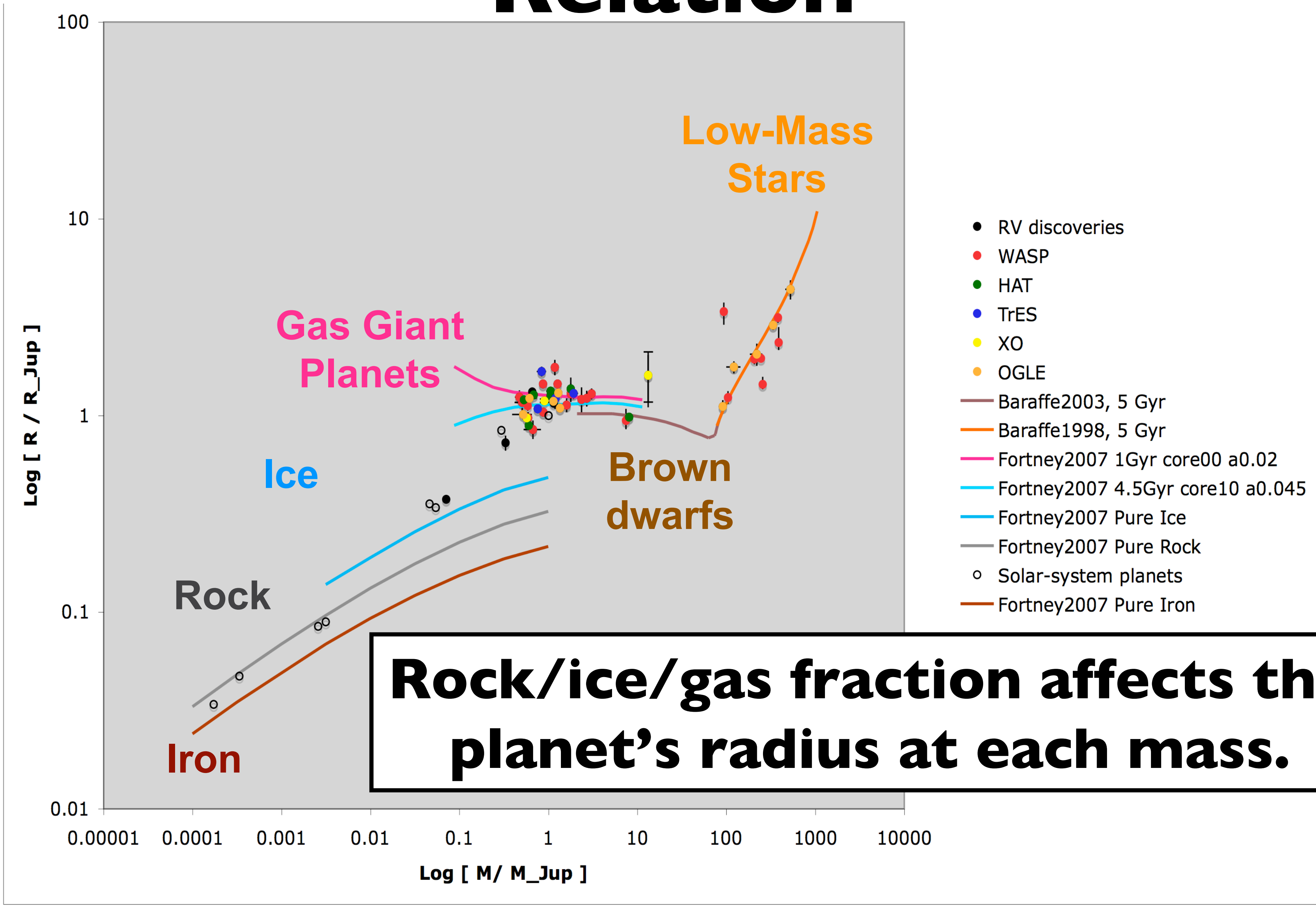
Paper Due Tue …

Udry & Santos 2007

ARA&A 45, 397.

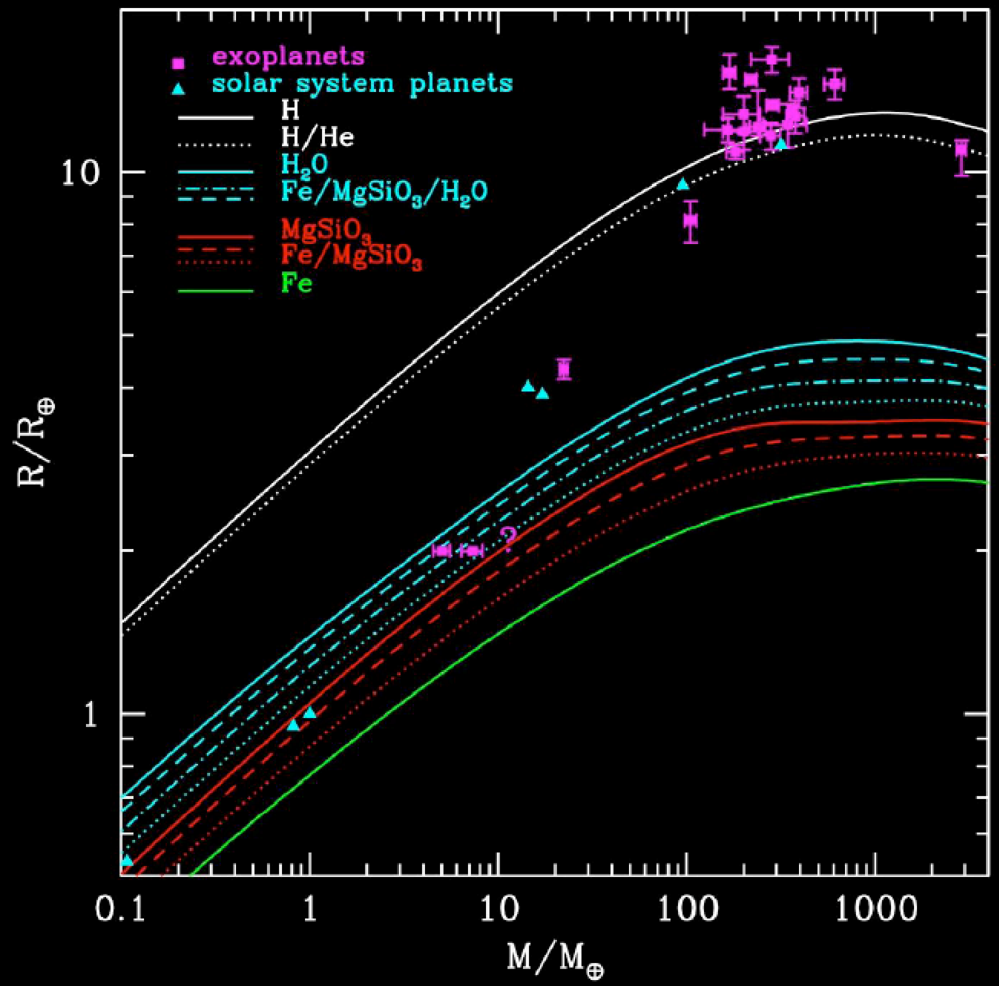
“Statistical Properties of Exoplanets”

Hot Jupiter Mass-Radius Relation



Rock/ice/gas fraction affects the planet's radius at each mass.

Exoplanet Mass-Radius Relations



Planet structure models, like stars, but without energy generation.

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r)$$

$$\frac{dP(r)}{dr} = \frac{-Gm(r)\rho(r)}{r^2}$$

$$\rho(r) = F(P(r))$$

Note: Hot Jupiter radii are larger than pure-H models!

Seager, Kuchner, Hier-Majumder, Militzer ApJ, 2007

We infer an exoplanet's bulk composition from its M and R

Hot Jupiter Radius vs Mass

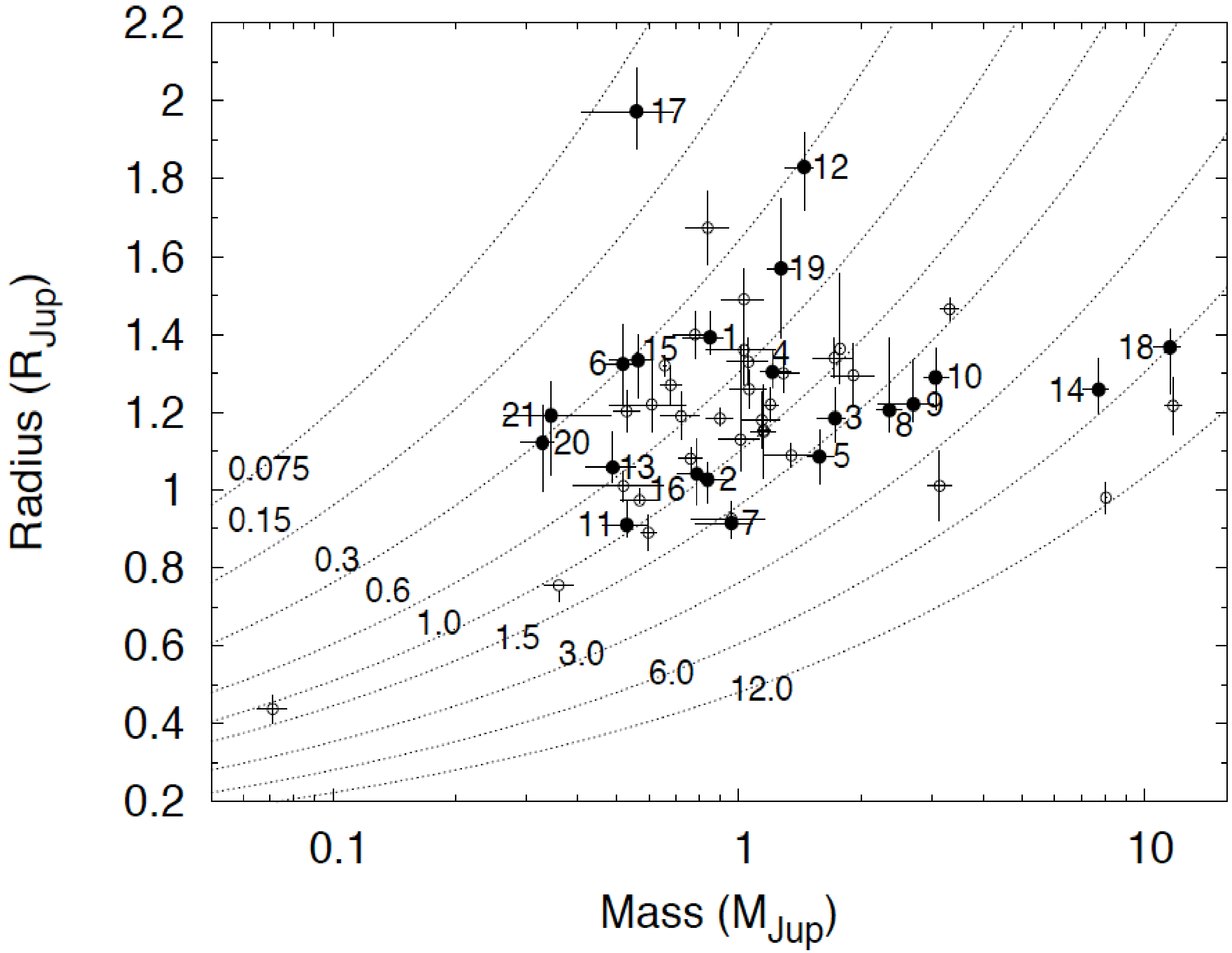
At least 2 parameters.

Planet mass + heating by star?

Tides ?
Irradiation ?

Rapid inward migration ?

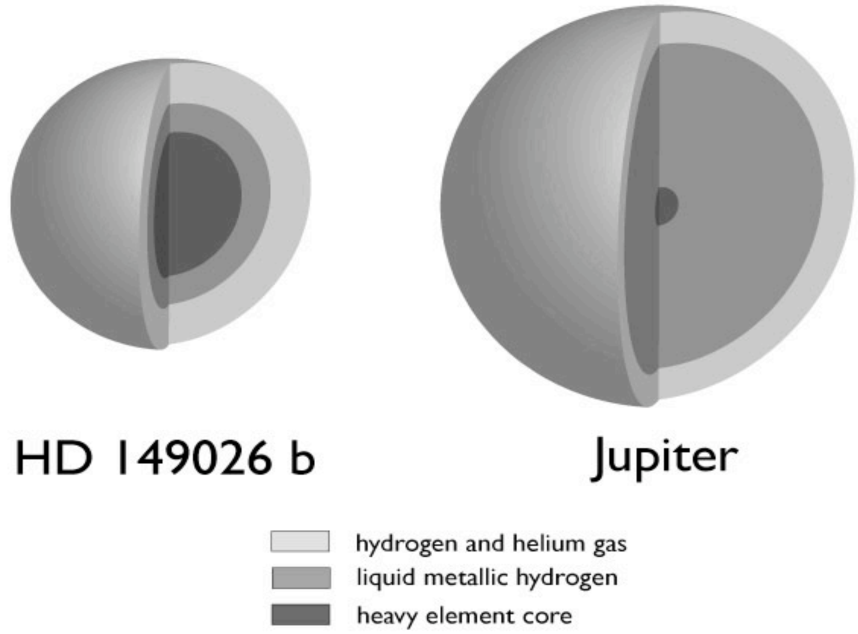
Mass of rocky core ?



Need statistics to sort out these effects.

HD 149026

A high-density transiting Hot Jupiter



$m = 0.36\ m_J$
$r = 0.73\ r_J$

$P = 2.9$ d

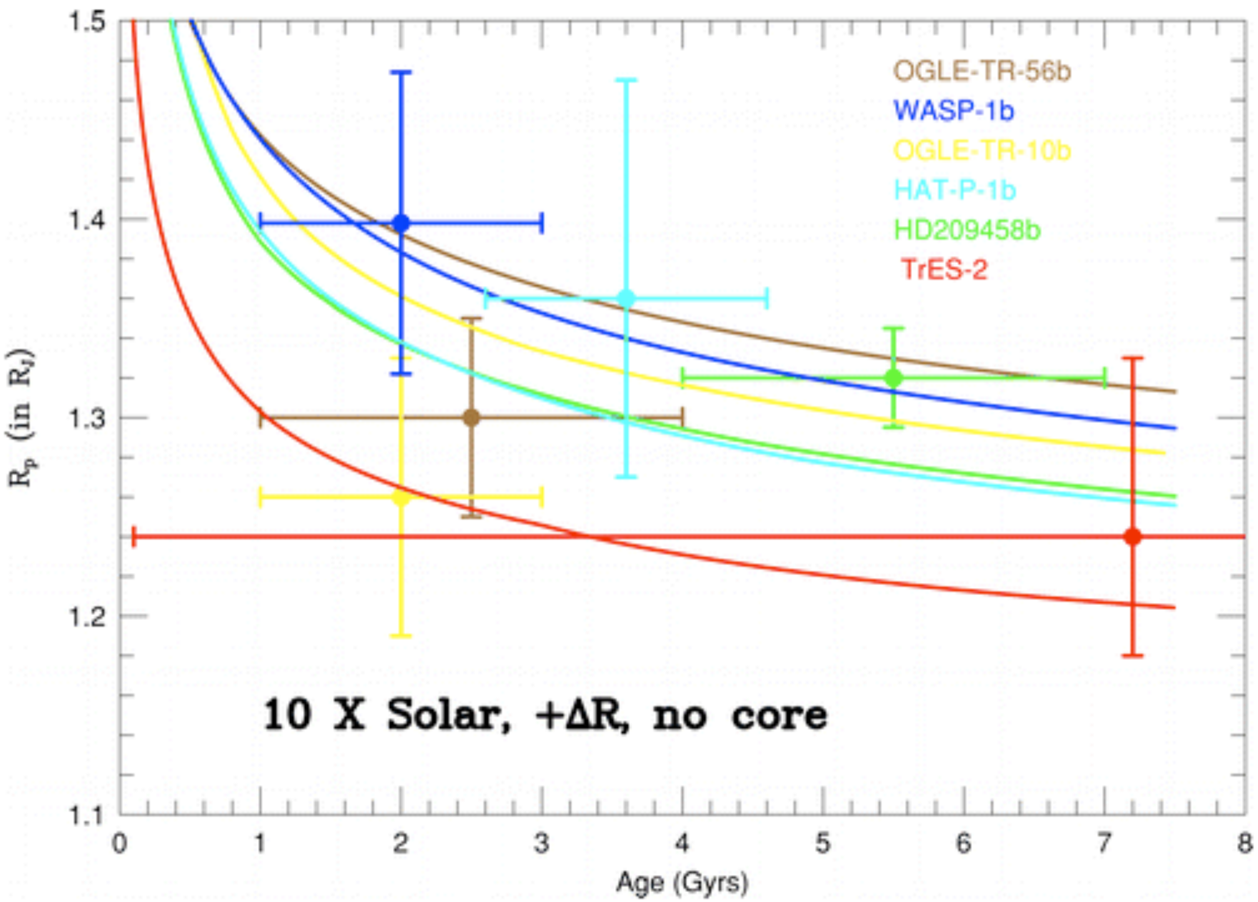
high density

1.2 g cm^{-3}

large core

Sato et. al 2005

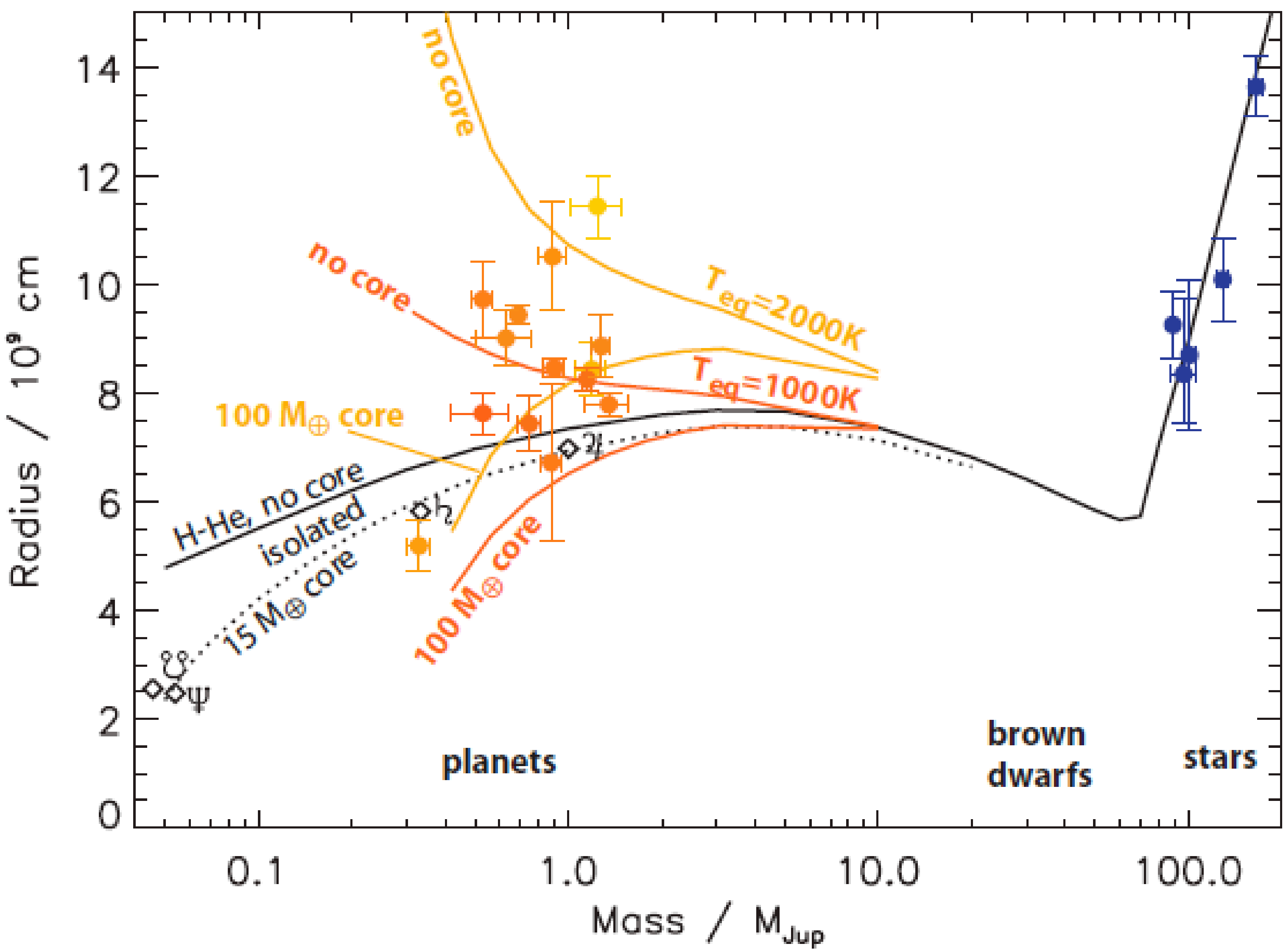
Mass-Radius Relation



Burrows et al 2007

Planet radius decreases (cooling) with age.

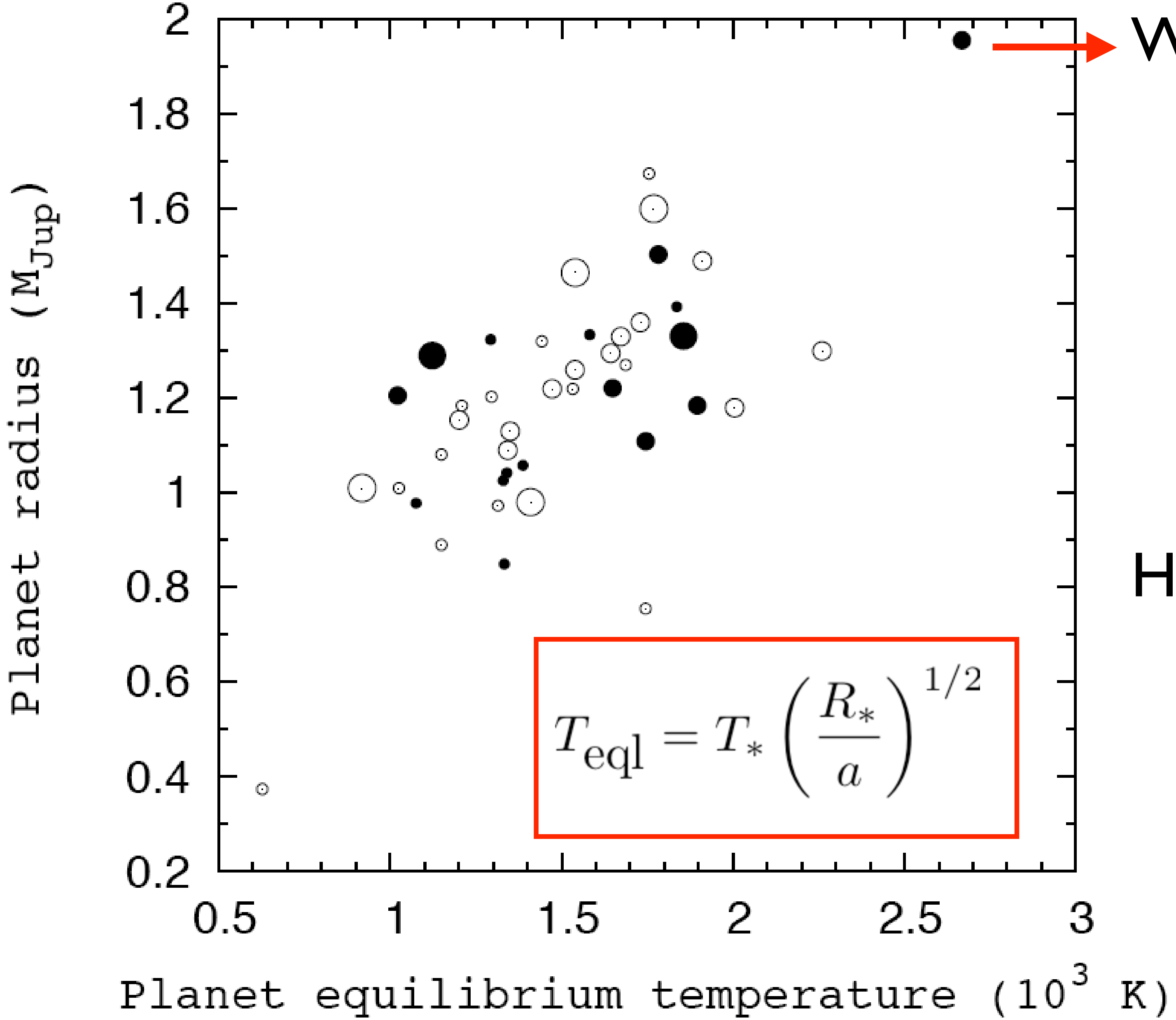
Irradiation -> Inflation



Guillot & Showman 2002

Fressin et al 2007

T_{eql} - Radius relation

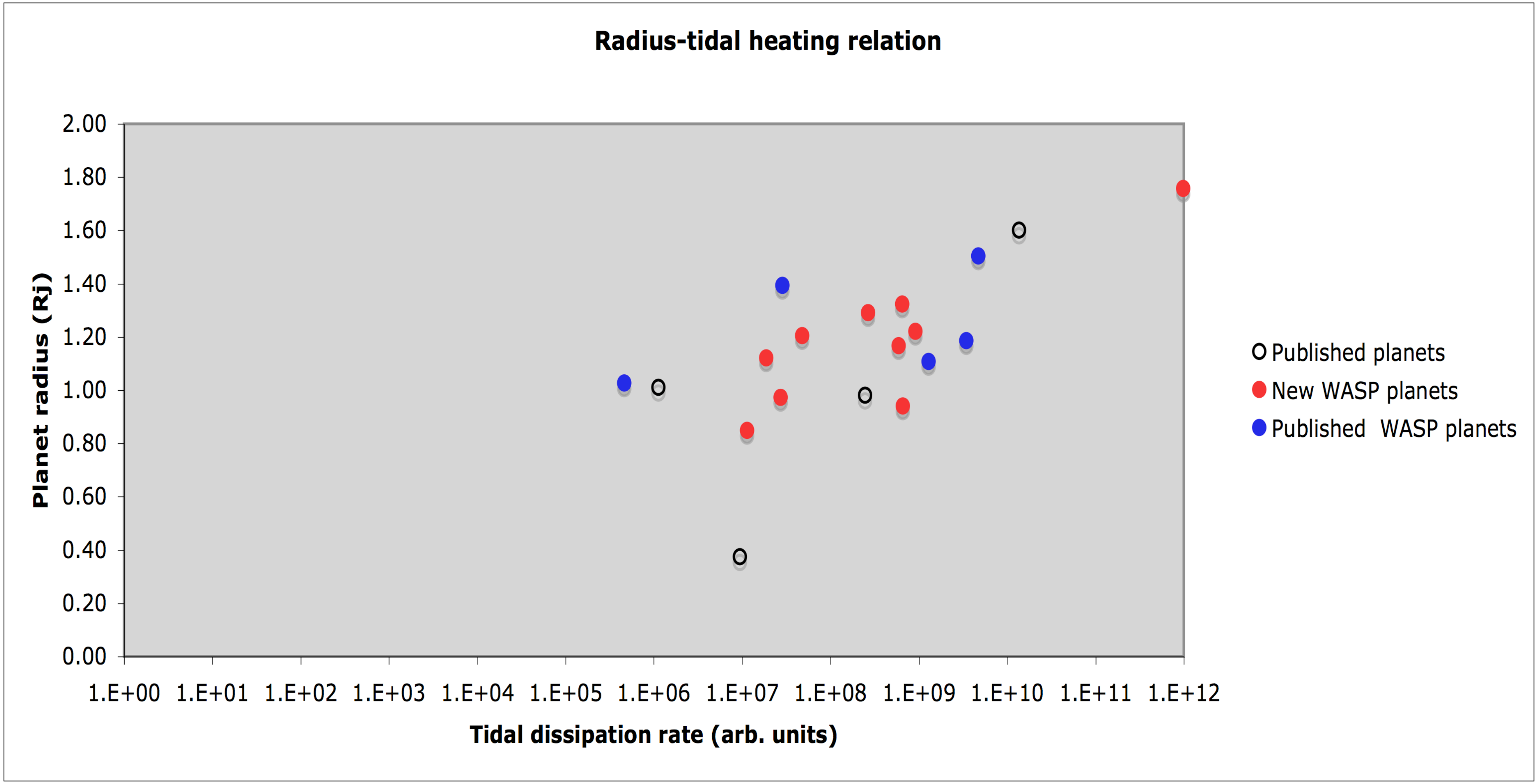


WASP-12:
Hottest,
fastest,
most
bloated.

Hebb et al. 2008

Tidal Heating

$$H = \left(\frac{63}{4}\right)\frac{(GM_*)^{3/2} M_* R_p{}^5}{Q_p'} a^{-15/2} e^2$$

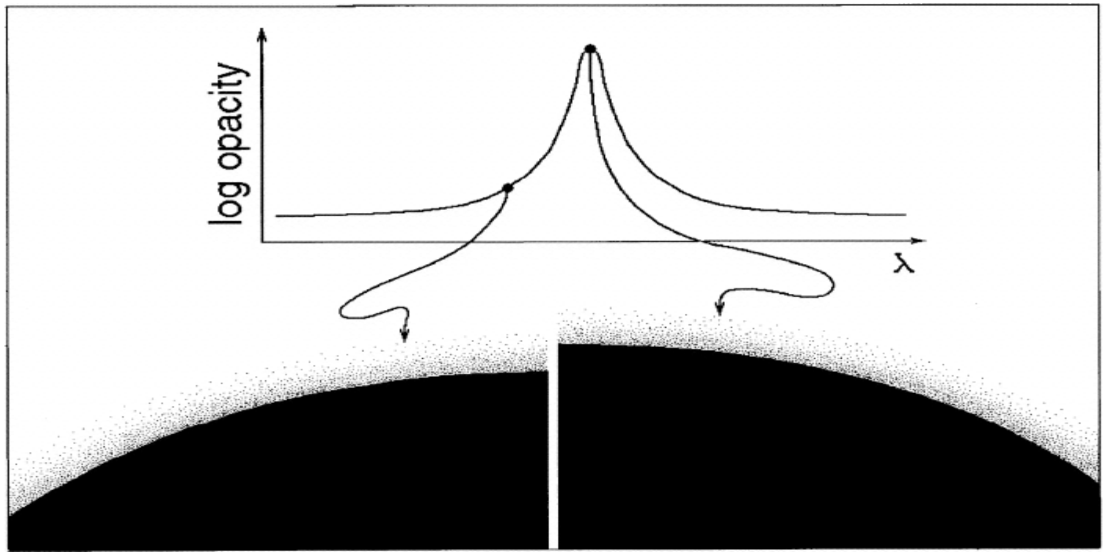


Follow-up Techniques

- Reflected light -- Direct spectroscopic separation
  - Reflected light Doppler shifted by planet's orbit velocity
  - Gives info about the planet albedo and radius
  - Upper limits only (e.g. albedo < 20%)
- Transmission spectroscopy (transit depth vs wavelength)
  - Gives info about the planet atmosphere, temperature, composition, clouds, perhaps eventually even winds.
- Infra-red emission of planet -- photometric and spectroscopic
  - Better flux ratio between planet and star in the mid-IR
  - Searches for water and methane from the planet -- which have molecular bands in the mid-IR
- Radio emission
  - Magnetic field of the planet interacts with charged particles from the stellar wind and creates cyclotron radio emission.
- Transit timing
  - Planets in larger orbits affect the timing of Hot Jupiter transits.
  - Most sensitive to planets in resonant orbits (upper limits on Earths).
  - Neptune was predicted to exist, before its discovery, based on the perturbed orbit of Uranus.

Transit (Transmission) Spectroscopy

Brown (2001)



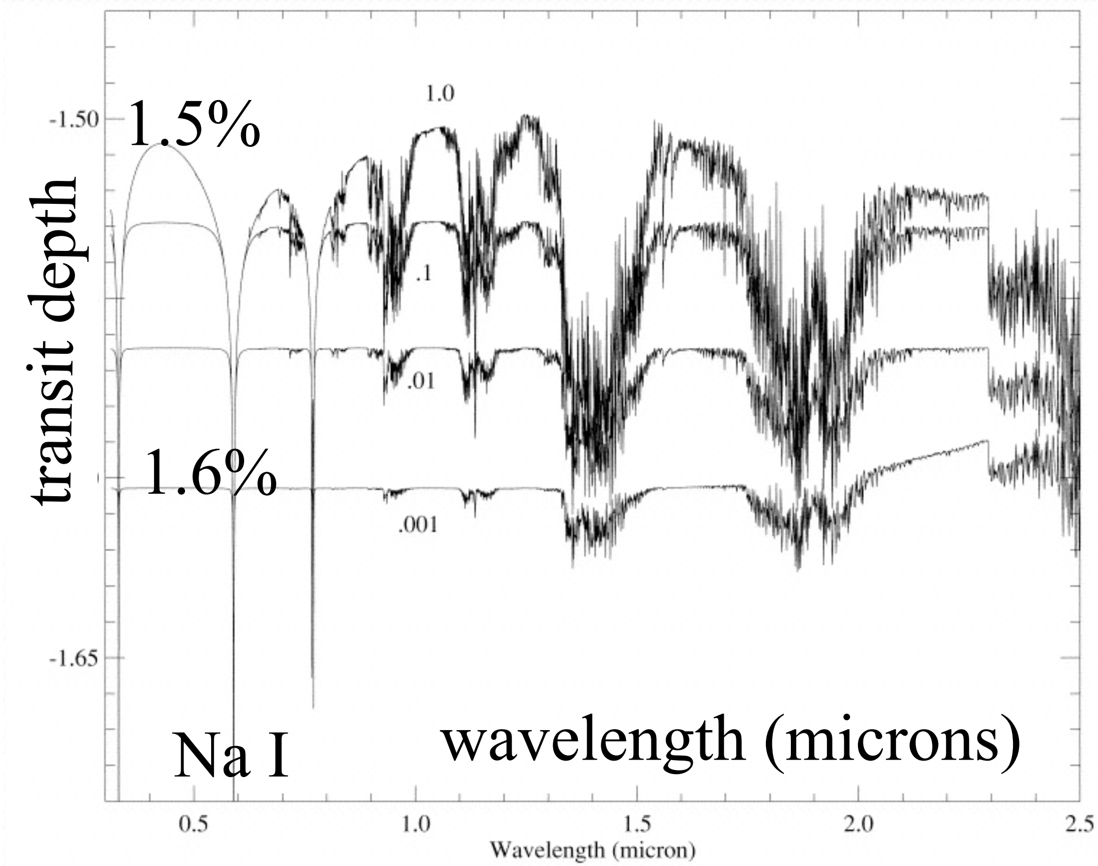
Silhouette larger (transit deeper) at wavelengths of high opacity.

planetary atmosphere

composition

cloud decks

perhaps even winds ?

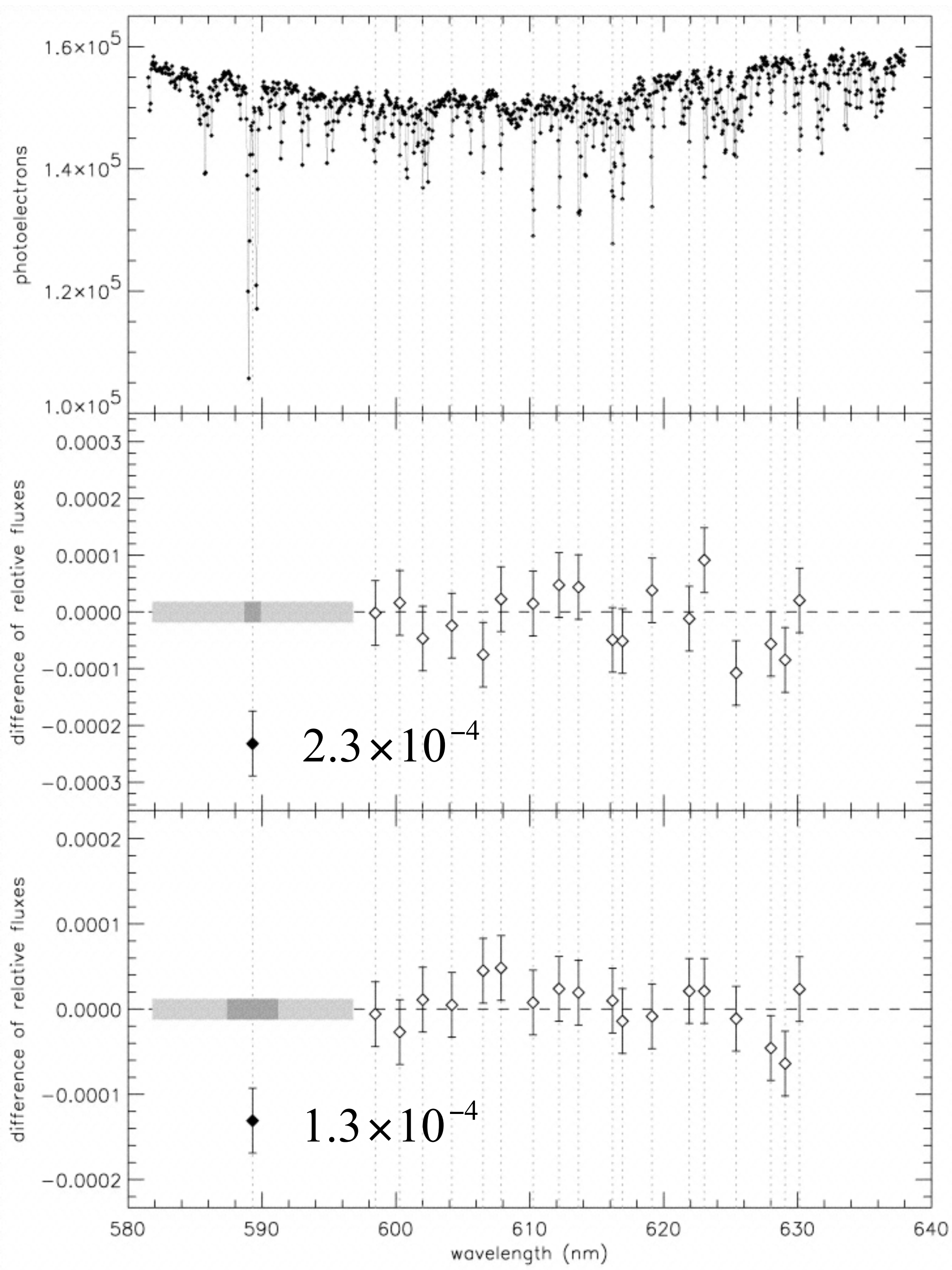


HST Transit Spectroscopy

detects Na I in the atmosphere of HD 209458b

NaI lines deeper during transits, but weaker than expected from Hot Jupiter atmosphere models.

Charbonneau et al. (2002)

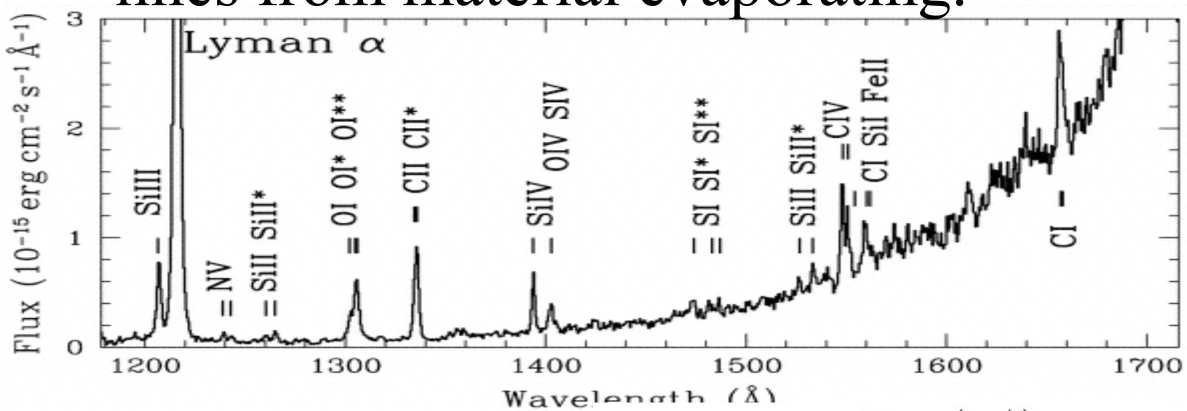


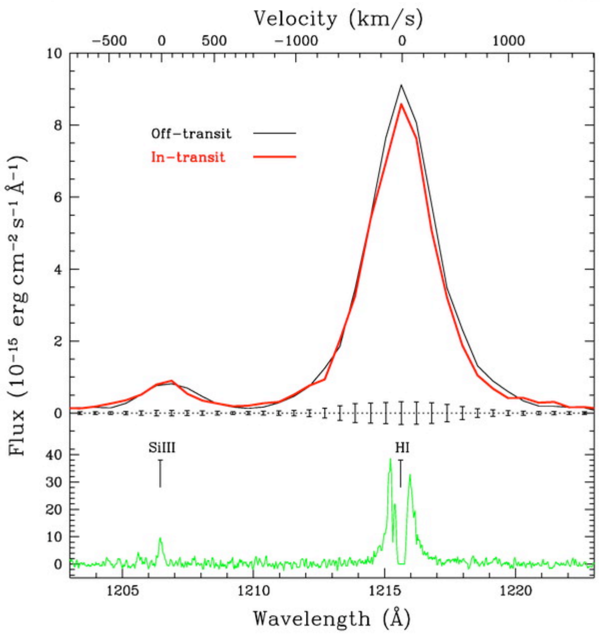
Evaporating Atmosphere

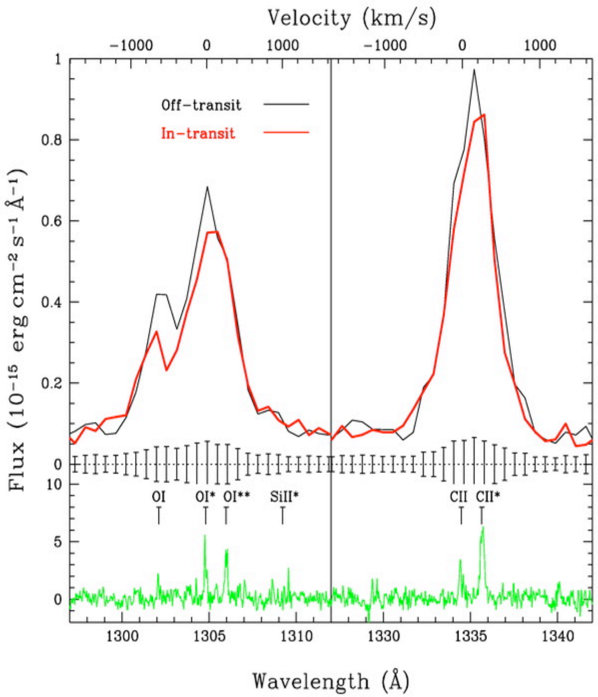
Vidal-Madjar et al. (2003)

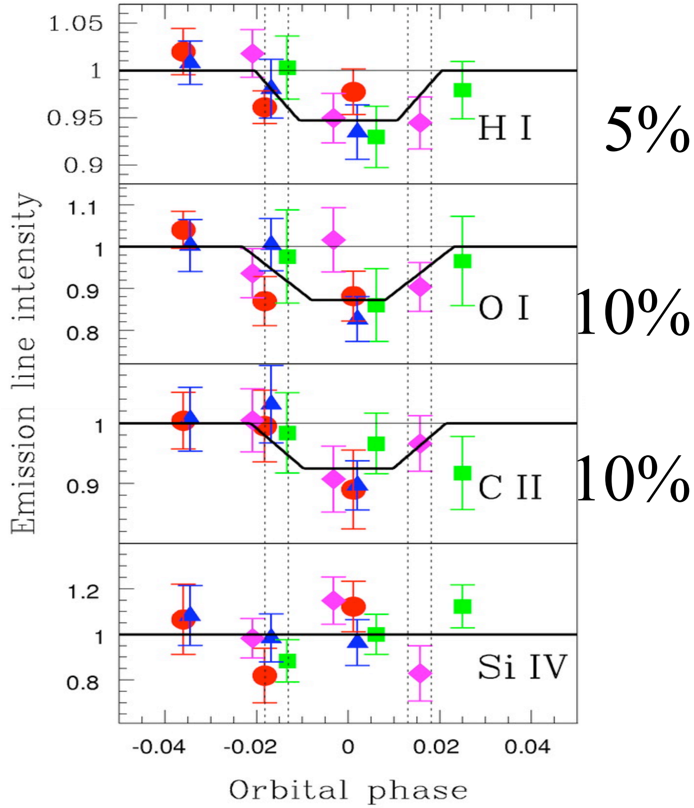
Larger silhouettes (5-10%) seen in UV lines from material evaporating.

ESA / A.Vidal-Madjar, CNRS / NASA

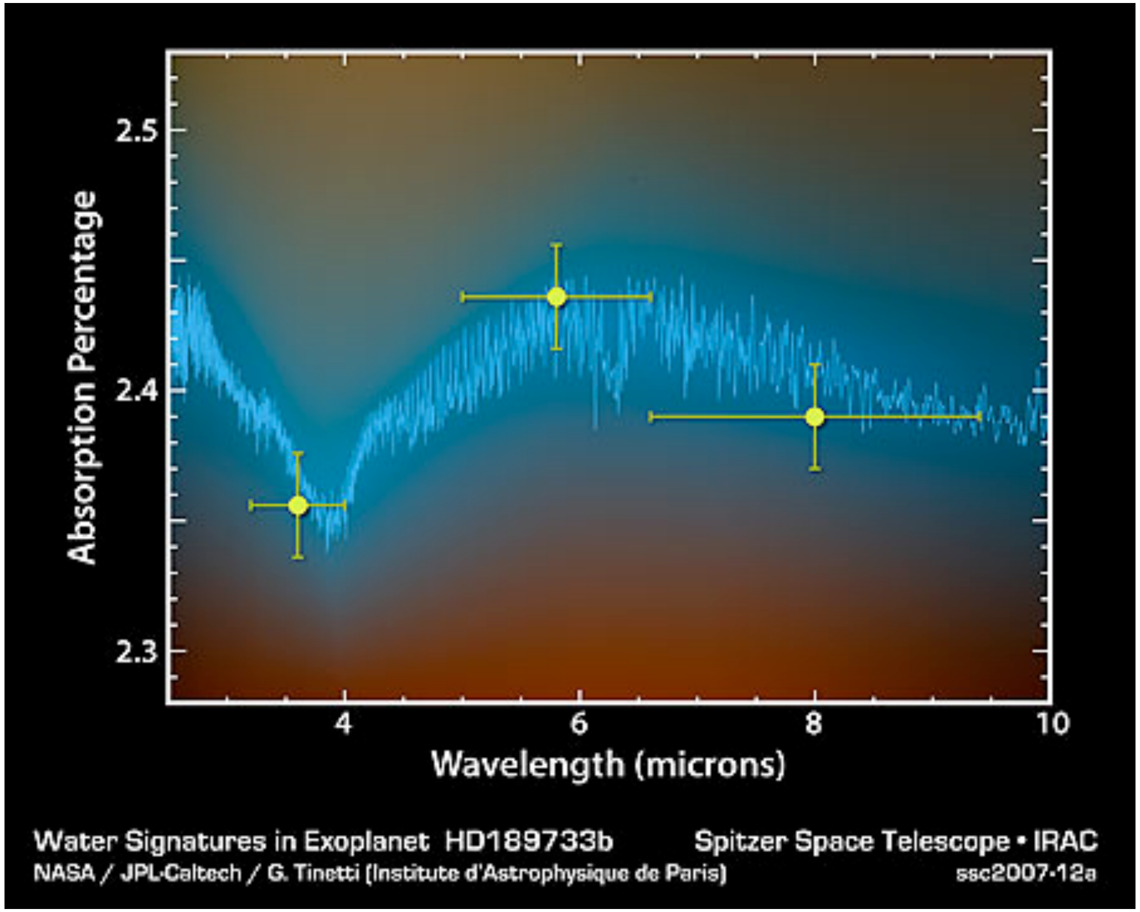






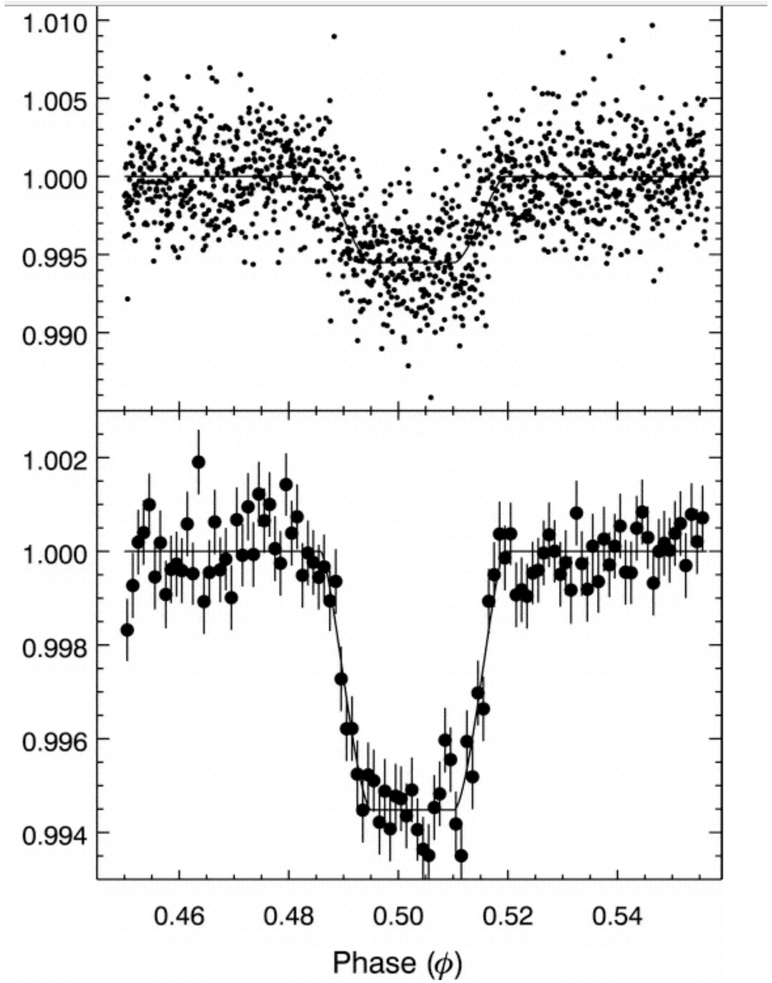


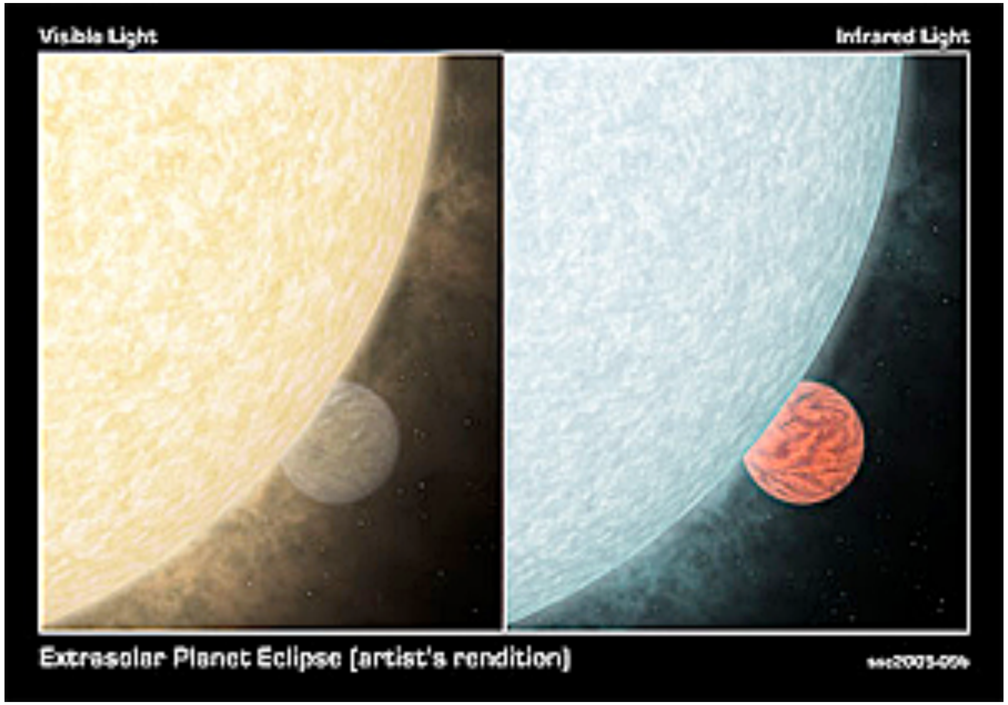
Broad band transmission spectroscopy in the Infra-red



Observations of the host star during the primary eclipse in the mid-IR bands at 3.6, 4.5 and 8 microns. The absorption by water in the atmosphere of the planet creates a drop in flux in the 3.6micron band.

Infra-red emission of planet

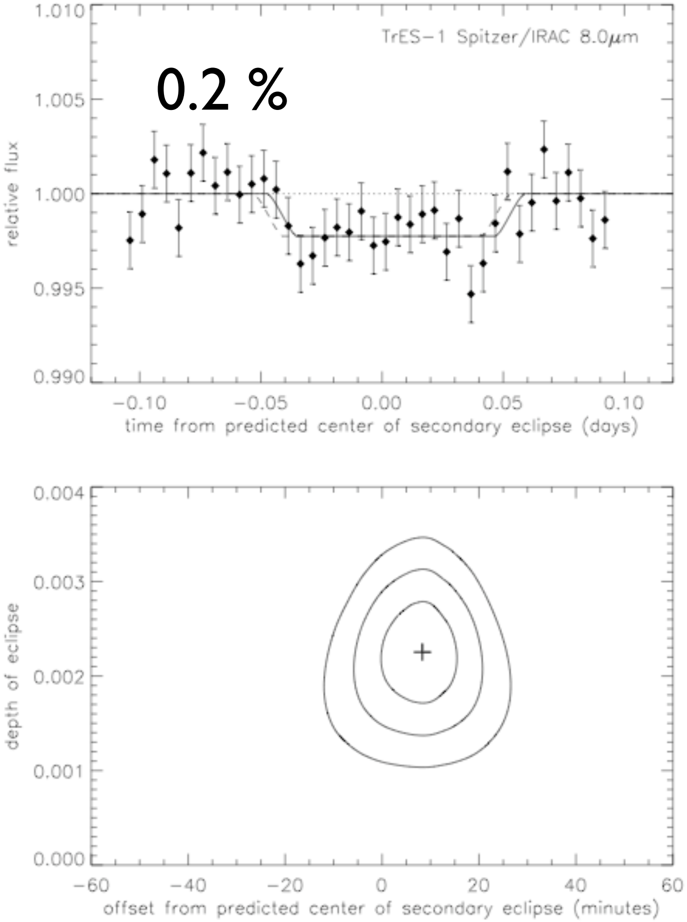




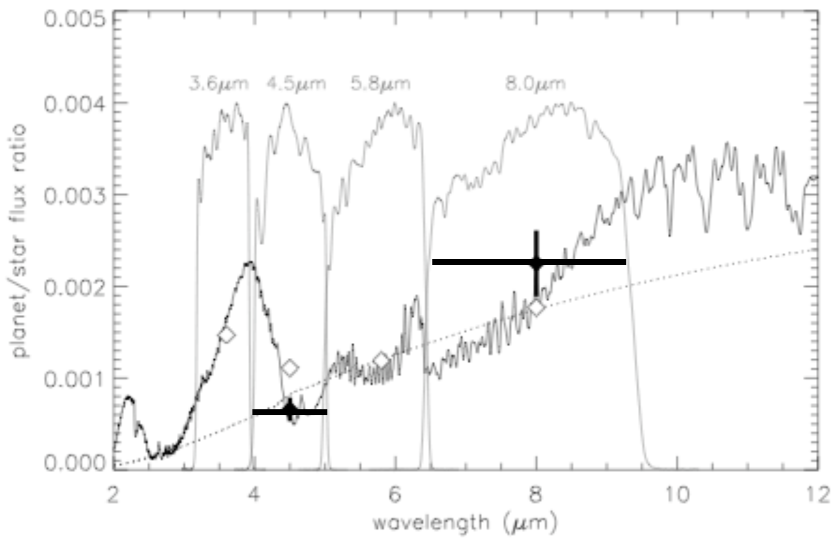
$$T_b = \frac{I_\nu c^2}{2\nu^2 k}$$

Observations of the secondary eclipse of this planet show the drop in flux as the planet moves behind the star. From this, the planet flux at 16 microns is 660 μJy and the brightness temperature of the planet is measured to be T_b=1117 K

Planet eclipsed by Star



Spitzer / IRAC 4.5, 8.0 micron



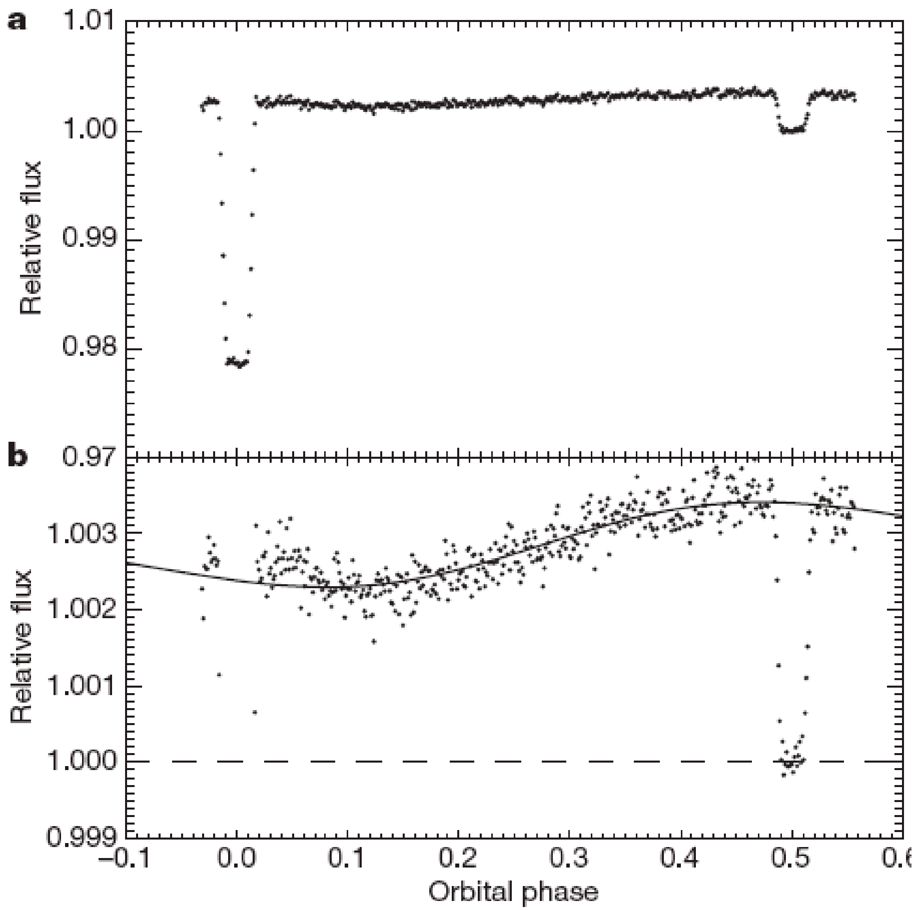
Direct detection of infrared light from hot side of the planet

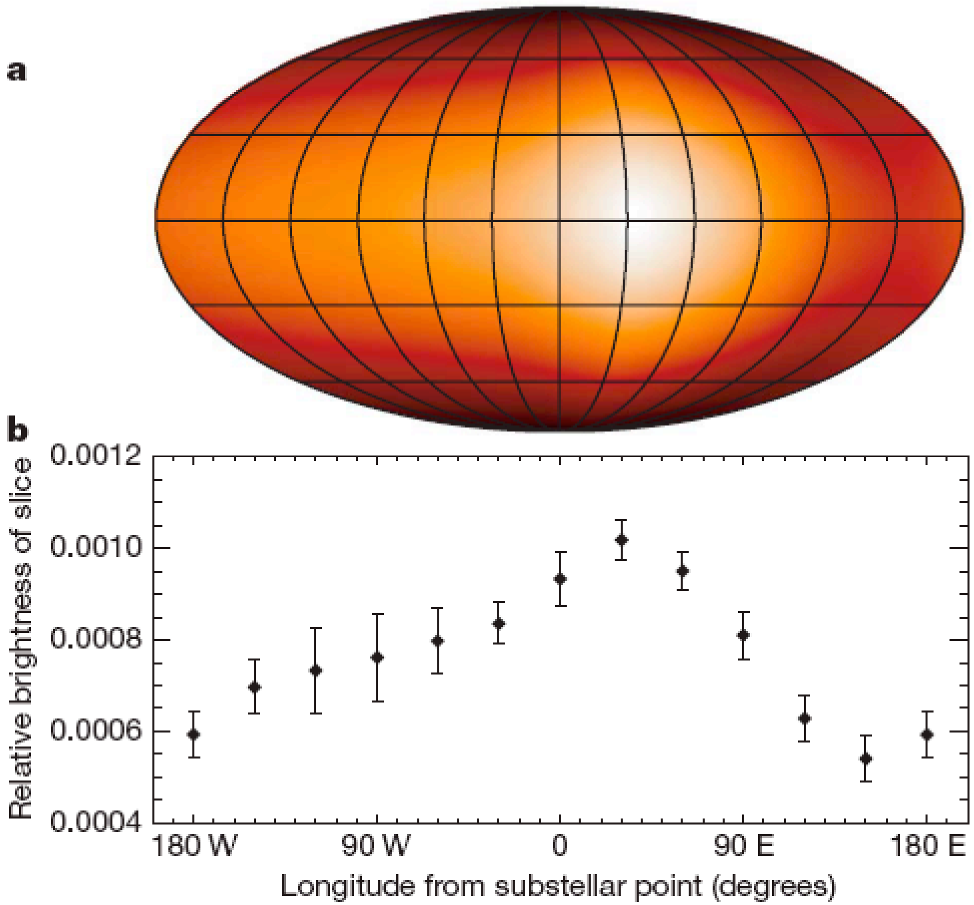
TrES-1: *Charbonneau et al. (2005)*

HD 209458: *Deming et al. (2005)*

HD189733b 8μm brightness map

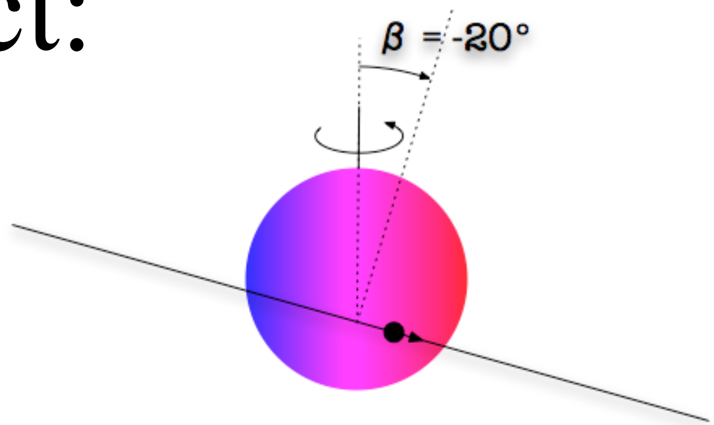
- Spitzer/IRAC phase modulation





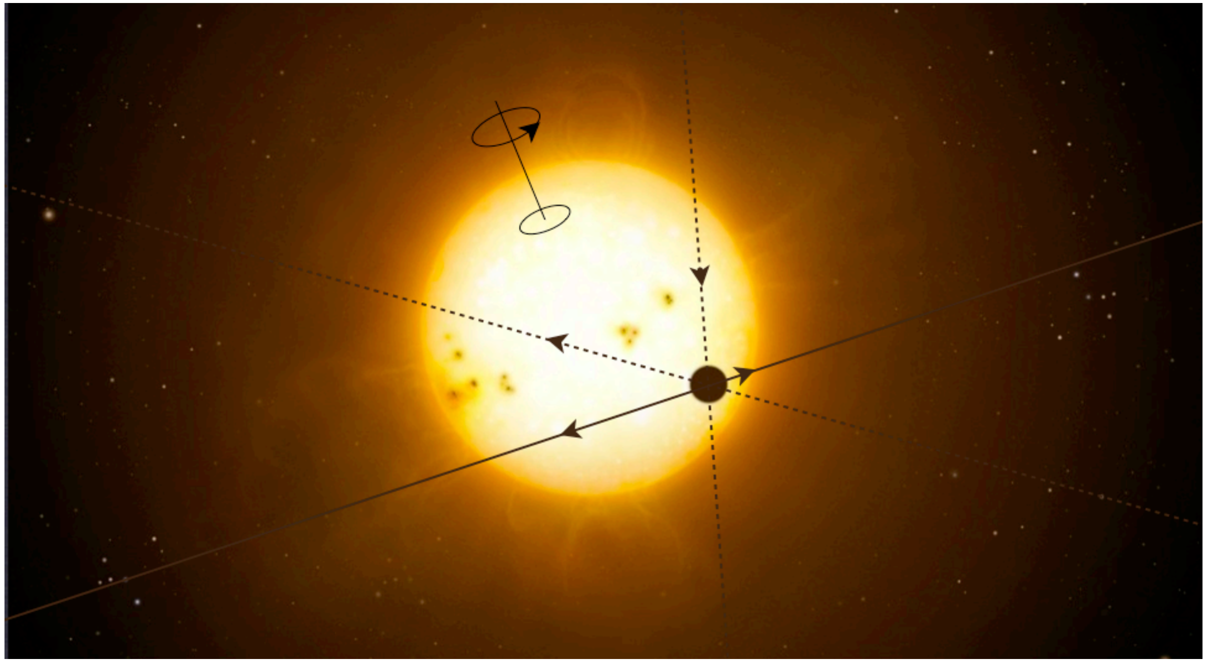
Knutson et al 2007, Nature 447, 183

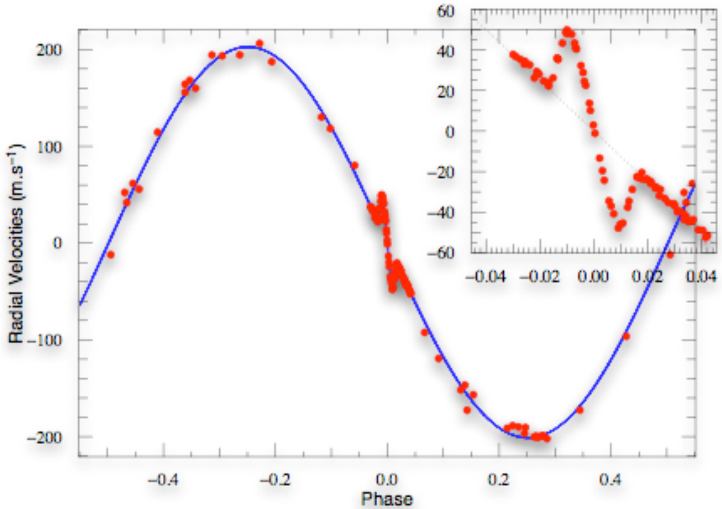
Rossiter Effect:



A planet transiting a rotating star perturbs the velocity curve.

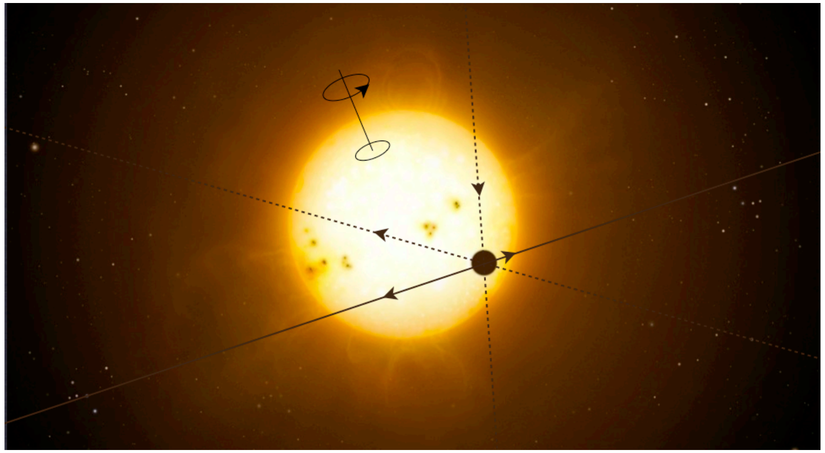
Determine orientation of planet's orbit relative to the star's spin.

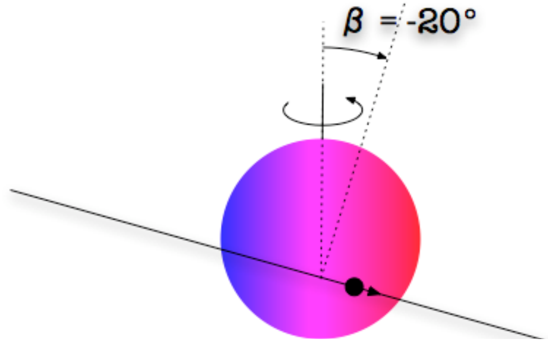


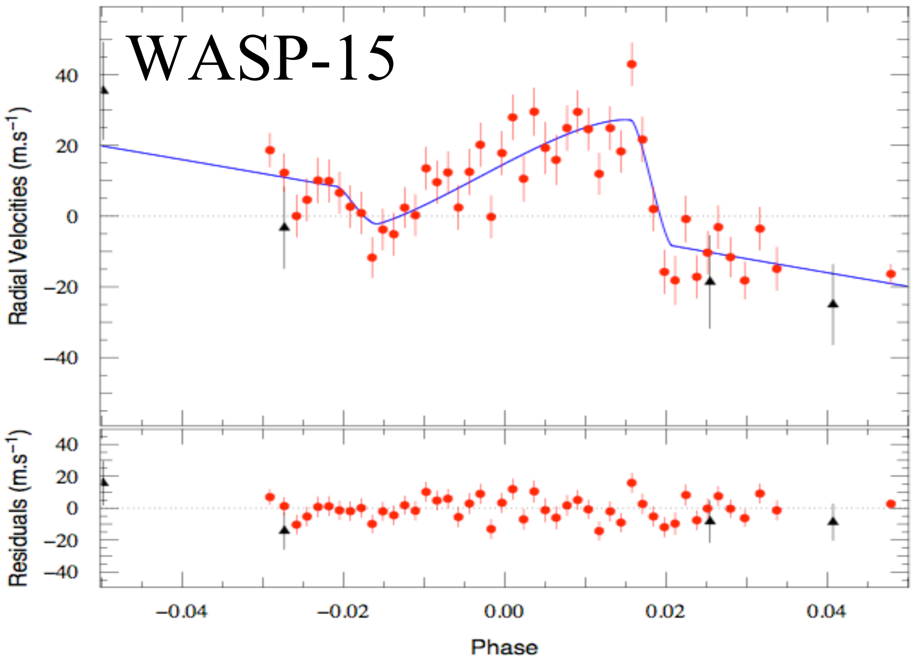


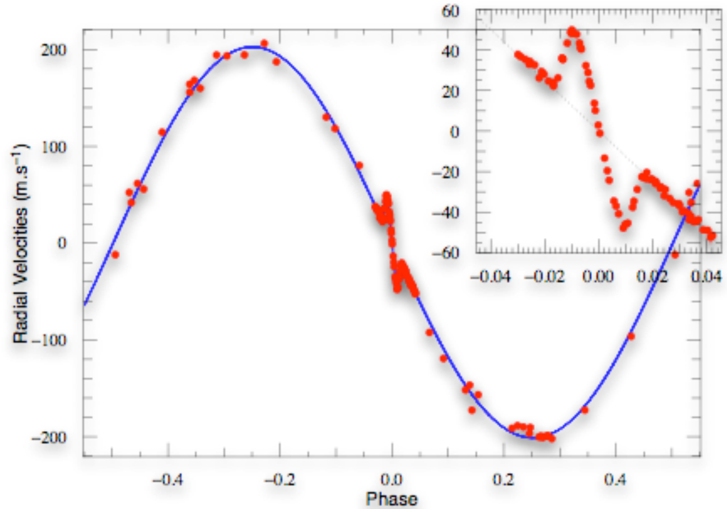
Radial velocity vs orbital phase.

Rossiter Effect:
Tilted and even Retrograde Orbits !









Radial velocity vs orbital phase.