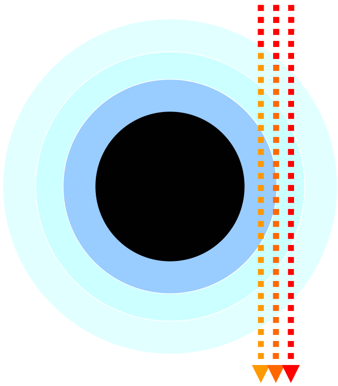
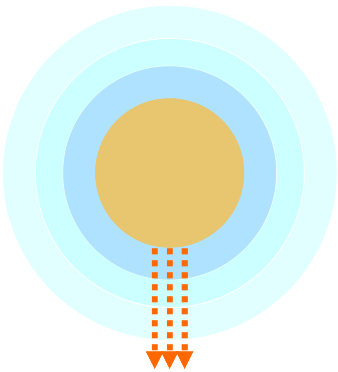
Characterization of Planets: Atmospheres (Transits Results Continued)

- Reflected Light: Albedo Measurements
- Radiated Light: Temperature
- In-transit and secondary eclipse spectroscopy: Atmospheric Features

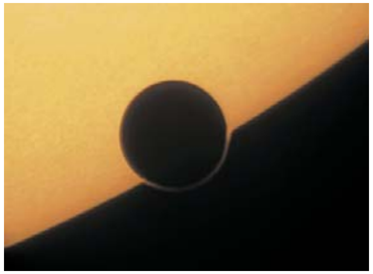
Getting Spectra of Exoplanetary Atmospheres

Two ways to characterize an exoplanet‘s atmosphere:

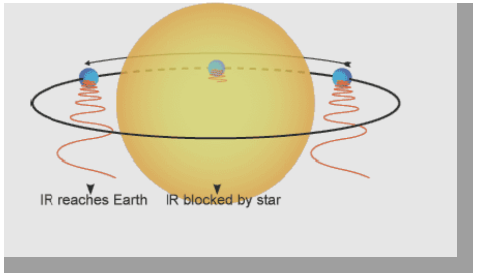




■ Spectra during primary eclipse: Chemical composition, scattering properties



■ Spectra during secondary eclipse: Chemical composition, temperature structure



I. Reflected Light Measurements

Defintion: Albedo

Albedo is the amount of light reflected from the planet and ranges between 0 (total absorption) and 1 (total reflection).

<u>Geometric Albedo:</u>

The **geometric albedo** of an astronomical body is the ratio of its actual brightness at zero phase angle (i.e. as seen from the light source) to that of an *idealized* flat, fully reflecting, diffusively scattering disk with the same cross-section.

<u>Bond Albedo:</u>

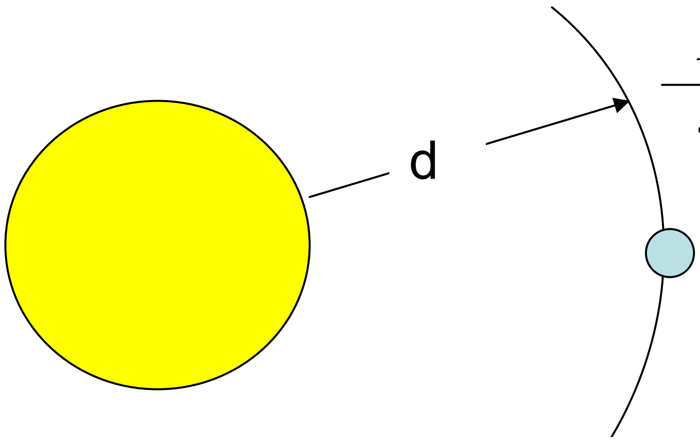
The fraction of power in the total electromagnetic radiation incident on an astronomical body that is scattered back out into space. It takes into account all wavelengths at all phase angles.

Albedo of the Solar System Planets

Source: Astrophysical Quantities

Planet	Geometric Albedo
Mercury	0.106
Venus	0.65
Earth	0.367
Mars	0.150
Jupiter	0.52
Saturn	0.47
Uranus	0.51
Neptune	0.41

I. Reflected Light Measurements



$$\frac{L_{\text{star}}}{4\pi d^2} = F \quad = \text{Flux from star}$$

planet intercepts F $\times\ \pi R^2$ and
reflects A × F x πR^2
Where R is the planet radius

We do not measure the absolute light from the star, but reference that the brightness of the central star:

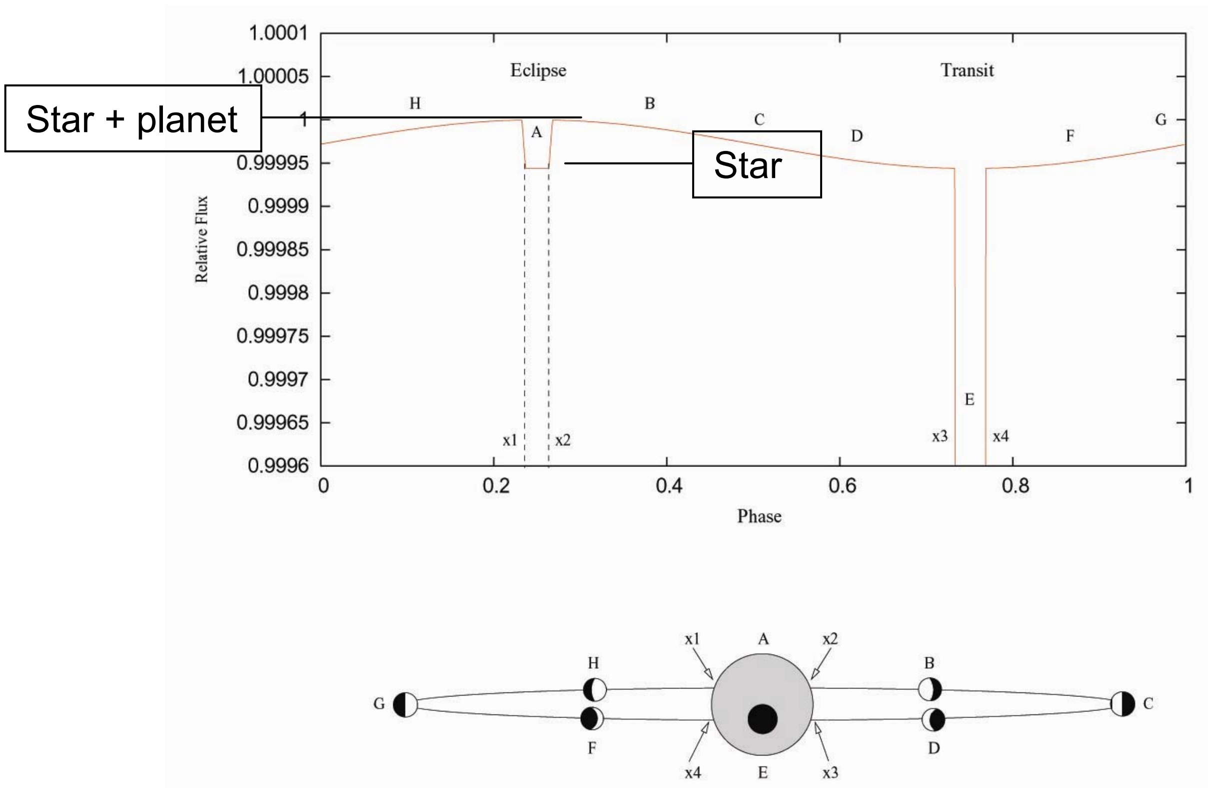
$$\text{Reflected light} = A\pi R^2 \frac{L_{\text{star}}}{4\pi d^2} \frac{1}{L_{\text{star}}} = \frac{AR^2}{4d^2}$$

A = geometric albedo, R = planet radius, d = distance from star

For A = 0.1, d=0.05 AU, R = 1 R_{Jup}

Reflected light $\approx 10^{-5}$

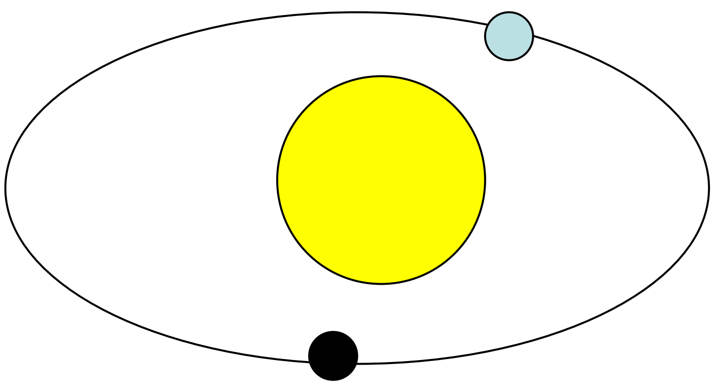
I. Reflected Light Measurements



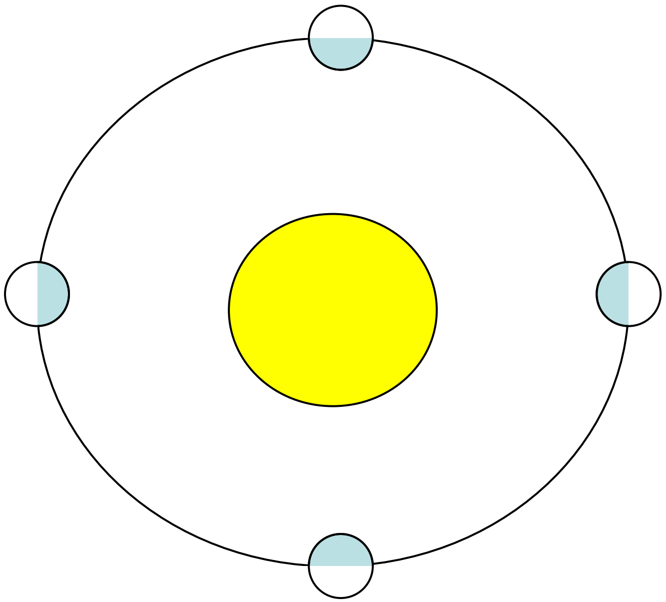
The planet reflects light, so one should see a modulation in the light curve, plus an eclipse of the planet

I. Reflected Light Measurements

Reflected light should be multiplied by a phase function, f(α), that depends on the orbital inclination

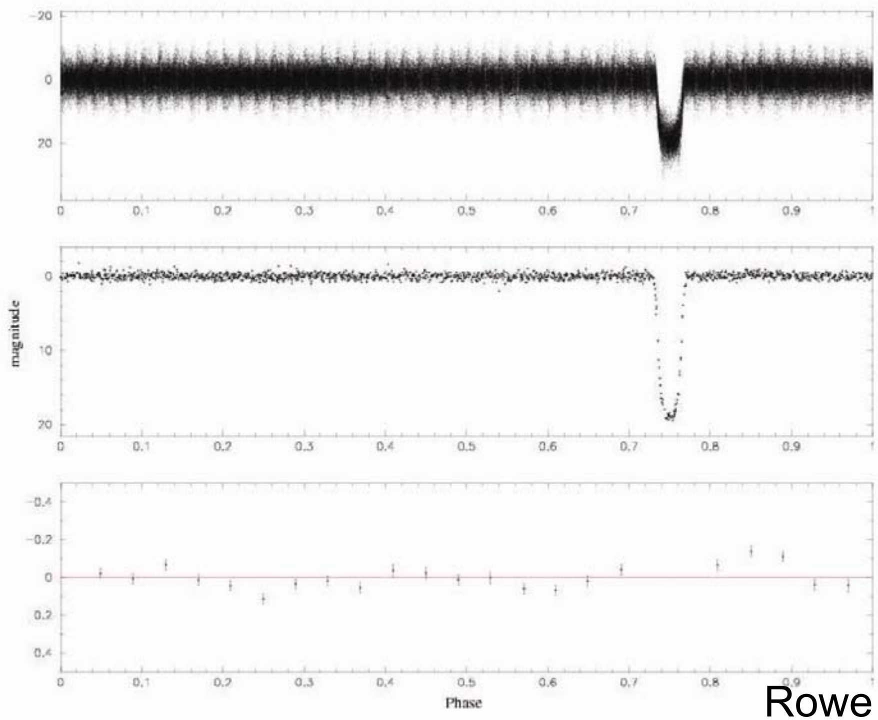


Variable: between 0 and maximum value



Constant: always ½ maximum possible value

Reflected Light Meaurements with MOST



Rowe et al. 2008

Fig. 3.— The reduced 2004 and 2005 MOST photometry of HD 209458 phased to the period of the exoplanet. Top: Unbinned data. The pattern outside of the phase of transit is due to the coincidental harmonic relationship (50:1) between the orbital frequencies of MOST and the exoplanet, so modulated scatter in the data due to scattered Earthshine is also in phase with the period of HD 209458b. Middle: The data averaged in 40-min bins. Bottom: The data in bins of width 0.04 cycle in phase. Note the different magnitude scales for the three plots.

No detection => upper limit on Albedo < 0.12 consistent with theoretical models

The Discovery of Ellipsoidal Variations in the *Kepler* Light Curve of HAT-P-7

William F. Welsh, Jerome A. Orosz

Astronomy Department, San Diego State University, San Diego, CA 92182 USA

Ellipticity effect

Normal Phase Variations of the planet

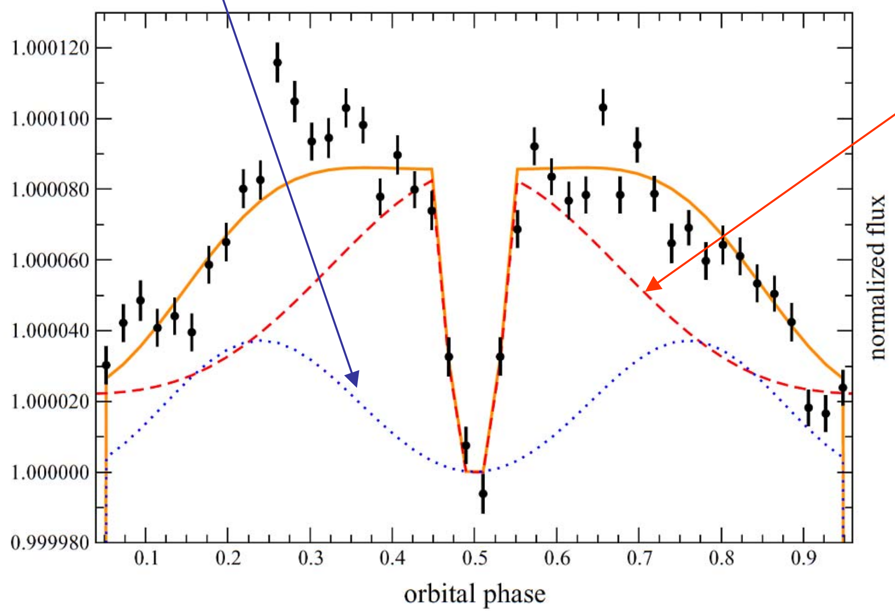
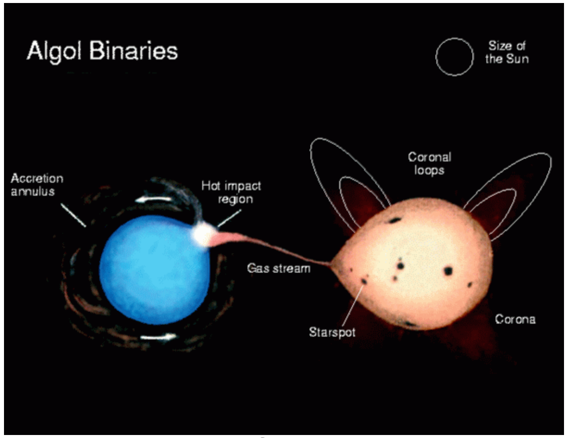


Fig. 3.— Phase-folded *Kepler* light curve with best fit model (solid curve). Also shown are the component stellar-only ellipsoidal model (dotted) and the planet-only model (offset by +1; dashed). Both the data and models have been cast into 30-min bins.

The planet is only 4 stellar radii from the star. Its gravity distorts the star making it ellipsoidal in shape. This causes the so-called ellipsoidal variations

Kepler will do this for many planets!



An extreme case of an elliptical star

At high temperatures, the detected light is a contribution of the reflected light and thermal emission:

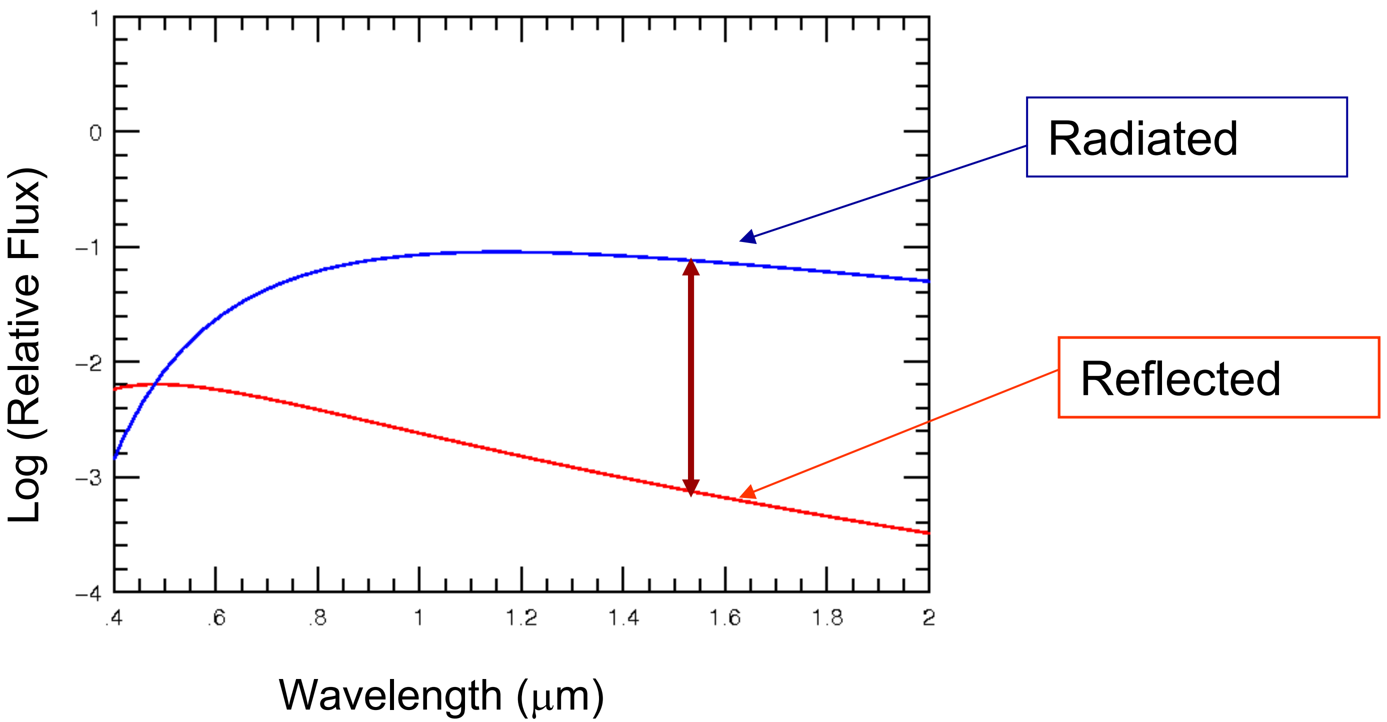
$$R = \frac{F_{refl} + F_{therm} + F_0}{F_0}$$

F_0 is flux from star

R is the ratio of observed flux before the secondary transit and during the transit.

It is difficult to disentangle the effects of Albedo and thermal emission without color information

For close in hot planets, the amount of reflected light = amount of radiated light at 5000 Å



R = 1.5 R_{Jup}, a=0.025 AU (P=1.5 d), T_p = 2500, A=0.1

Interestingly, the Earth is the brightest planet in the solar system at 10 microns

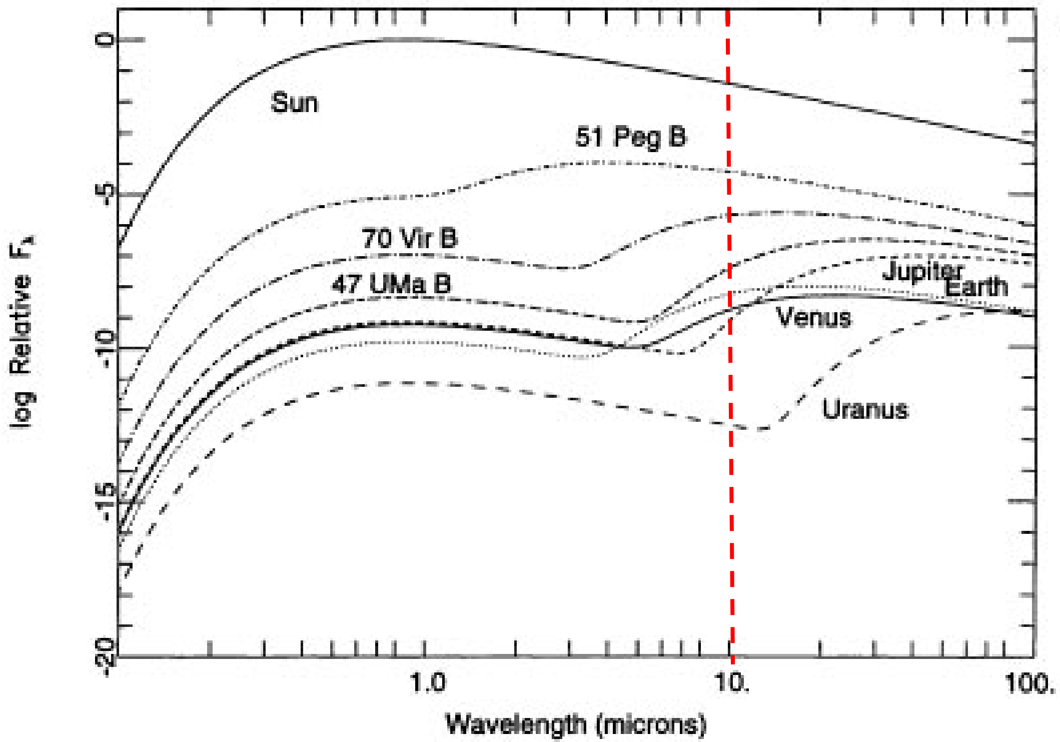
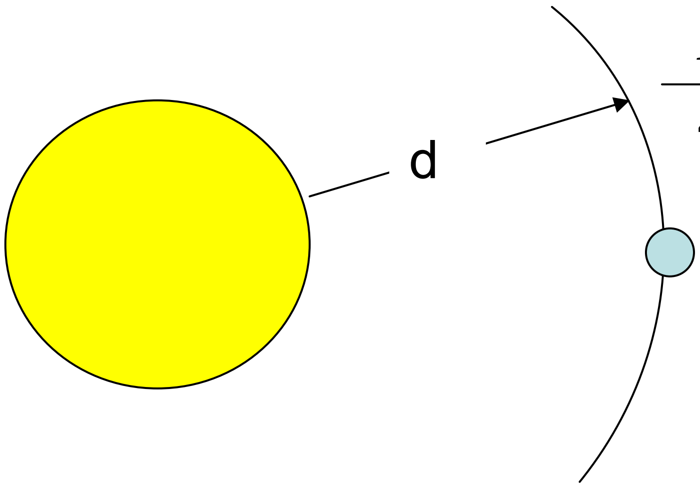


Figure 1. Relative fluxes of the Sun, Venus, Earth, Jupiter, Uranus, and the companion objects to 51 Pegasi, 70 Virginis, and 47 Ursae Majoris from 0.10 μm to 100 μm.

Note: at 10 microns the Earth is the brightest planet in our solar system → look in the Infrared

The Equilibrium Temperature

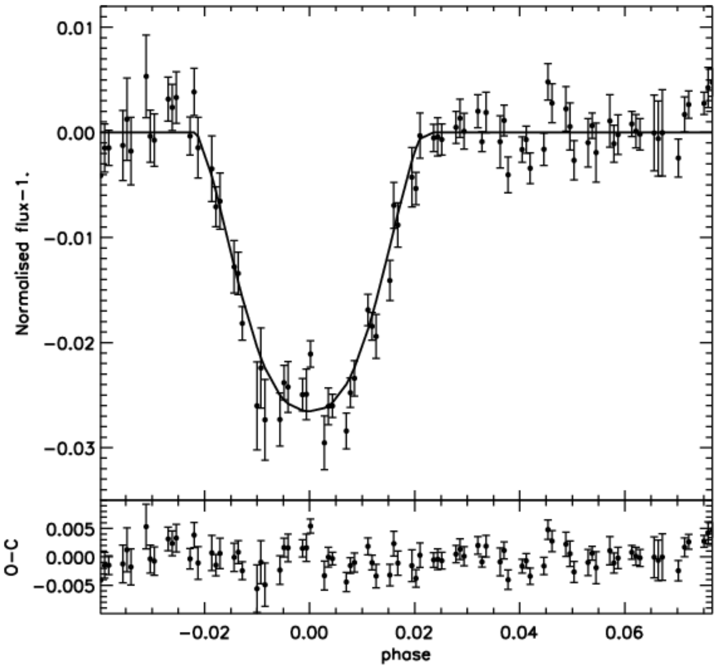


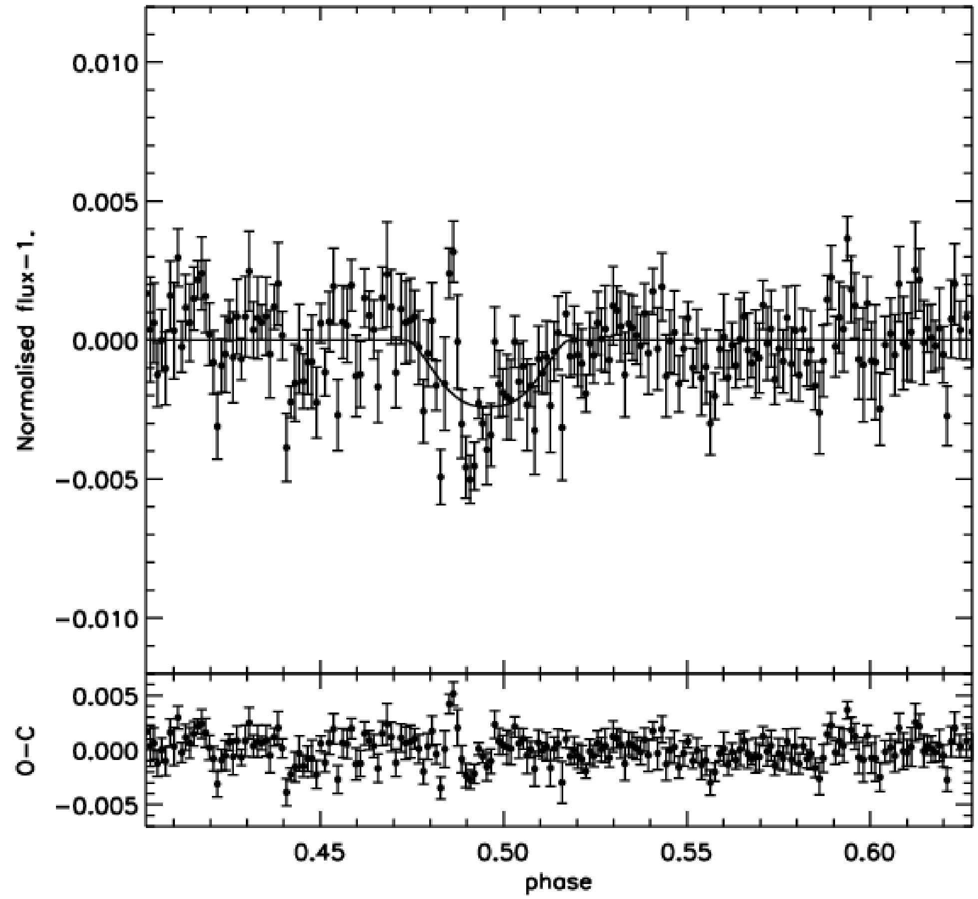
$$\frac{L_{star}}{4\pi d^2} = F$$ = Flux from star

Planet intercepts F × πR^2 and absorbs (1– A) × F x πR^2 where A is now the Bond albedo

Planet heats up and has a temperature T_p. It thus radiates in 4π directions. It keeps heating up until the flux intercepted from the star balances the flux radiated from the planet. At this temperature the planet cannot heat up any more. This is the T_{equ}, the equilibrium temperature.

TrEs 3 from the ground at 2 μm





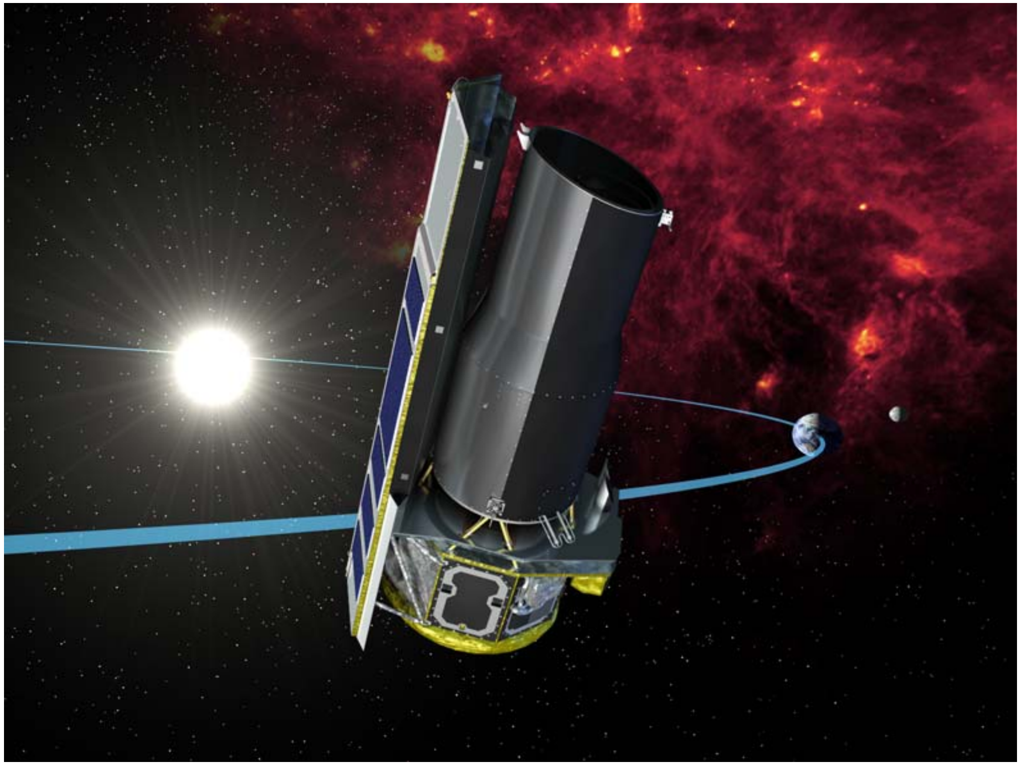
Temperature = 2040 ± 185 K

Radius = 1.3 R_{Jup}

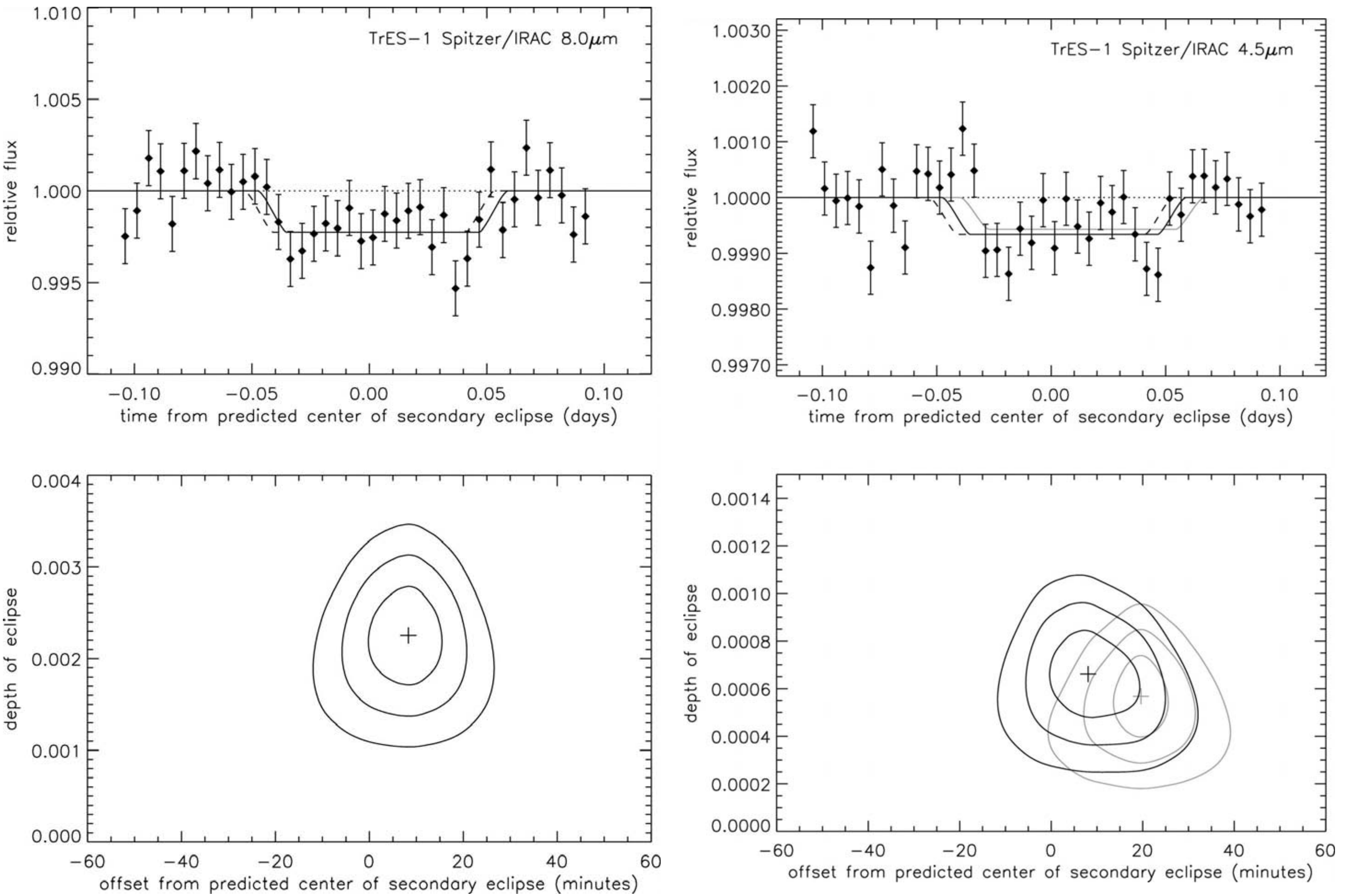
Period = 1.3 d

By observing the secondary transit at different wavelengths one can construct a „crude" (low resolution) spectrum of the planet.

Spitzer Measurements of Exoplanets



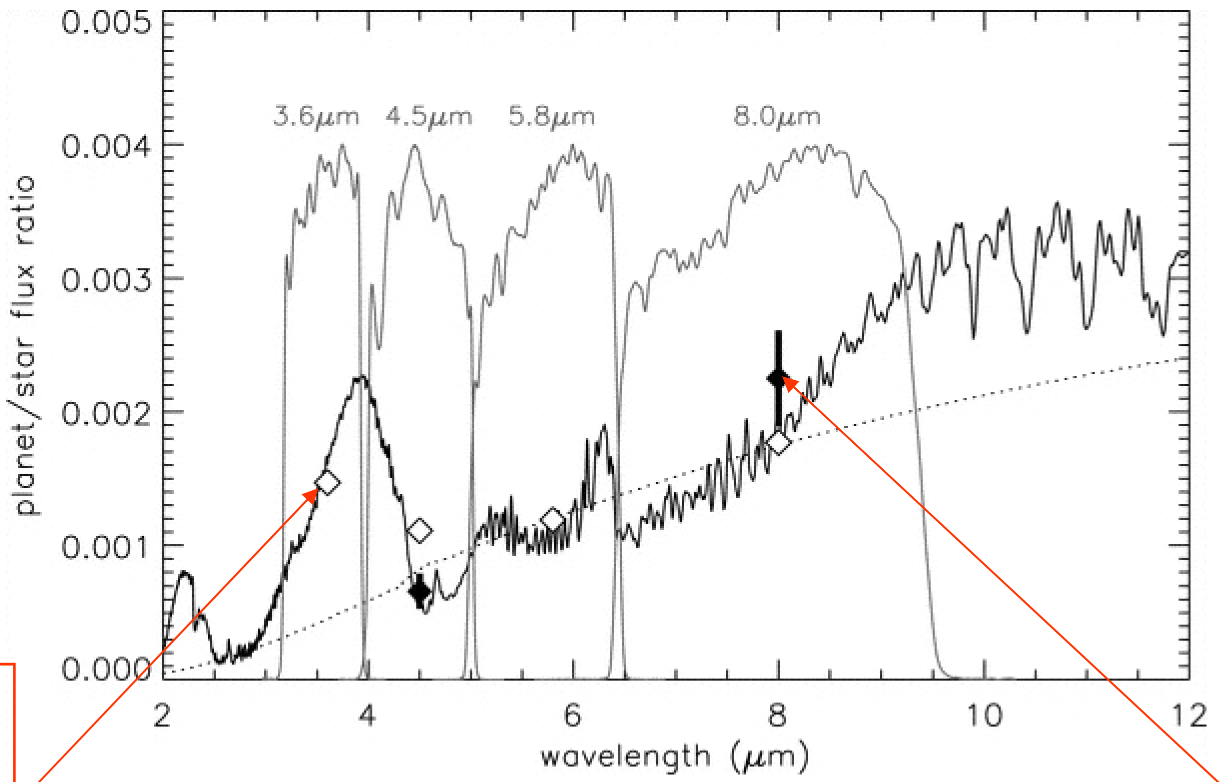
Spitzer is a 0.85m telescope that can measure infrared radiation between 3 and 180 μm



TrES−1 Spitzer/IRAC 8.0μm
relative flux
time from predicted center of secondary eclipse (days)
TrES−1 Spitzer/IRAC 4.5μm
relative flux
time from predicted center of secondary eclipse (days)
depth of eclipse
offset from predicted center of secondary eclipse (minutes)
depth of eclipse
offset from predicted center of secondary eclipse (minutes)

From The Astrophysical Journal 626(1):523–529.

Crude (low-res) "spectroscopy":



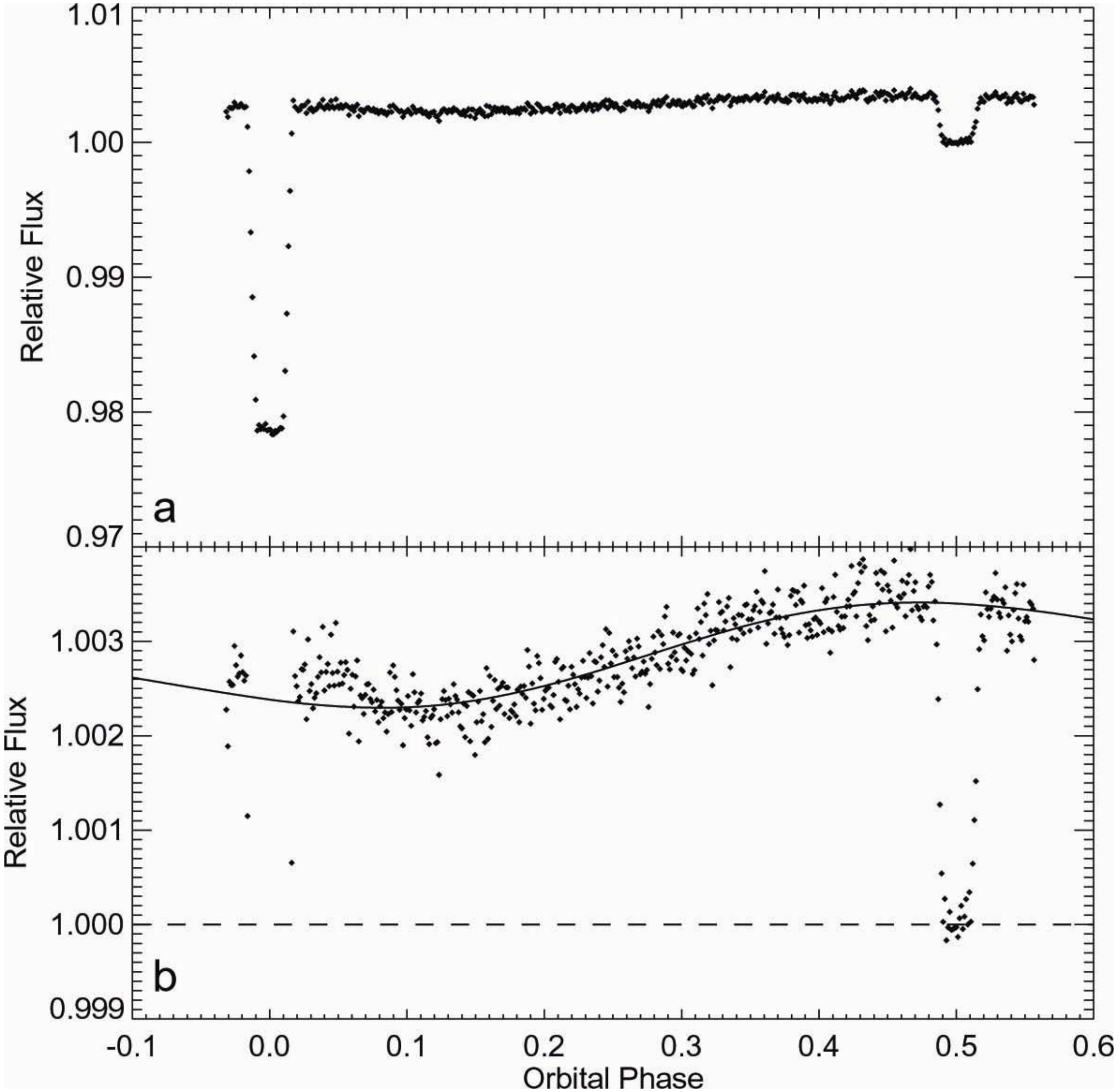
Predicted flux in bandpass (open triangles)

Observed flux in bandpass (solid triangles)

Fig. 3.— Solid black line shows the Sudarsky et al. (2003) model hot Jupiter spectrum divided by the stellar model spectrum (see text for details). The open diamonds show the predicted flux ratios for this model integrated over the four IRAC bandpasses (which are shown in gray and renormalized for clarity). The observed eclipse depths at 4.5 and 8.0 μm are overplotted as black diamonds. No parameters have been adjusted to the model to improve the fit. The dotted line shows the best-fit blackbody spectrum (corresponding to a temperature of 1060 K), divided by the model stellar spectrum. Although the Sudarsky et al. (2003) model prediction is roughly consistent with the observations at 8.0 μm, the model overpredicts the planetary flux at 4.5 μm. The prediction of a relatively large flux ratio at 3.6 μm should be readily testable with additional IRAC observations.

Spitzer Measurements of Radiated Light at 8 μm of HD 189733

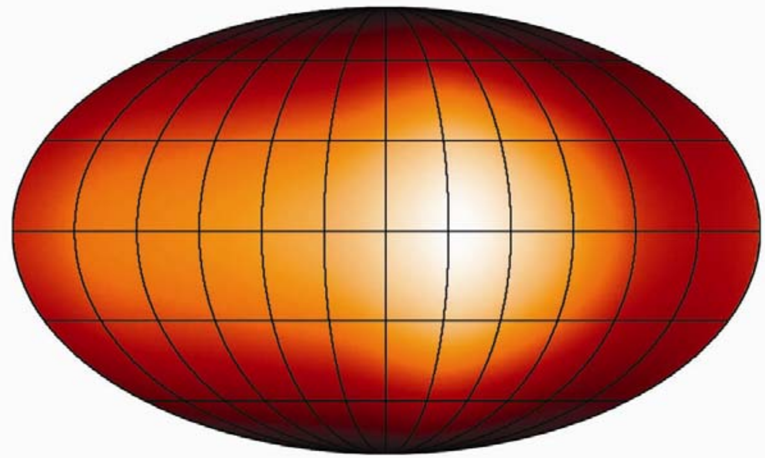
Knutson et al. 2007



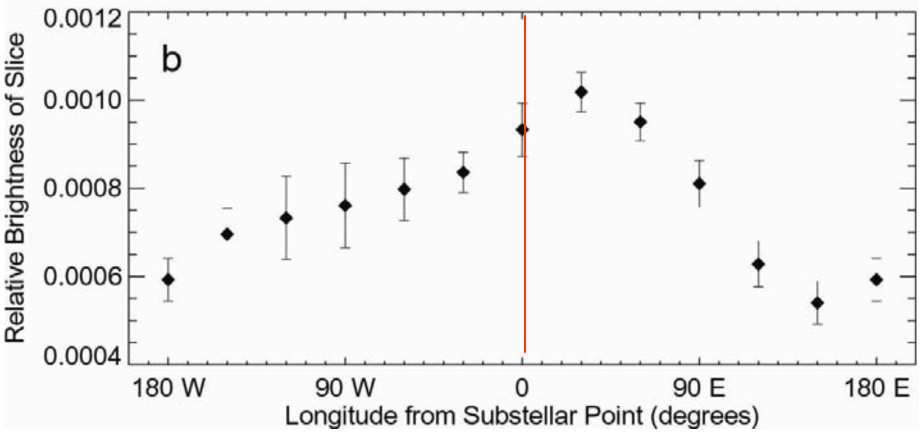
$T_{max} = 1211$ K

$T_{min} = 973$ K

The Brightness distribution on the planet:

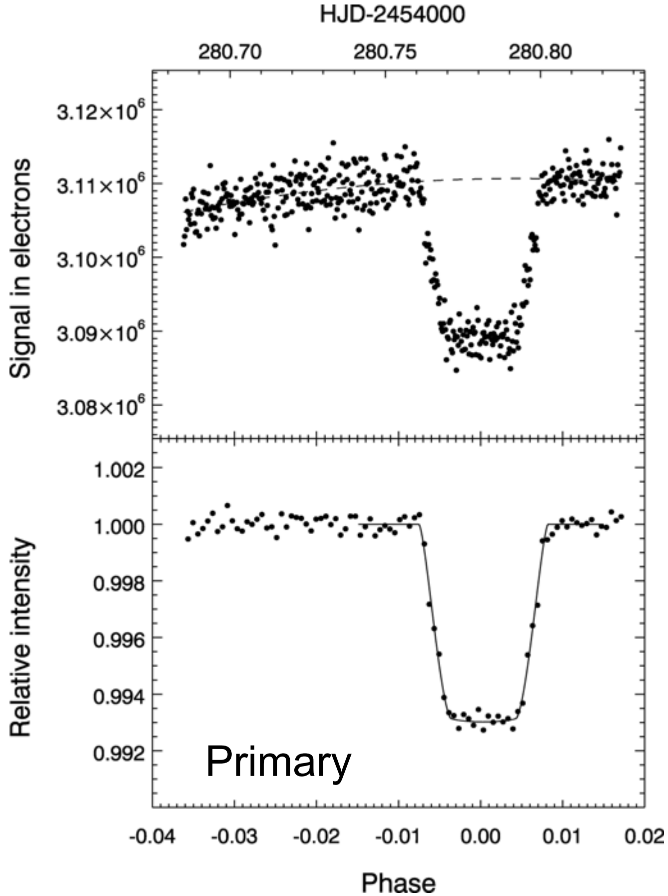


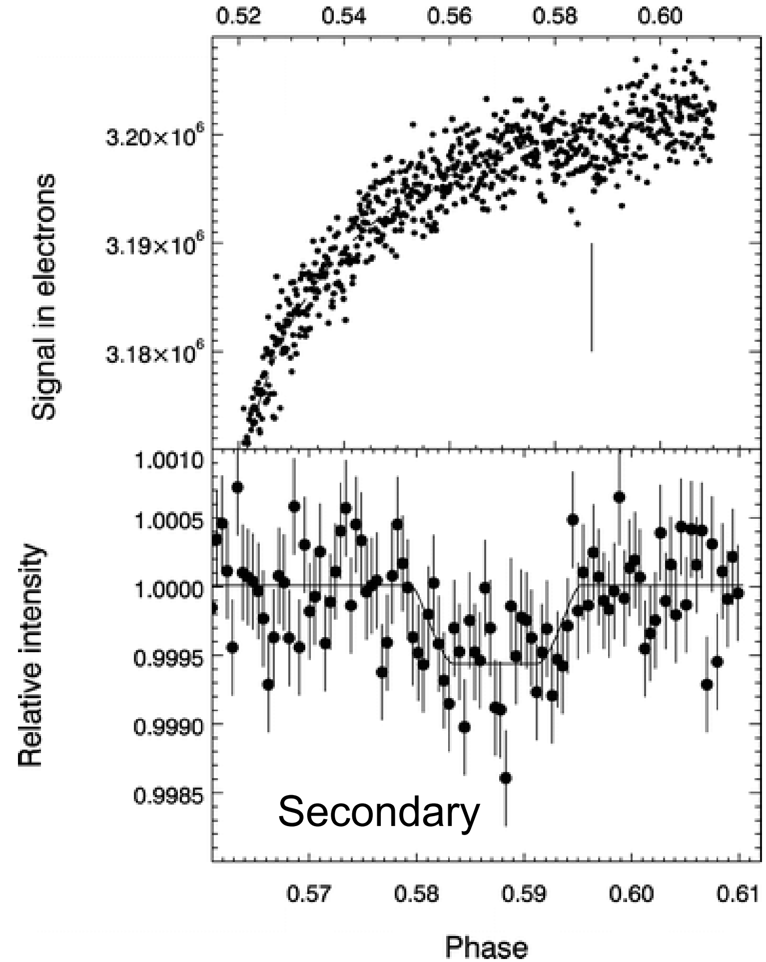
The first evidence of exoplanetary „weather“ (winds)

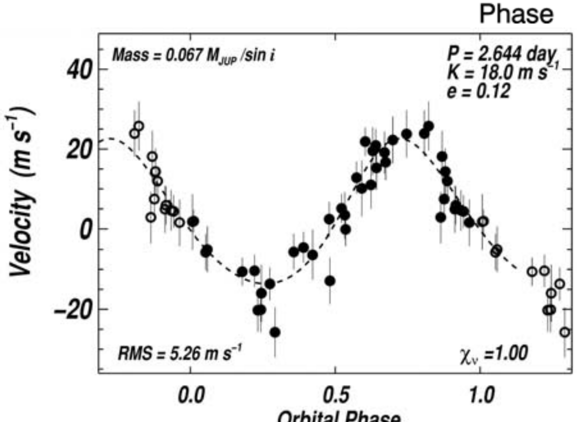


Brightest point is shifted by 16 degrees from the sub-stellar point. The planet is most likely tidally locked (rotation period = orbital period) thus the same face points to the star.

GJ 436 (Hot Neptune) Spitzer measurements





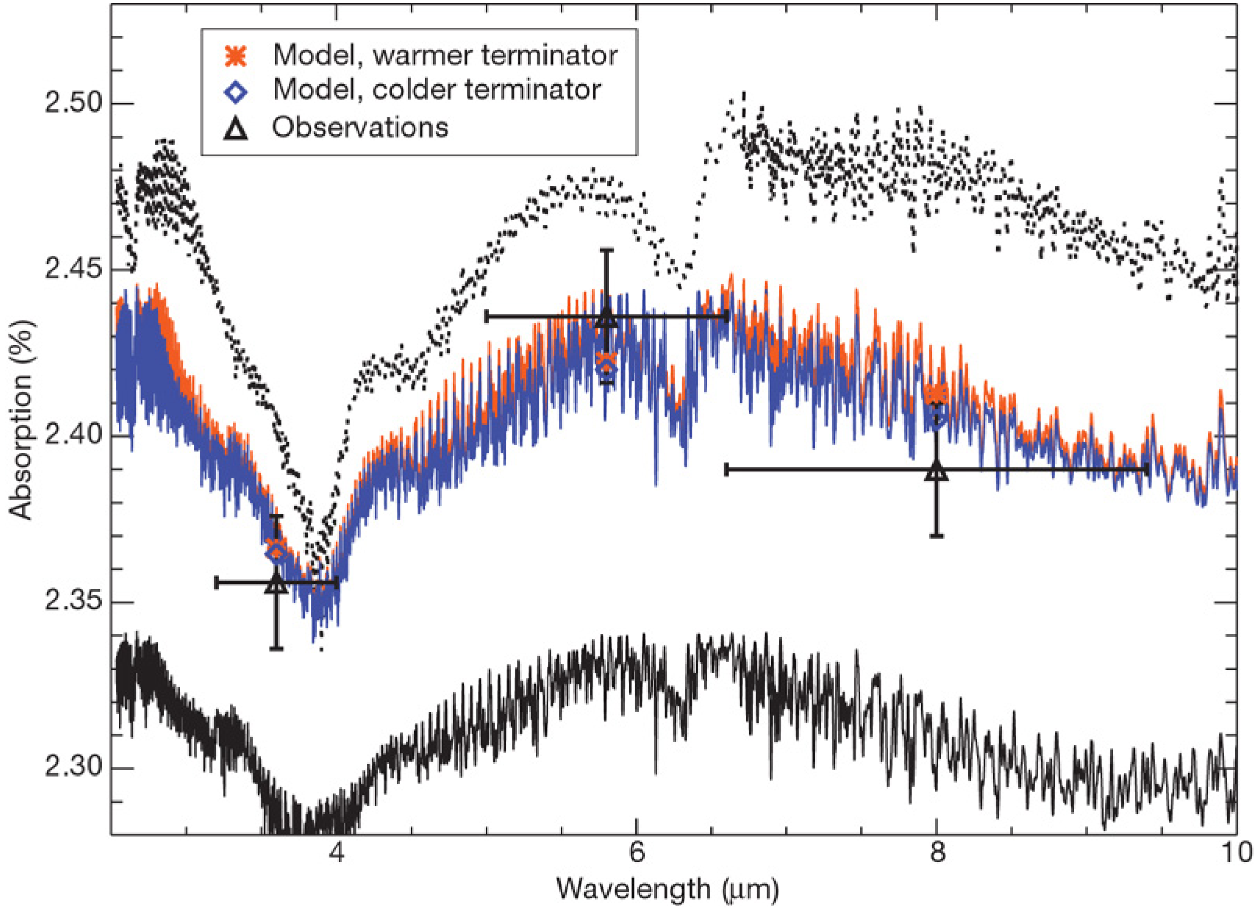


Radius = $4.33 \pm 0.18\ R_E$

T_p = 712 K

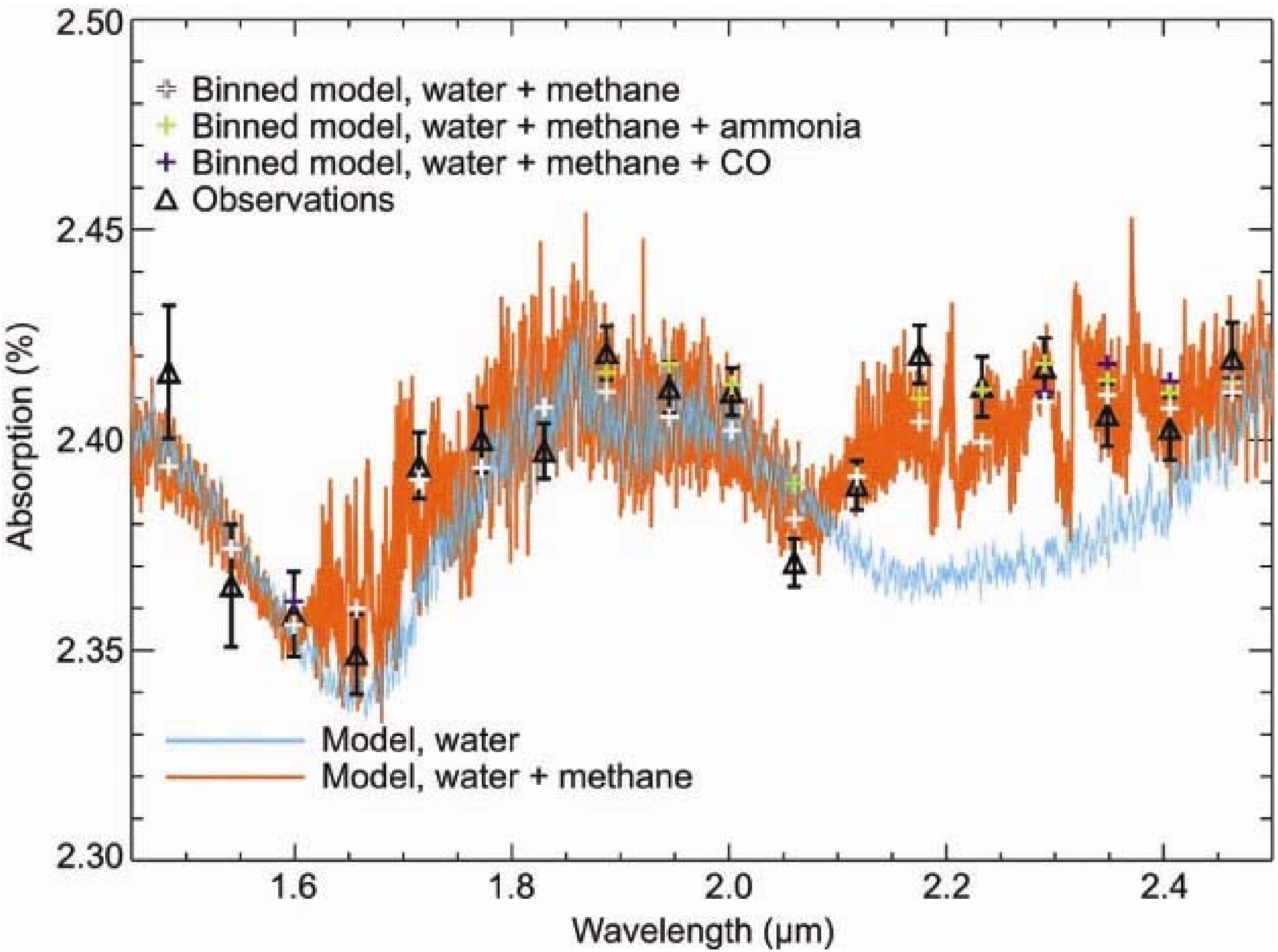
Eccentricity = 0.15

Detection of water in HD 189733b with Spitzer

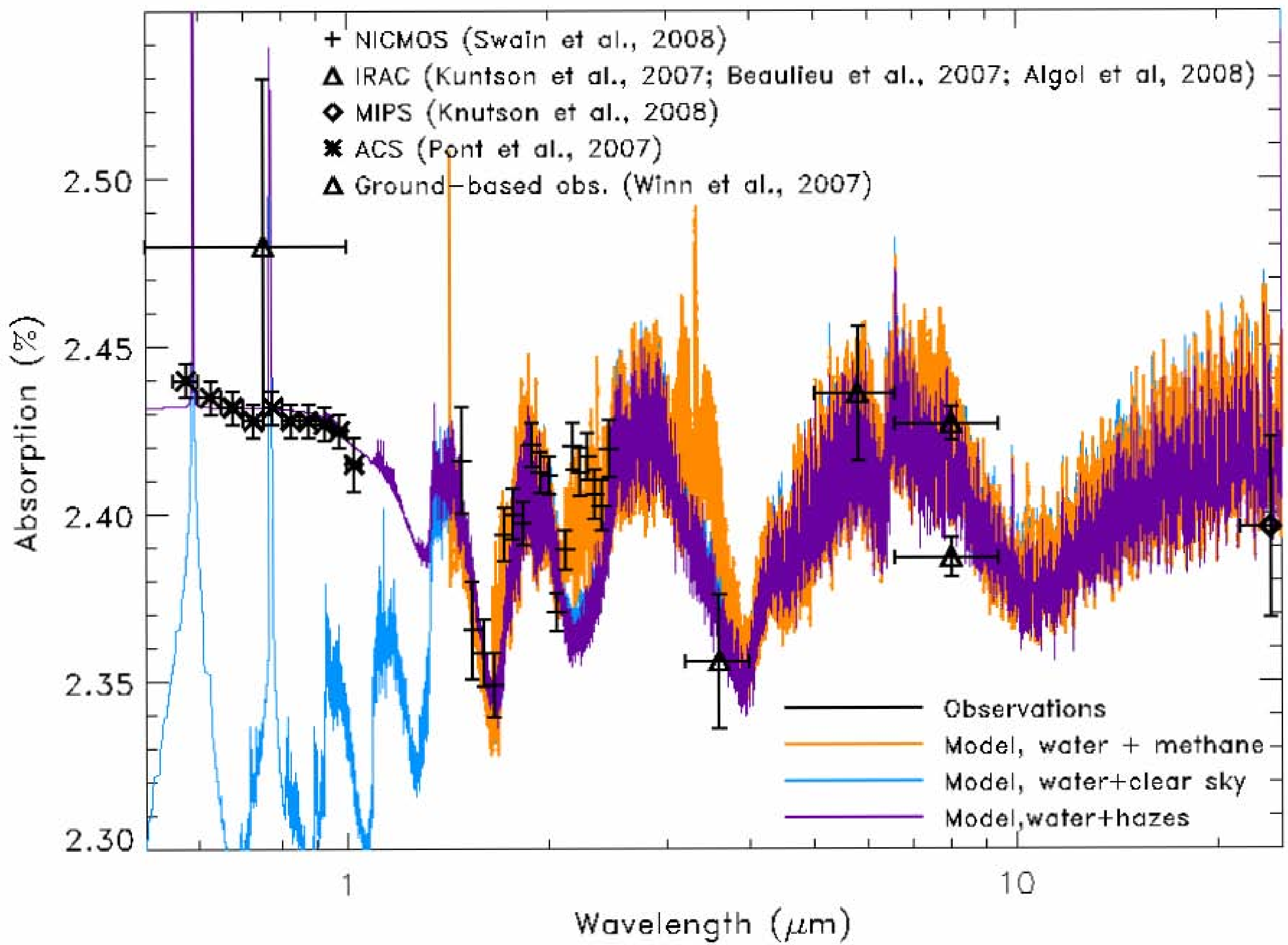


Tinetti et al. 2007, Nature

Detection of water and Methane in HD 189733b with *HST*

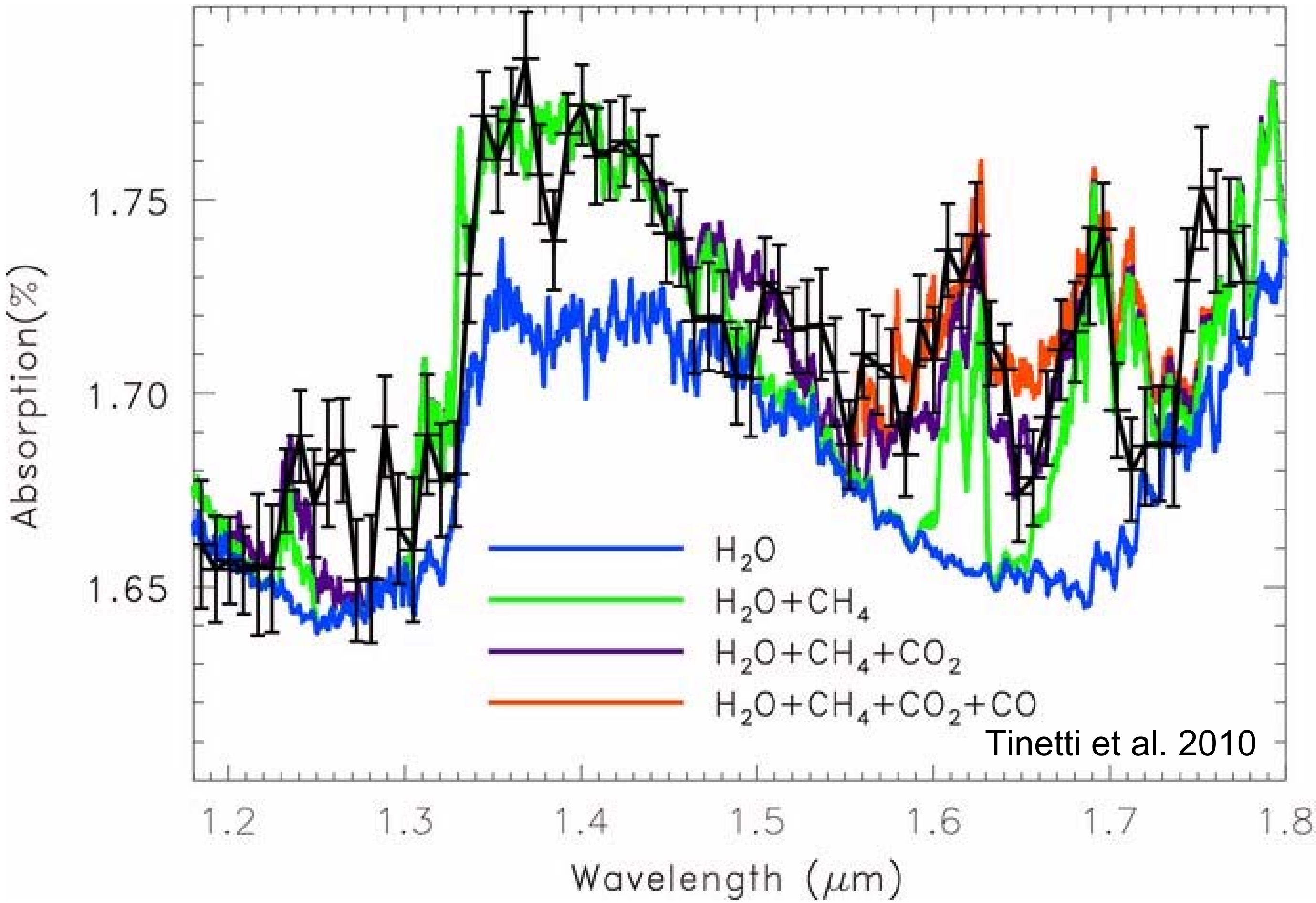


HD189733b

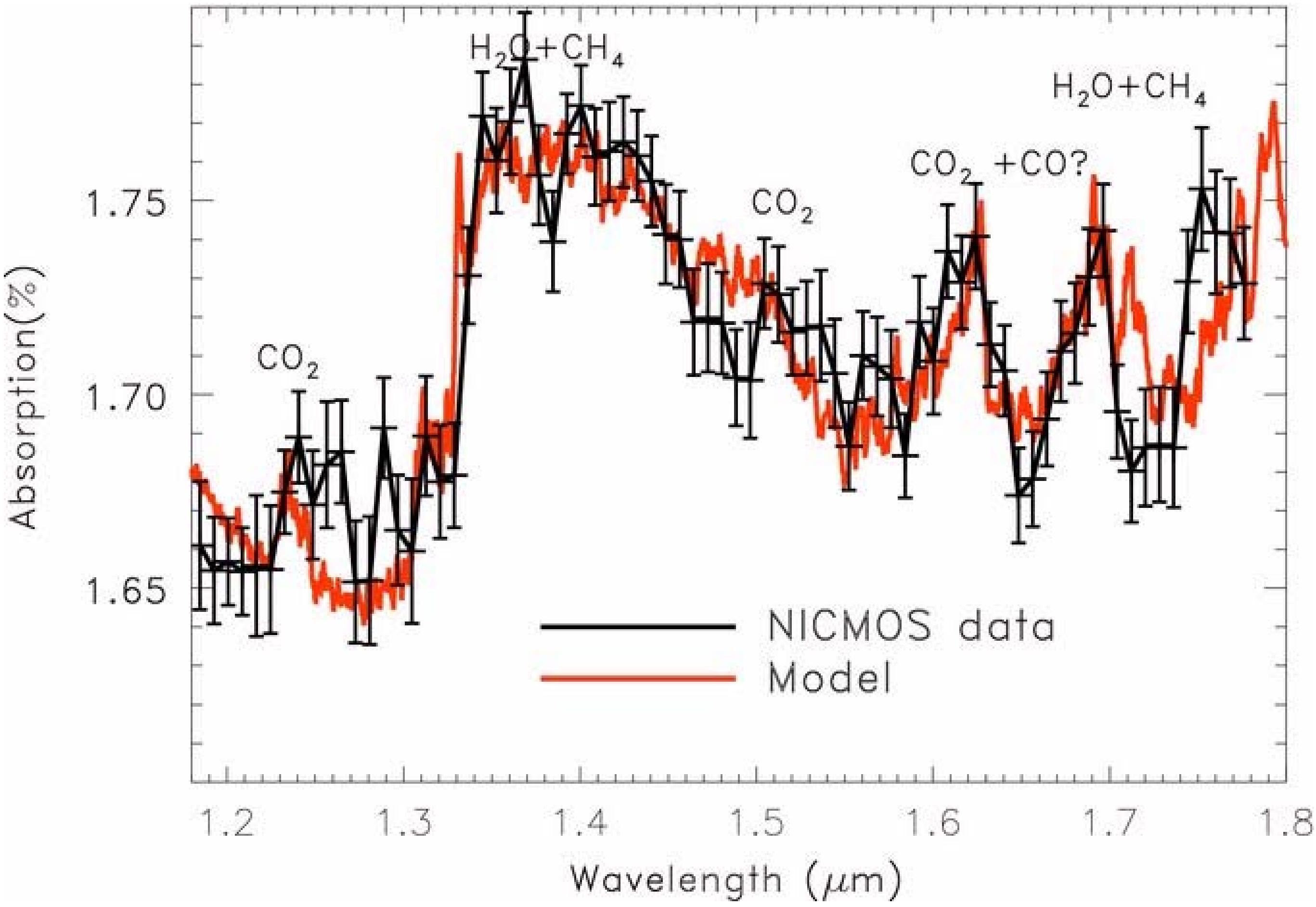


Tinnetti et al. 2009

Take your observational data and try to fit it with the „usual set of suspects“ (molecules) expected for giant planets.

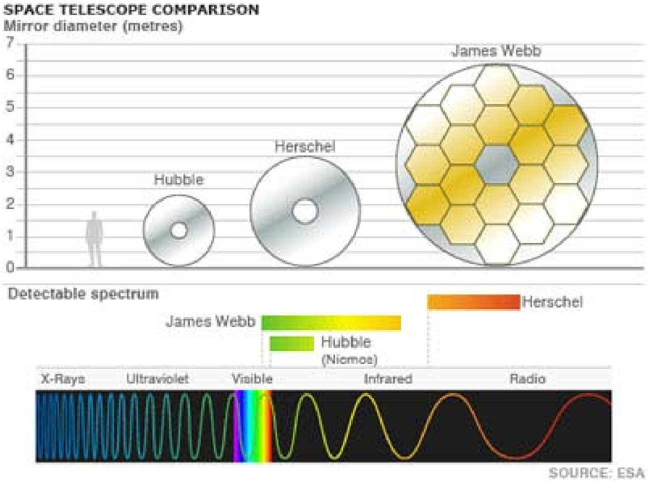


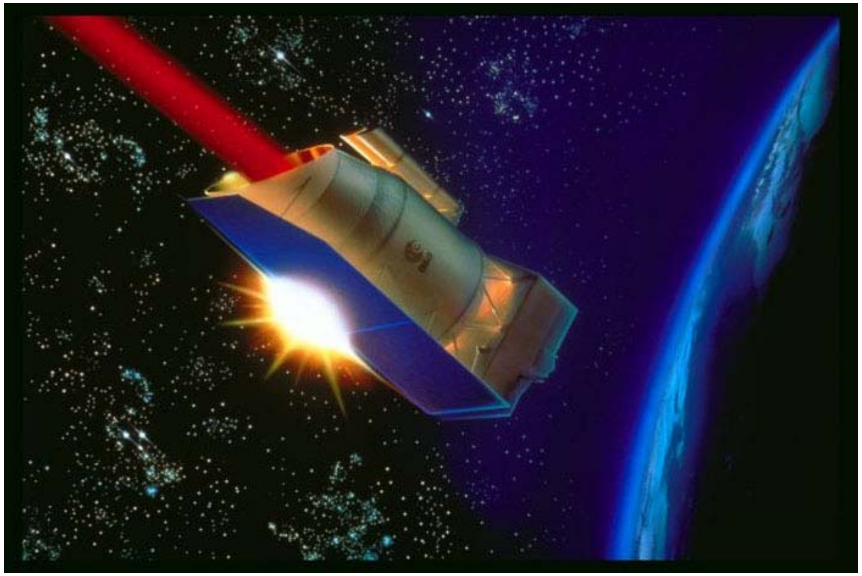
Evidence for CO and CO_2 in giant exoplanet atmospheres



H_2O+CH_4
H_2O+CH_4
CO_2 +CO?
CO_2
CO_2
NICMOS data
Model
1.75
1.70
1.65
Absorption(%)
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Wavelength (μm)

Herschel will now continue the IR work started on Spitzer



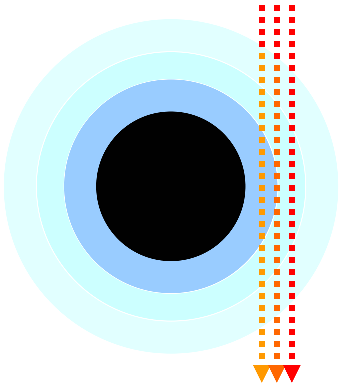


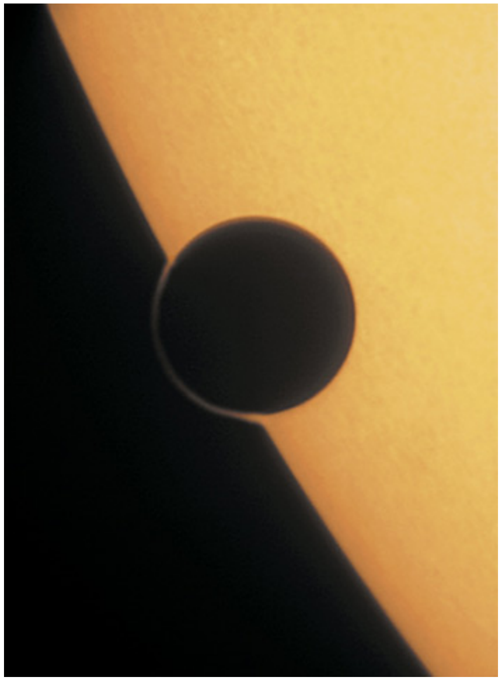
III. In-transit Spectroscopy

• Take a spectrum of the star during the out-of-transit time

• Take a spectrum of the star during the transit

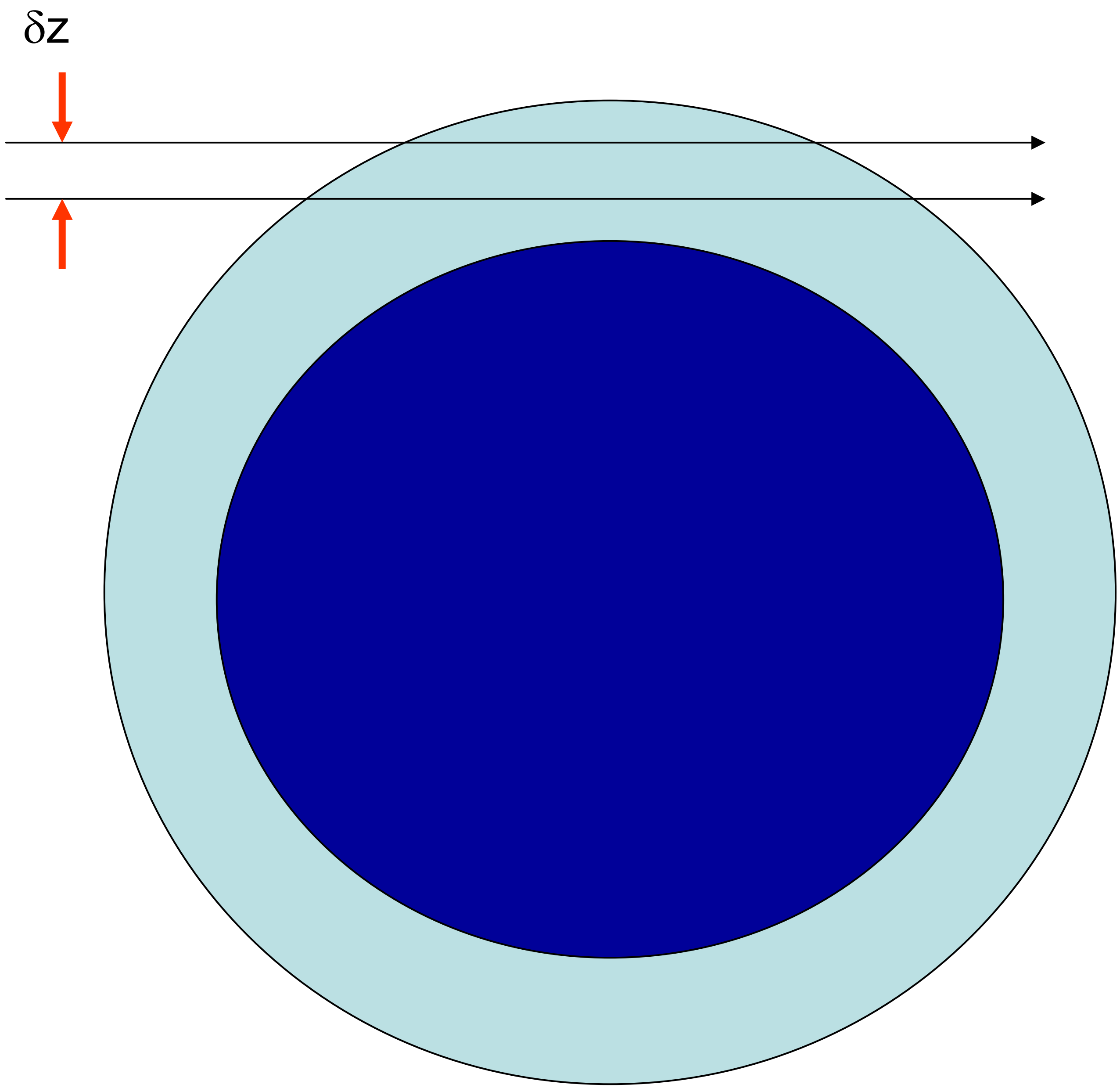
• Subtract the two and what remains is the spectrum of the planet atmosphere





Questions to be answered:

1. How big is the effect?
2. What spectral lines do we expect to find?
3. What are the best targets?
4. How good must the data be?



Opacity of the upper ray going through the planetary atmosphere is reduced by $e^{-\delta z}$

Take the scale height, H, as the typical size of the planet atmoshere

What objects do we look at?

	Jupiter	HD 209458	WASP 12	CoRoT-7
Mass	1.0	0.63	1.41	0.019
Radius	1.0	1.35	1.79	0.0015
Temperature	125	1400	2500	2600
μ	1	0.6	0.6	23 (Na)
H (km)	40	3400	2800	< 1
R_{star} (solar)	1	1.146	1.57	0.9
$\delta A/A$	10^{-5}	6.0×10^{-4}	6.0×10^{-4}	2.0×10^{-12}

$M_{Jup} = 2 \times 10^{30}$ gm

$R_{Jup} = 7 \times 10^{9}$ cm

How good does your data have to be?

We want to detect a signal of ≈ 10^{-3} that of the star. Suppose you want detect 1000 photons from the planet (signal to noise ratio of 33). This means you need to detect 10^6 photons from the star (+ planet)

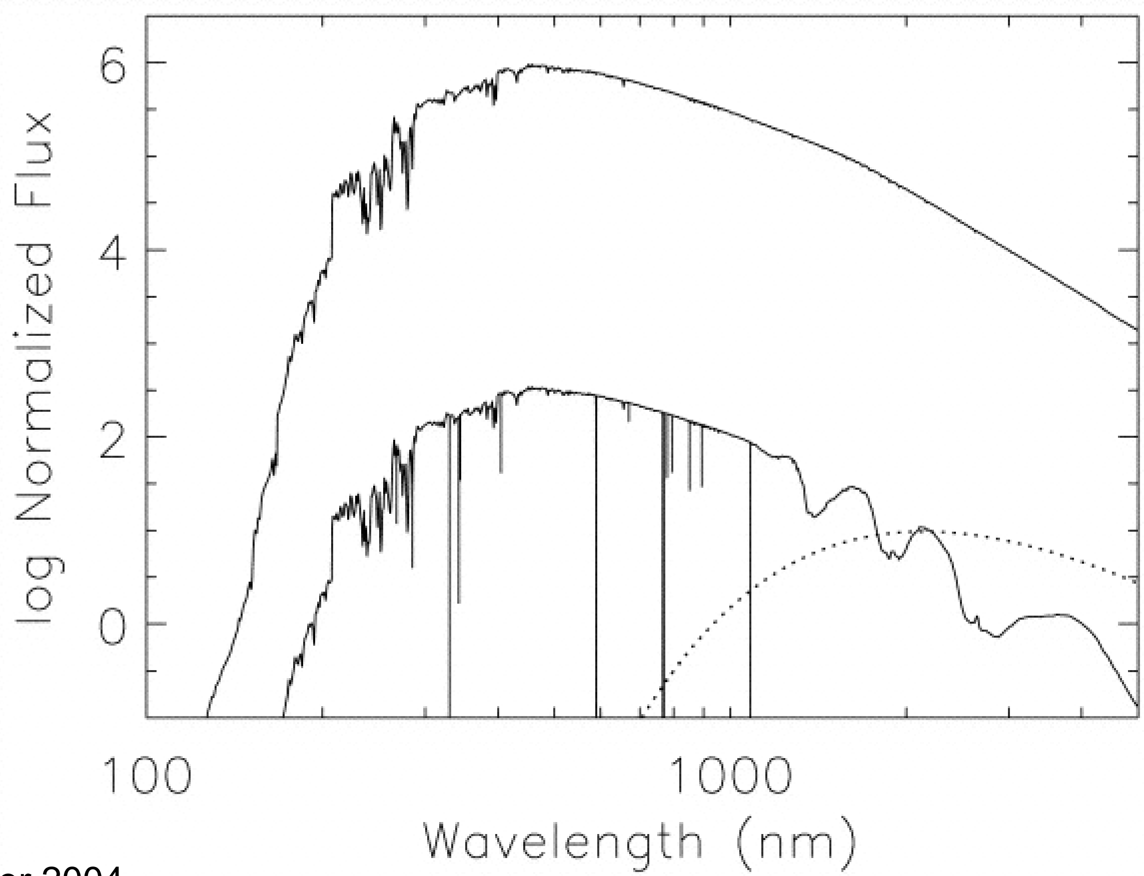
For a star of magnitude HD 209458 (V = 7.65) you can get 90000 photons in about 3 minutes (including overhead) on the 8m VLT.

Number of observations = 10^6/90000 = 11 observations ≈ 0.5 hour.

You have to take this many observations, but both in and out of transit

E.g. take V=12, A detection will require ≈ 30 hours

What spectral features do we expect?



Sasselov & Seager 2004

Fig. 1.— Flux of HD 209458 a (upper curve) and the transmitted flux through the planet's transparent atmosphere (lower curve). Superimposed on the transmitted flux are the planetary absorption features, including the He i triplet line at 1083 nm. The other bound-bound lines are alkali metal lines (see Fig. 2 for details). The H2O and CH4 molecular absorption dominates in the infrared. The dotted line is a blackbody of 1350 K representative of the CEGP's thermal emission, but the thermal emission can be larger than a blackbody blueward of 2000 nm.

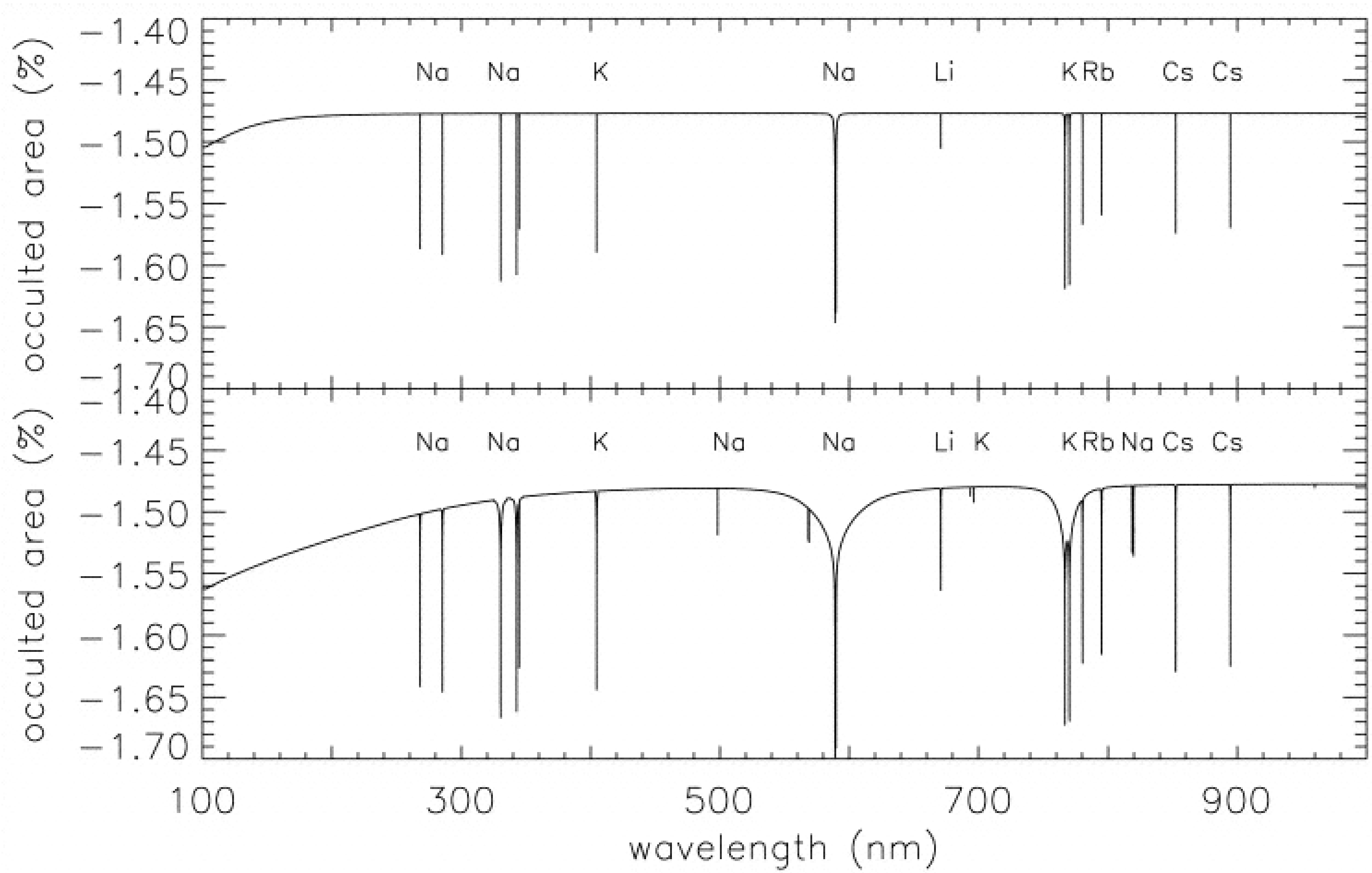
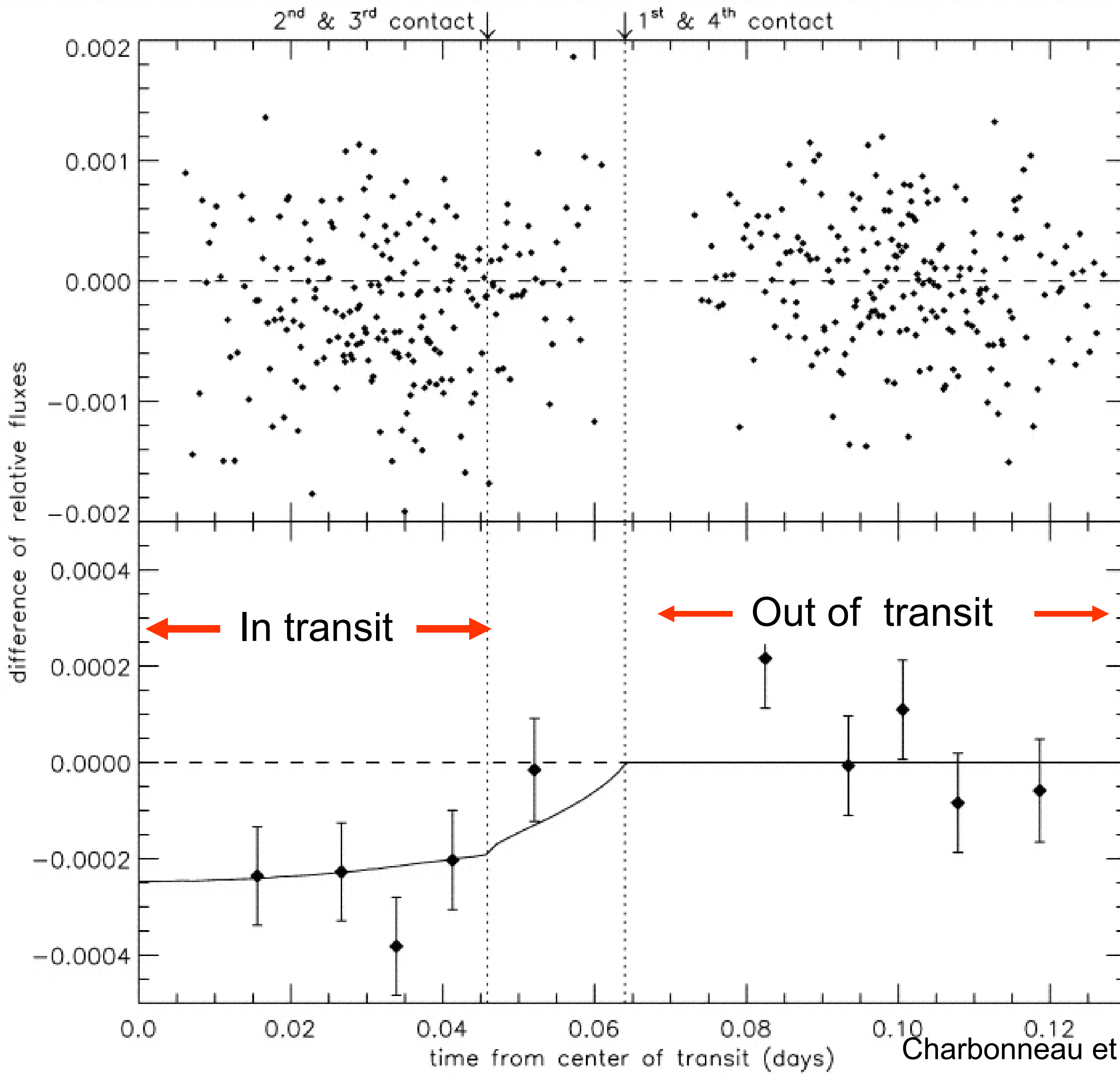


Fig. 2.—Upper plot: The normalized in-transit minus out-of-transit spectra, i.e., percent occulted area of the star. In this model the cloud base is at bar. Rayleigh scattering is important in the UV. Lower plot: A model with cloud base at 0.2 bar. The stellar flux passes through higher pressures, densities, and temperatures of the planet atmosphere compared to the model in the upper plot. In addition, a larger transparent atmosphere makes the line depth larger. Observations will constrain the cloud depth. See text for discussion.

The first detection of Sodium in an exoplanet?

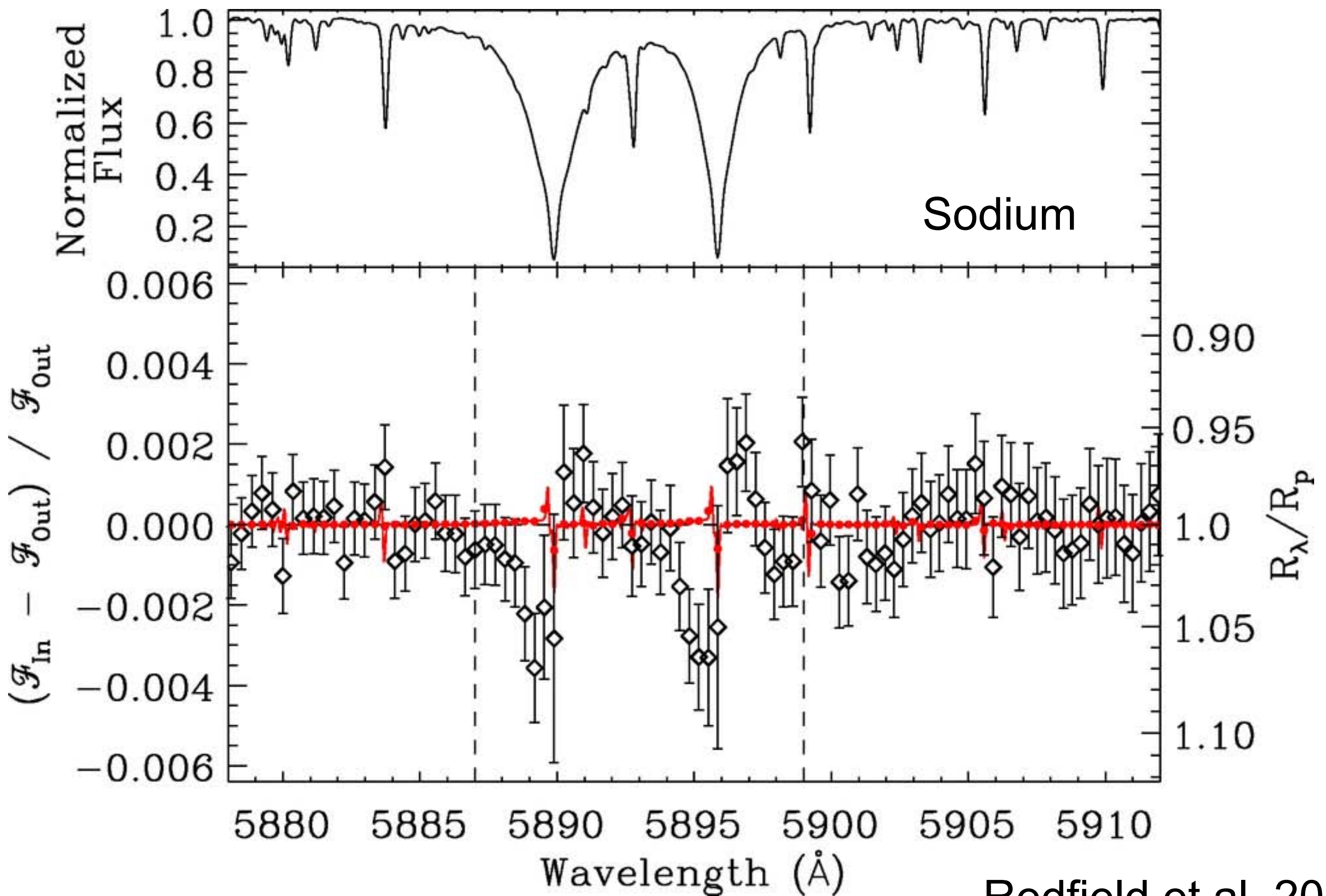
HST data



Charbonneau et al. 2001

Fig. 4.—Top: Unbinned time series nNa (Fig. 2, top panel). Bottom: These data binned in time (each point is the median value in each bin). There are 10 bins, with roughly equal numbers of observations per bin (42). The error bars indicate the estimated standard deviation of the median. The solid curve is a model for the difference of two transit curves (described in § 3), scaled to the observed offset in the mean during transit, ΔnNa = −2.32 × 10−4.

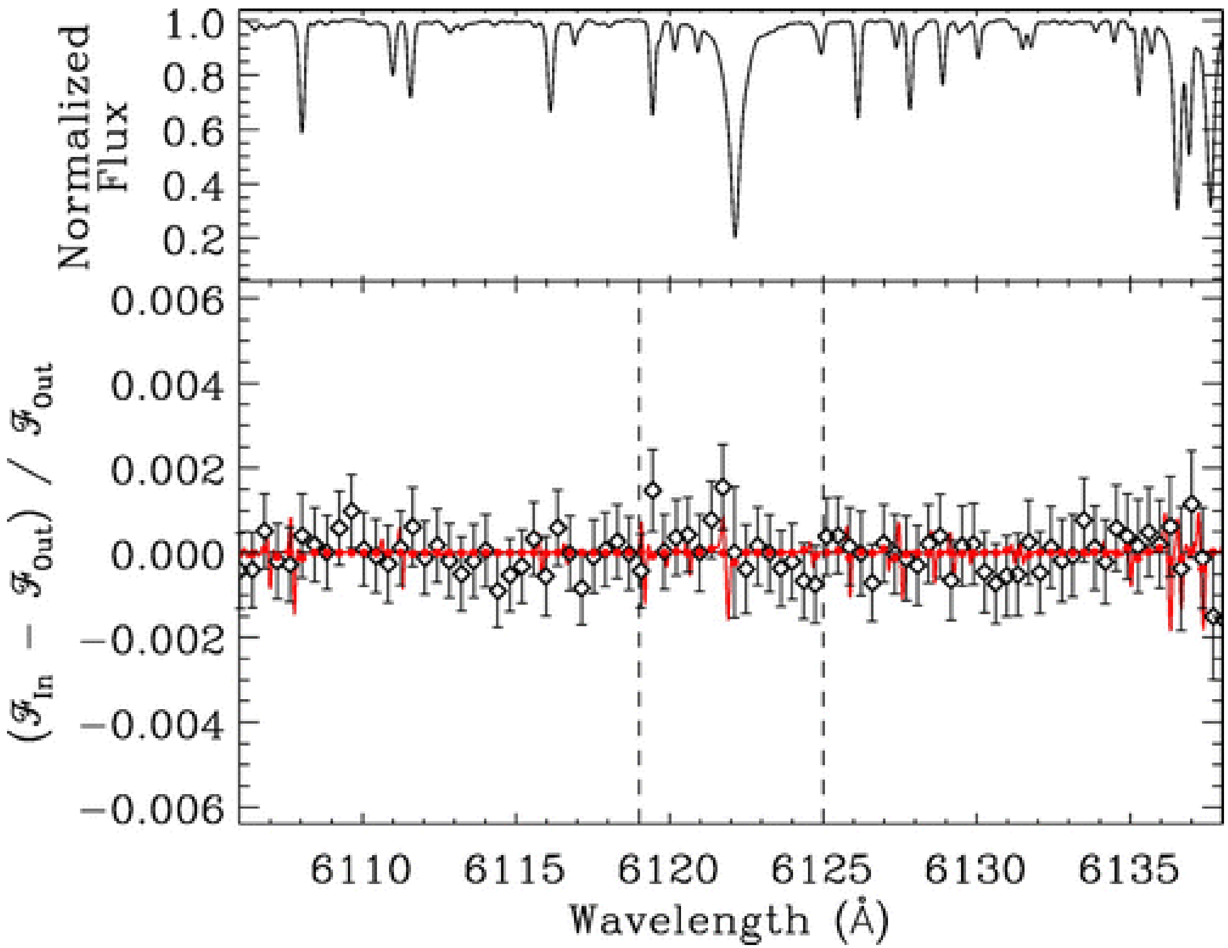
A Detection from a ground-based telescope



Redfield et al. 2007

Data taken on 11 in transit observations and 25 out of transit observations with a 9m telescope (HET) and S/N=320 (each)

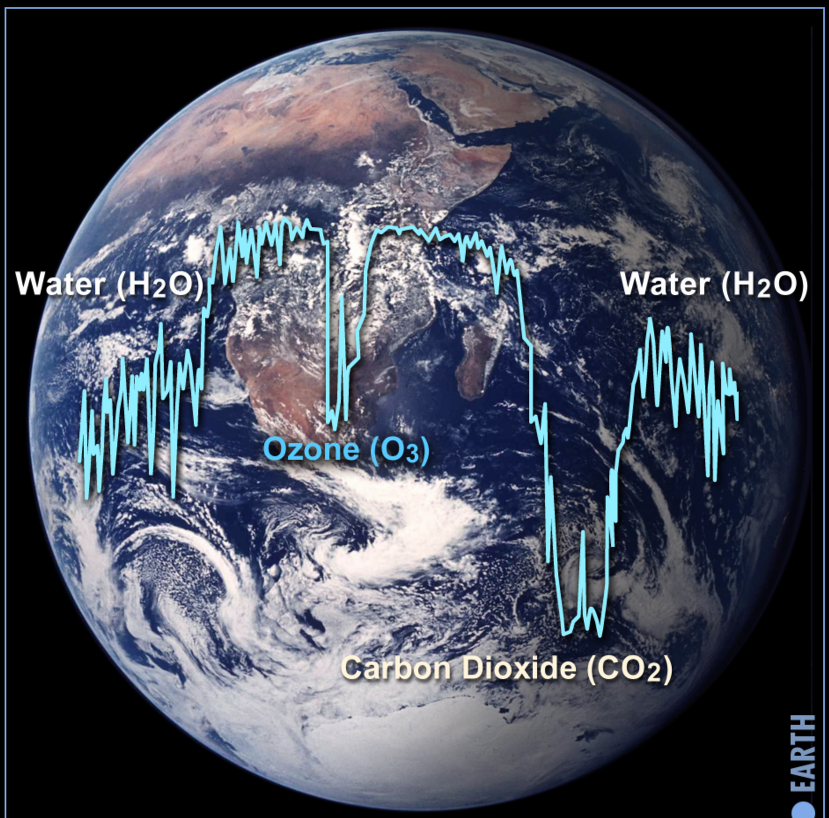
Calcium

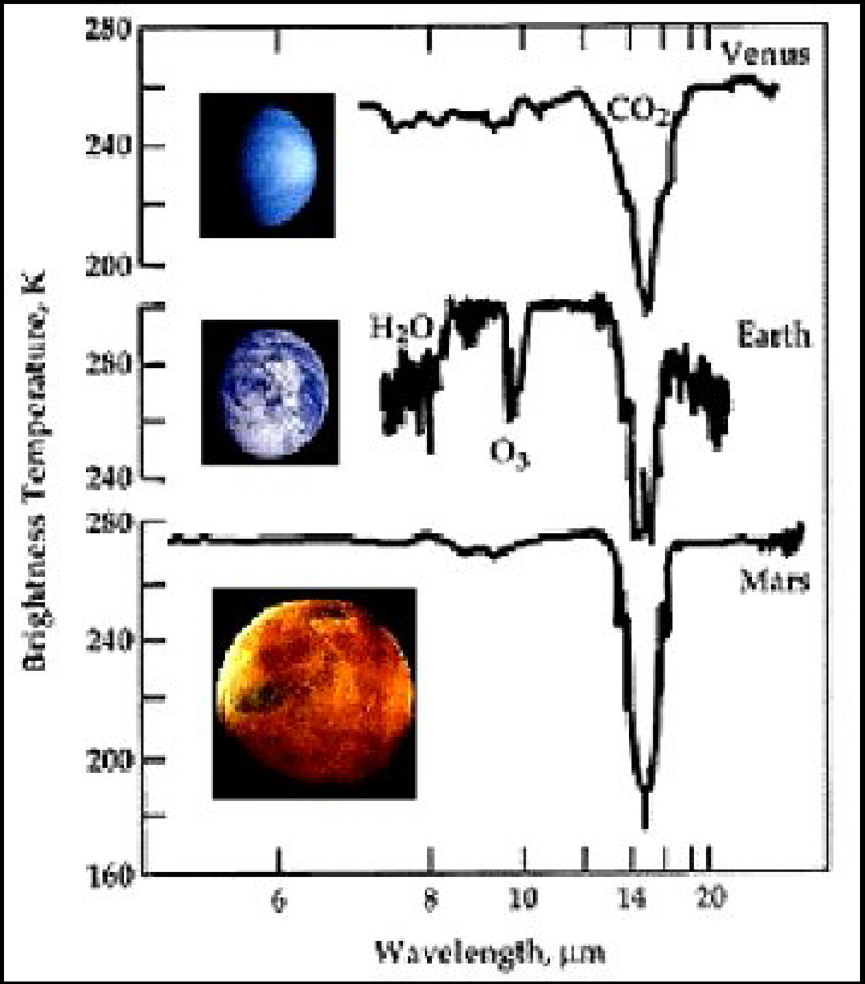


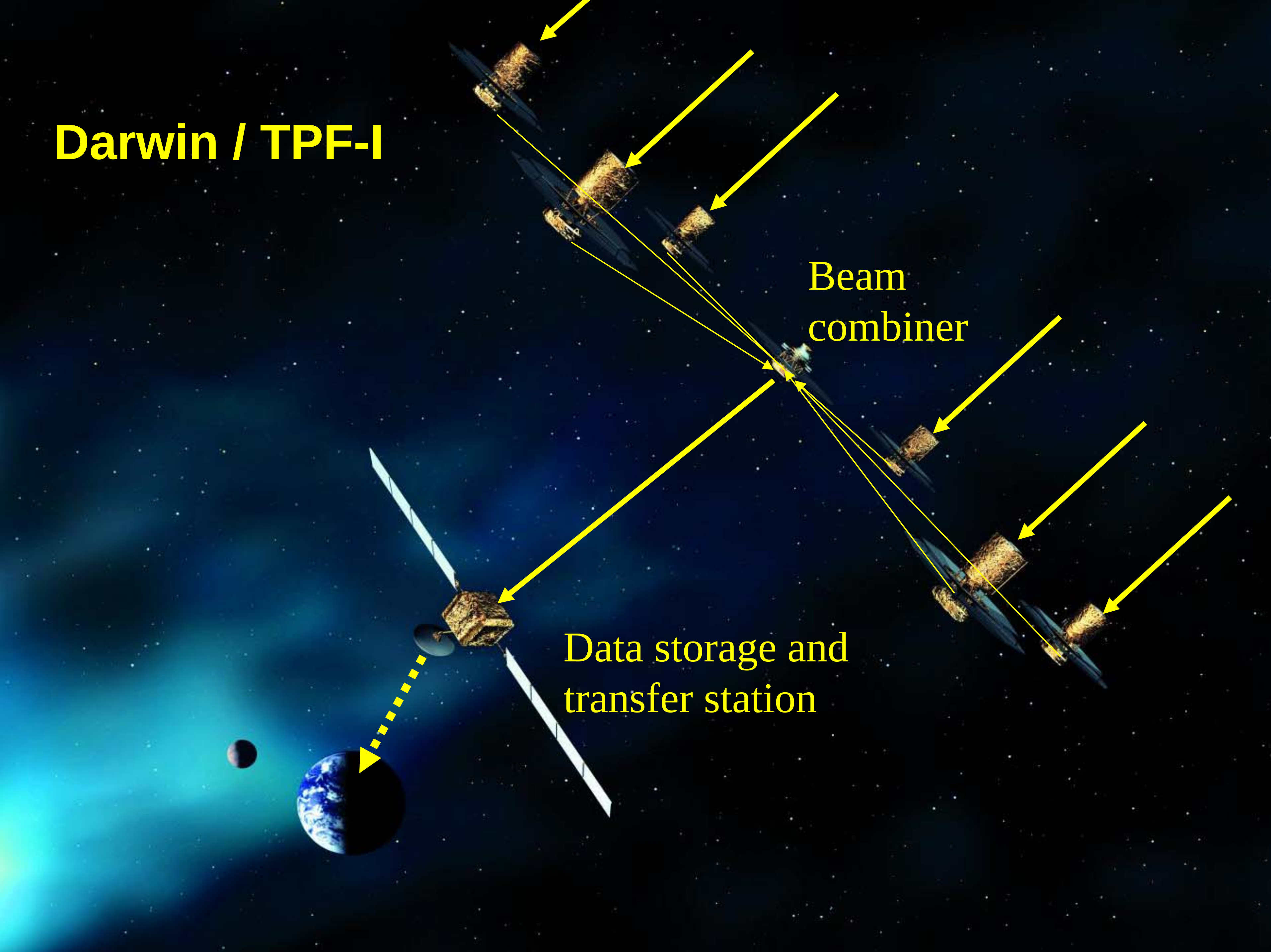
An element not expected to show excess absorption shows none

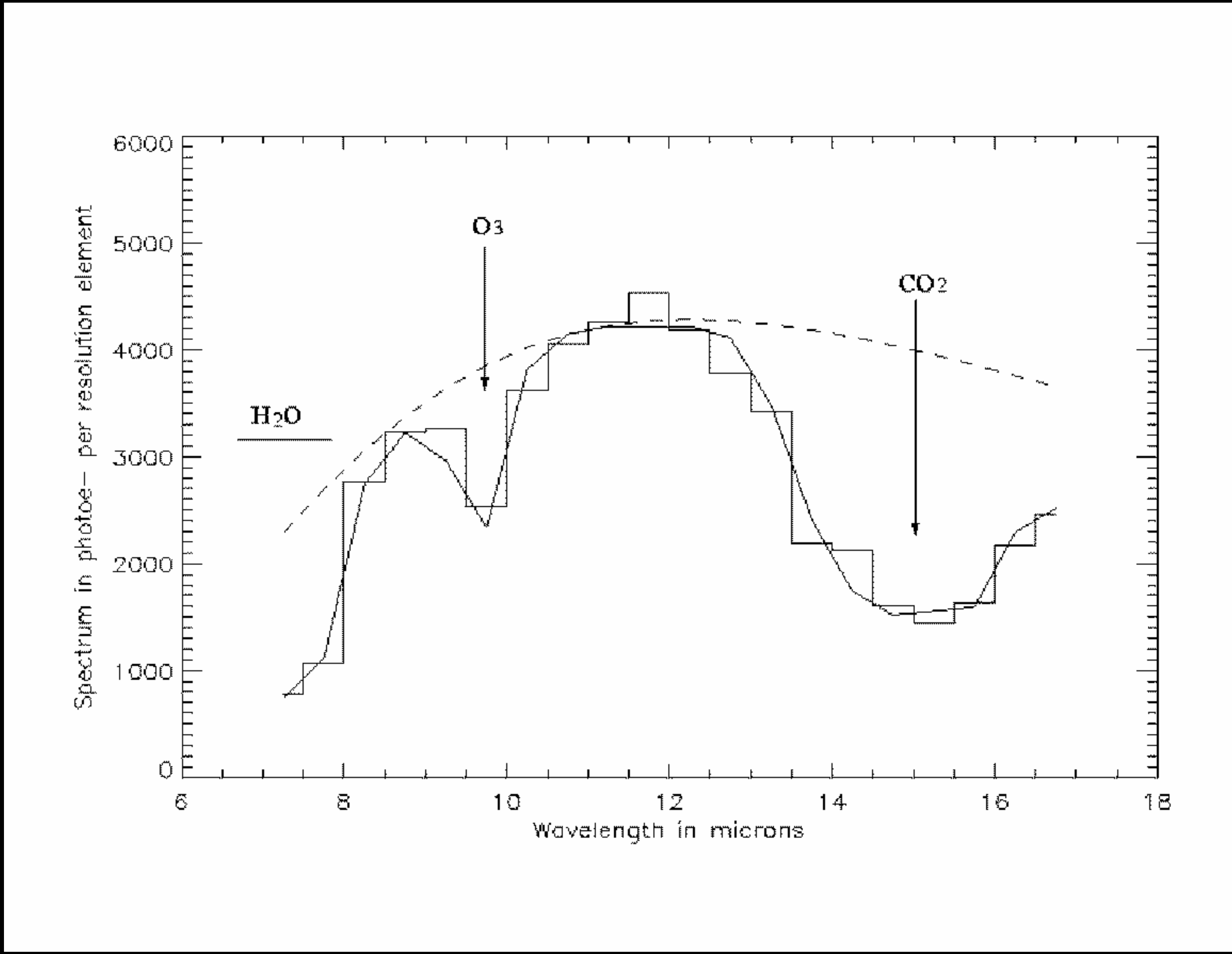
We have just completed a survey of 6 hot Jupiters and 1 hot Neptune with the HET: stay tuned....

What about the atmosphere of terrestrial planets?





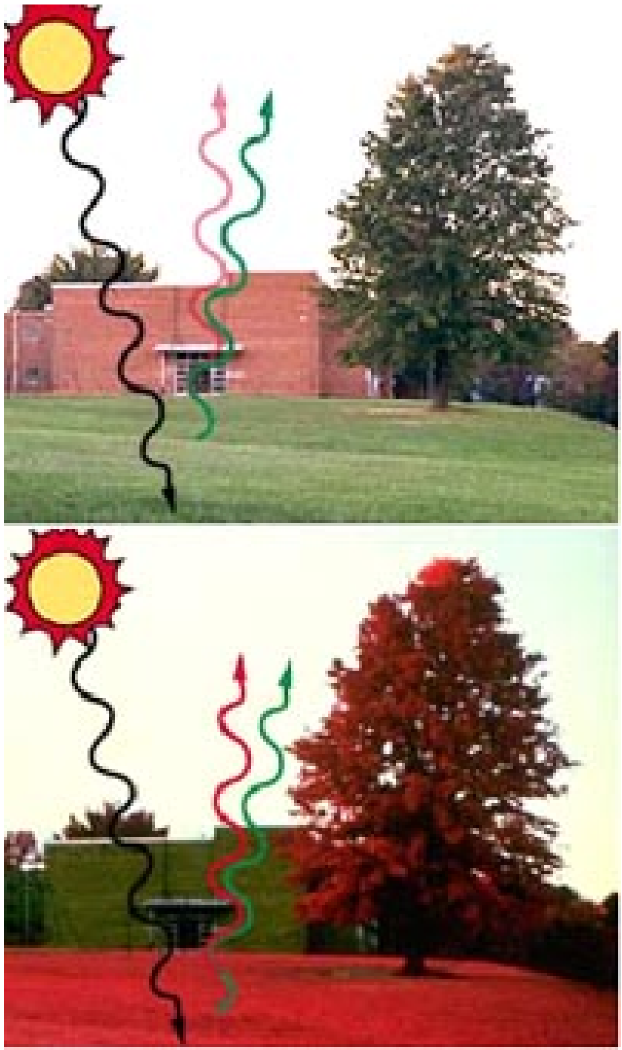

Darwin / TPF-I
Beam combiner
Data storage and transfer station



Simulation of spectrum acquired in 40 days with the proposed (and not accepted) Space mission Darwin

The Red Edge

Plants have Chlorophyll which absorbs in green wavelengths. Planets are thus more reflective in the infrared.



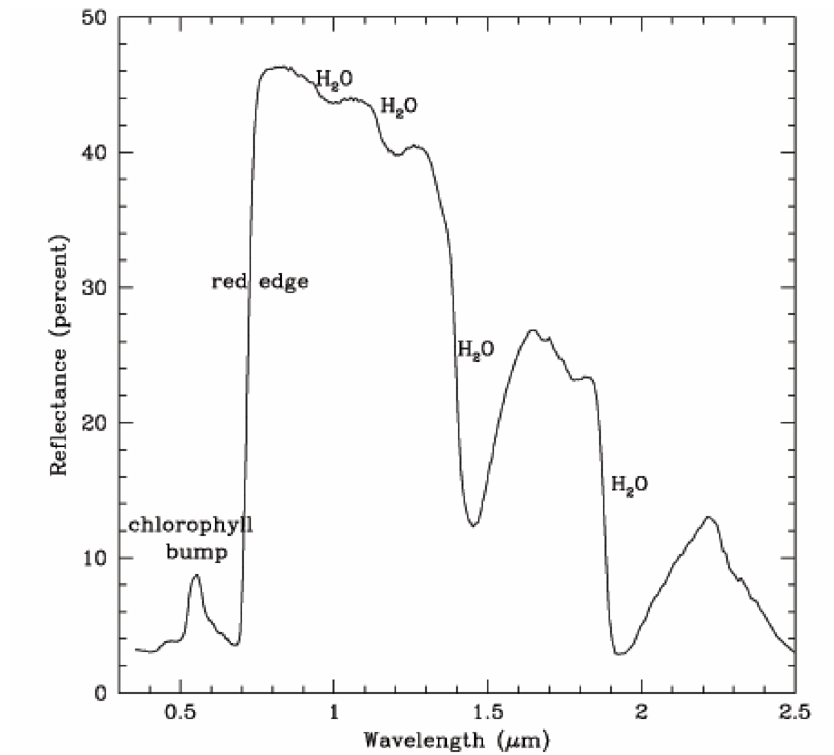
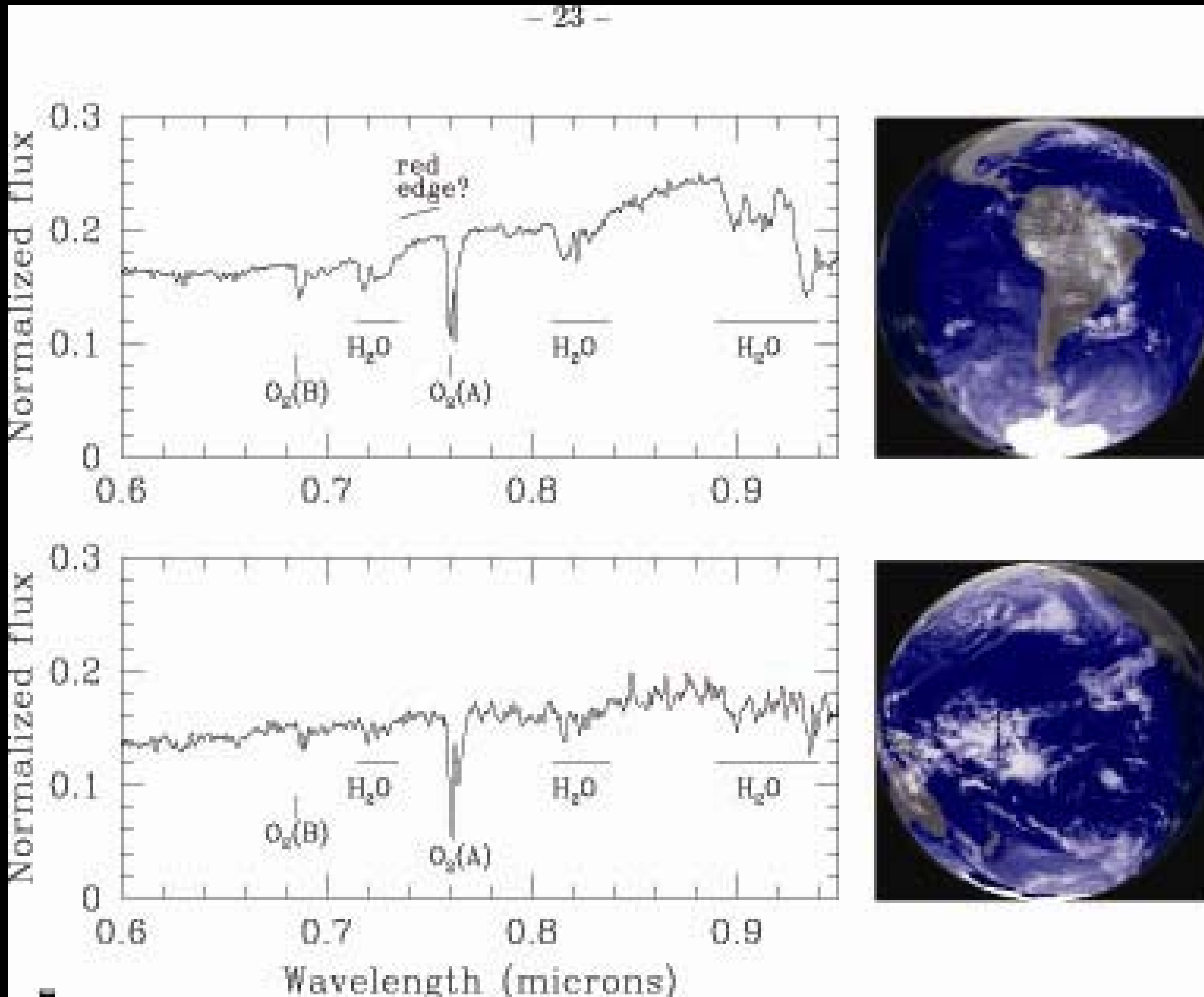


Fig. 1.— Reflection spectrum of a deciduous leaf (data from Clark et al. 1993). The small bump near 500 nm is a result of chlorophyll absorption (at 450 nm and 680 nm) and gives plants their green color. The much larger sharp rise (between 700 and 800 nm) is known as the red edge and is due to the contrast between the strong absorption of chlorophyll and the otherwise reflective leaf.

Earthshine Spectra



Summary

- Temperatures have been measured for a number of planets.
- Upper limits to Albedo that are consistent with theoretical predictions.
- Evidence for circulation currents in atmosphere (weather!)
- Chemical species detected in transiting planets: Na, H, CO, CO_2, CH_4, and H_20