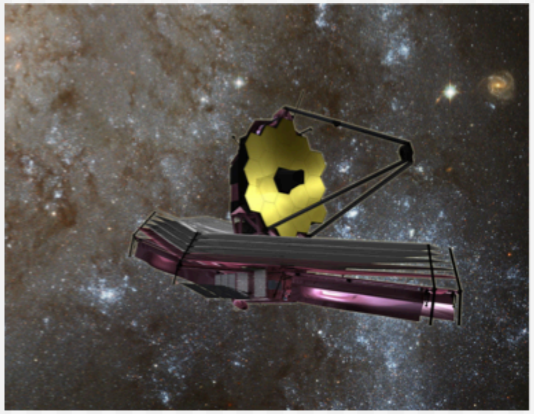
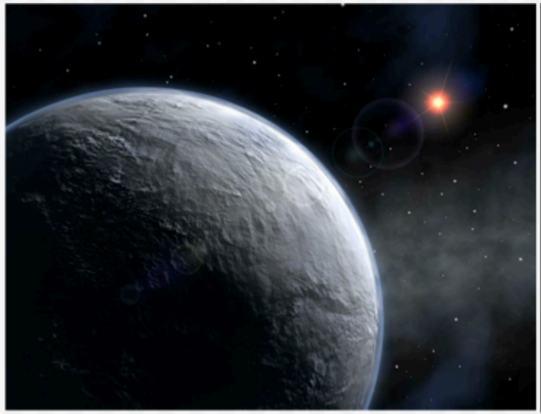
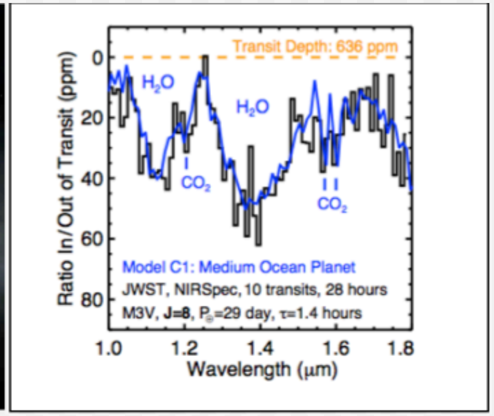
Exoplanetary atmospheres: from hot Jupiters to habitable planets







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Overview

- From solar to extrasolar planetary atmospheres
- Phase curves of non-transiting planets
- Transiting planets

  Transit transmission spectrophotometry

  Occultation emission spectrophotometry

  Phase curves

  2D emission maps
- Direct spectroscopy of extrasolar planets
- Conclusions

Before extrasolar planets: solar planets atmosphere observations

XIXth century: **imagery** and **photometry** establish the existence of an atmosphere for several planets

* Occultation of stars are gradual
* Variable features incompatible with surface origin

From 1920s: **spectroscopic** studies of planets, *e.g.*

* No O_2 in Venus' atmosphere (Webster 1927)
* CH_4 in the atmosphere of giant planets (Adel & Slipher, 1934)
* CO_2 in the atmosphere of terrestrial planets (Adel 1937)
* Detection of the atmosphere of Titan (Kuiper 1944)

Second half of XXth century to now: ***in situ* measurements** with probes (orbiters & landers)

➔ Accurate thermal profiles & composition (*e.g.* Seiff et al. 1998)

The planetary atmospheres zoo: theoretical expectations

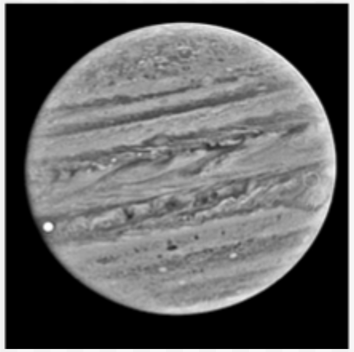
Seager & Deming (2010)

- **Primordial atmospheres** captured from the protostellar nebula and dominated by H and He in cosmic proportions (giant planets)
- **Outgassed atmospheres rich in H** (up to 50%) around planets in the 10 to 30 Earth masses range, massive enough to retain H. No He.
- **Outgassed atmospheres dominated by CO_2** (Venus, Mars) around lower-mass planets. Could be found around planets having lost their primordial atmosphere.
- **Outgassed atmospheres dominated by N_2** (Earth), CO_2 having been trapped in a liquid ocean.
- **Silicate dominated atmospheres** of hot low-mas planets having lost their volatil content. Enriched in refractory elements.
- **Atmosphere free planet** (Mercury): low-mass and/or large irradiation.

From solar to extrasolar planets: a giant step

Theory: solar planet atmospheres observations established the theoretical foundations needed to understand exoplanet atmospheres.
Observations: much more difficult!

Jupiter



Alpha Cen A

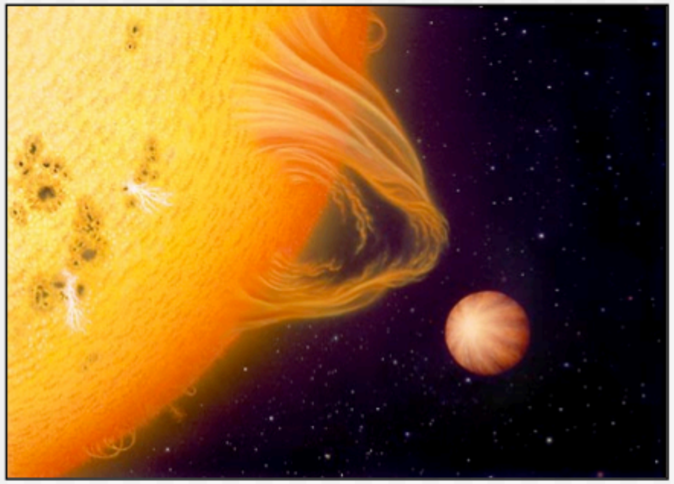
Exoplanets are very distant relative to solar planets.
Furthermore, they lie very close to much brighter objects.
SNR + resolution + contrast (space-resolution)
SNR (time-resolution)

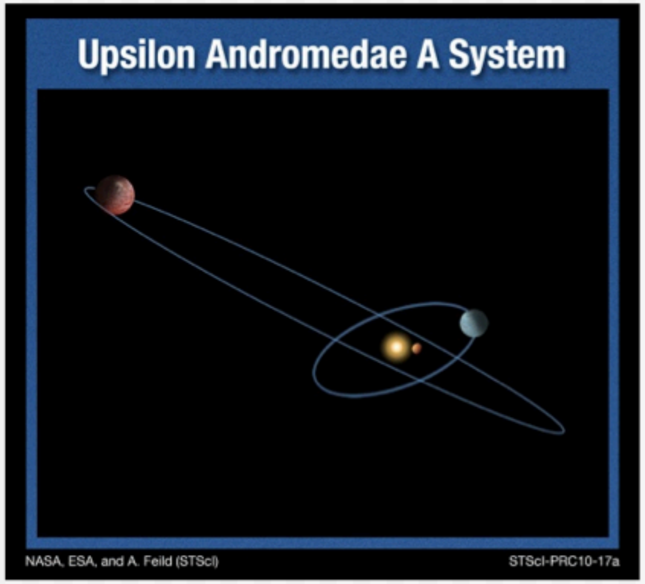
Phase curves of non-transiting planets

***Ups* And b**: a hot Jupiter orbiting around nearby F8V star in a multiplanetary binary system.

M sin i = 0.7 M_{Jup}, a = 0.059 AU, F_{inc} ~1.4 10^9 erg s^{-1} cm^{-2}

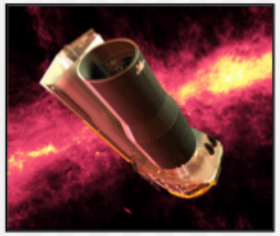
(Jupiter: a = 5.2 AU and F_{inc} ~ 5.1 10^4 erg s^{-1} cm^{-2})



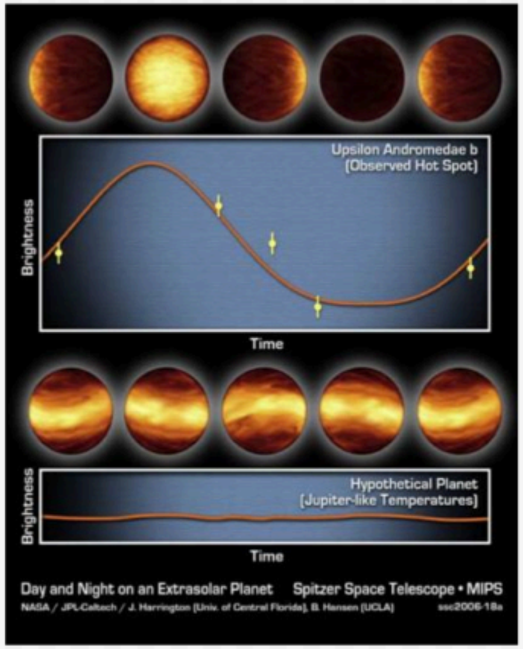


Phase curves of non-transiting planets

***Ups* And b** is most certainly tidally locked.
Question: is there a temperature gradient between day and night side of its atmosphere?



Spitzer/MIPS 24 μm photometry at five different phases of the orbit (Harrington et al. 2006)



Peak-to-through = 0.3%
-> **large temperature gradient**

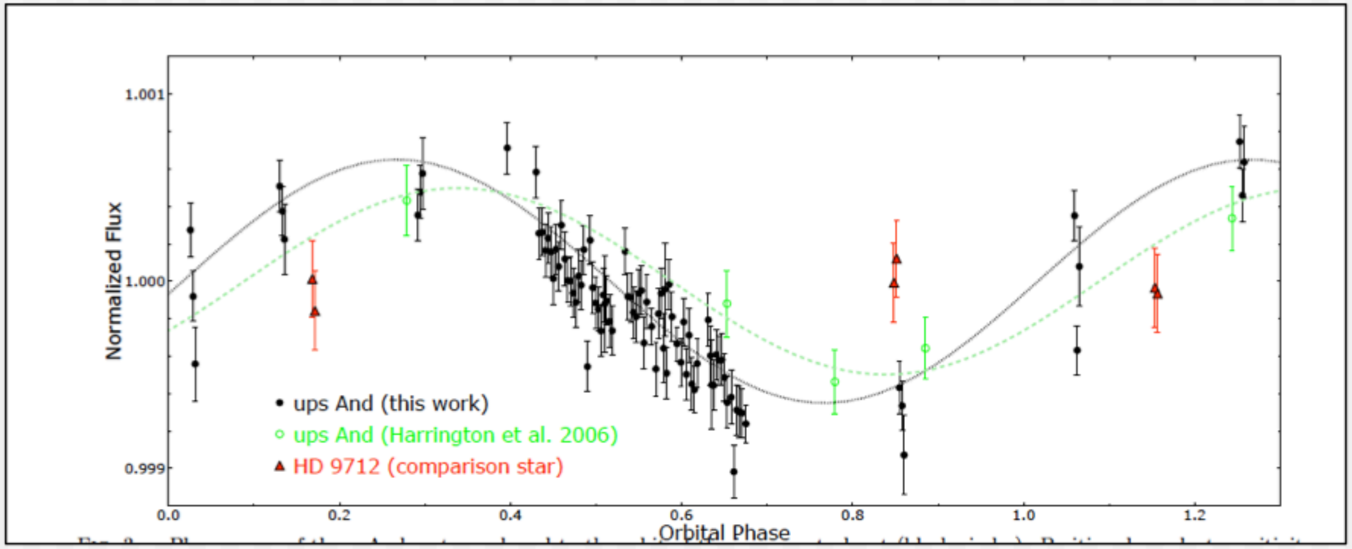
$$\frac{\Delta F_P}{\langle F \rangle} = \frac{B_\nu(T_{P1}) - B_\nu(T_{P2})}{B_\nu(\gamma T_{\rm eff})} \left(\frac{R_P}{R_*}\right)^2 \sin i,$$

i and R_p unknown

Not phase offset:
-> **immediate reemission of incident flux**

Phase curves of non-transiting planets

Ups And b: reanalysis + new Spitzer data (Crossfield et al. 2010)



Amplitude drops to 0.13%! -> **calibration issues**

Phase offset of 84.5° ± 2.3°

Phase curves of non-transiting planets

$$(1 - A_B)\,\frac{R_*^2}{2a^2}T_{\rm eff}^4 = T_{P1}^4 + T_{P2}^4.$$

$$\frac{\Delta F_P}{\langle F \rangle} = \frac{B_\nu(T_{P1}) - B_\nu(T_{P2})}{B_\nu(\gamma T_{\rm eff})}\left(\frac{R_P}{R_*}\right)^2 \sin i,$$

2 wedge models, no internal luminosity

If A_B and R_p known -> T_{P1} and T_{P2} can be computed for all *i*

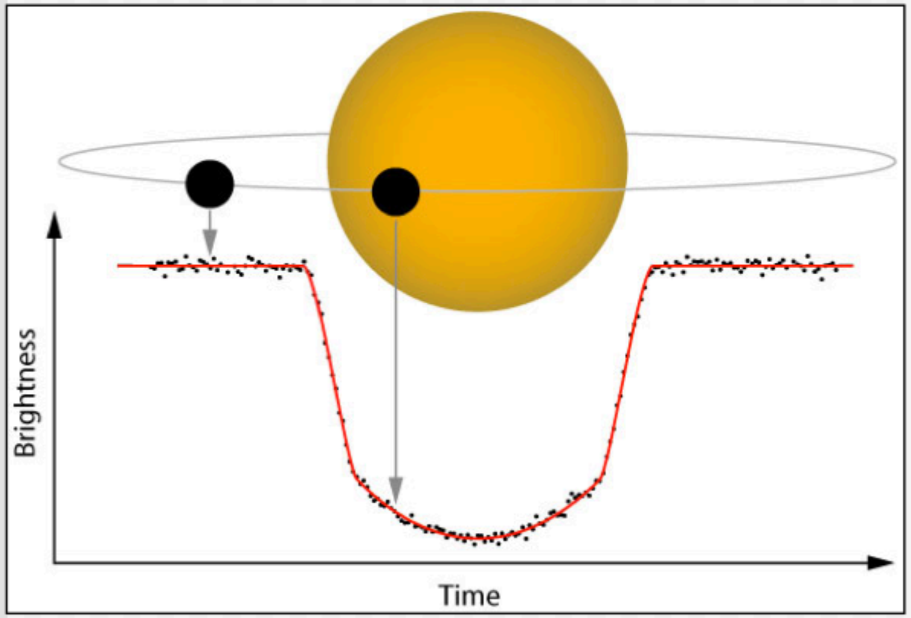
Assuming $A_B = 0$ and $R_p \approx 1.3\ R_{jup}$

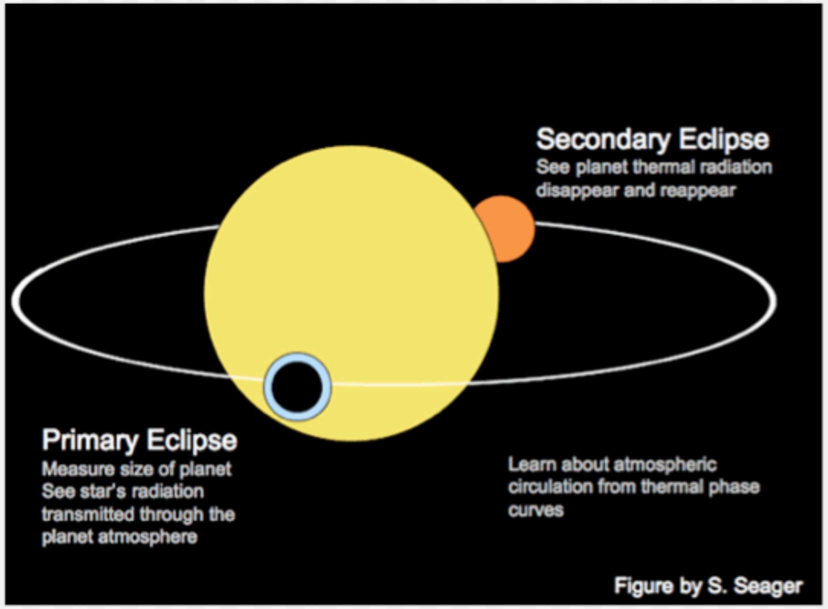
➜

$i > 28°$, $\Delta T > 900$K

The phase offset implies a hot spot at the East terminator, and thus atmospheric heat transport (vs direct reemission)

Transiting planets: treasures in the sky





$R_p + \rho_* + i$ from photometry
With RVs: $M_p + \beta$

Transit: limb transmission
Occultation: day side emission

Transit transmission spectrophotometry

Basic of the technique: dividing the spectrum of star + planet (during transit) by the spectrum of the star alone (before & after transit). Practically: getting high-precision transit light curves in many different (as narrow as possible) spectral bands and compare the resulting planetary radii.

Expected signal? (Seager & Sasselov 2000)

For a strong transition, the effective R_p increases by a few atmospheric scale heights **$H = k_B T / (\mu_m g)$**

The signal is

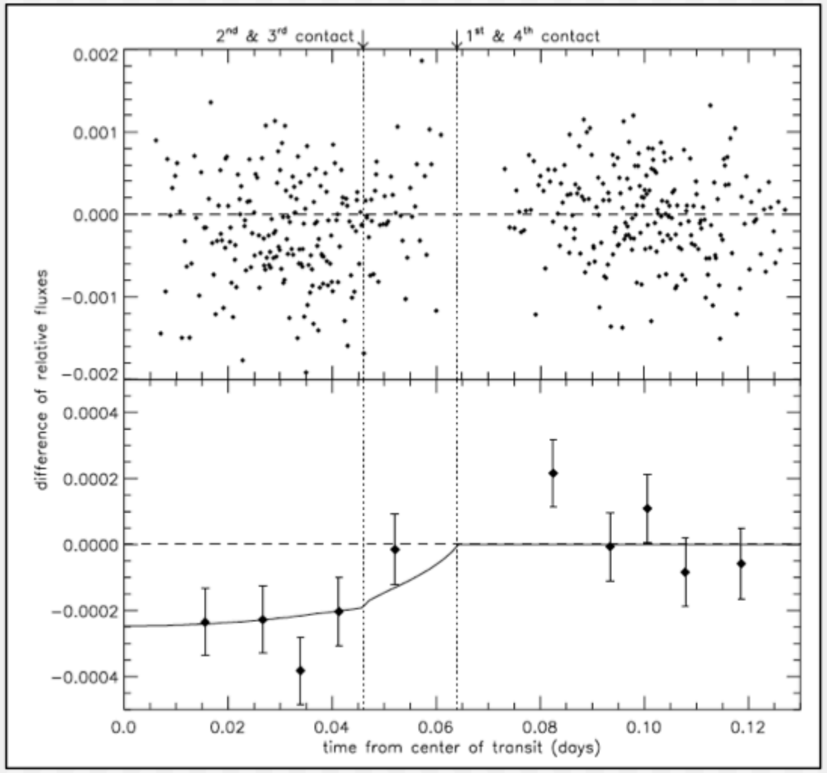
$$\Delta\delta = \frac{\pi(R_p + N_H H)^2}{\pi R_\star^2} - \frac{\pi R_p^2}{\pi R_\star^2} \approx 2 N_H \delta \left(\frac{H}{R_p}\right)$$

Hot Jupiter: ~100ppm, Earth-Sun: ~1ppm

Atomic Na in the atmosphere of HD 209458 b

Instrument: STIS spectrograph aboard HST

Goal: detecting the 589.3 nm Na resonance doublet, based on theoretical predictions by Seager & Sasselov (2000)



~4 sigma detection

~3 times shallower than "expected"

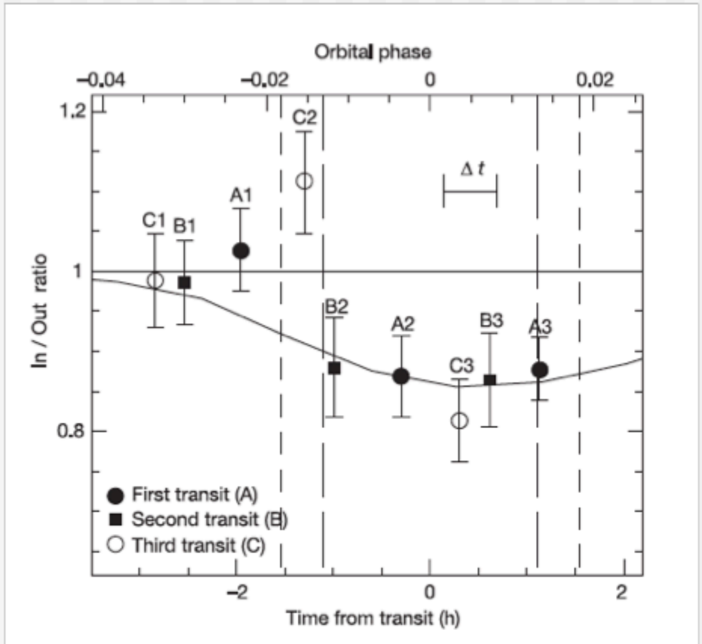
- depletion of Na? maybe due to competition Na – Na2S? It requires that only 1% of Na in atomic form
- High cloud deck?

(Charbonneau et al. 2002)

The evaporating atmosphere of HD 209458 b

Instrument: STIS spectrograph aboard HST

Goal: detecting the H Lyman-α121.6 nm signature



Vidal-Madjar et al. (2003)

~4 sigma detection

Effective R_p of 4.3 R_{Jup}!

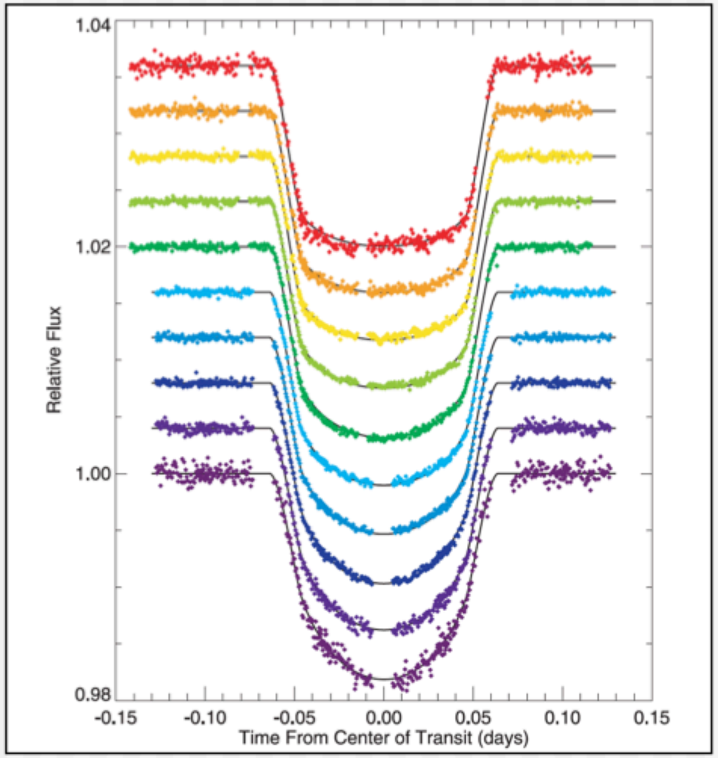
Roche lobe limit ~ 3.6 R_{jup}

Evaporating H upper atmosphere forming a comet-like coma around the planet

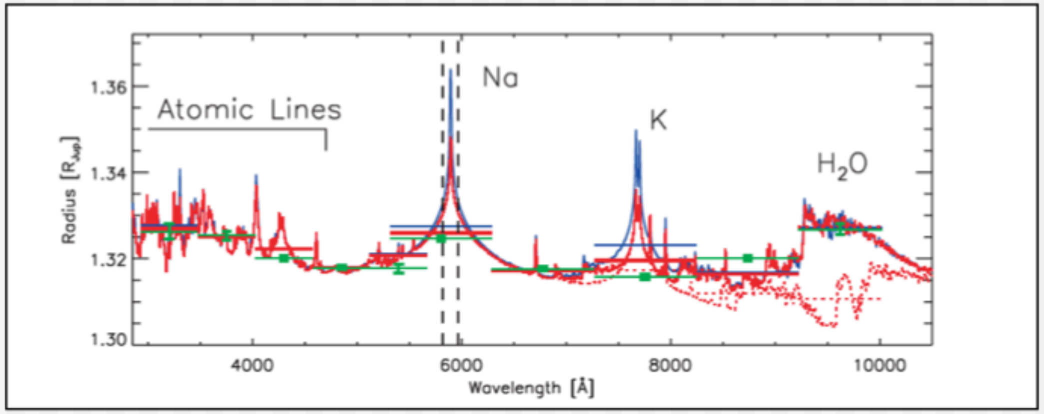
Minimum escape rate translates in negligible loss over the life of the star (~0.1%)

Detection of water in the atmosphere of HD 209458b?

Instrument: HST/STIS



Knutson et al. (2007)



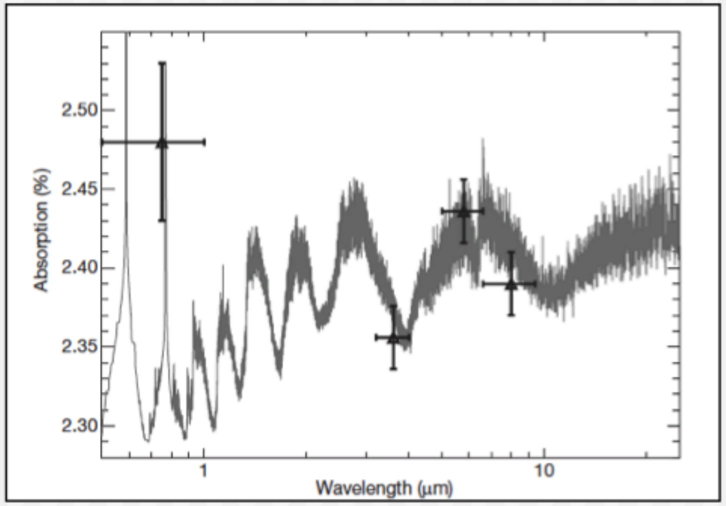
Barman (2007)

Possible systematic effects make this detection tentative (Knutson 2007; Tinetti et al. 2007)

Detection of water in the atmosphere of HD 189733 b?

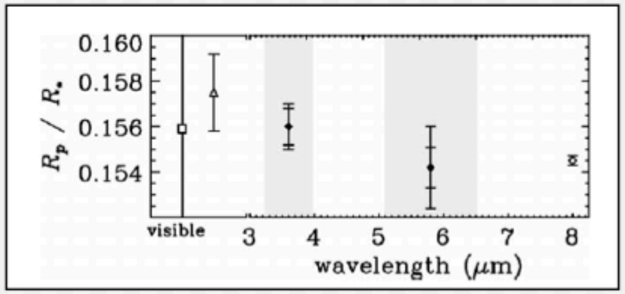
Instrument: Spitzer/IRAC

H_2O should give ΔdF(5.8μm – 3.6μm) ~ 1.7 – 3.4%



Only water explains the IRAC R_p measurements

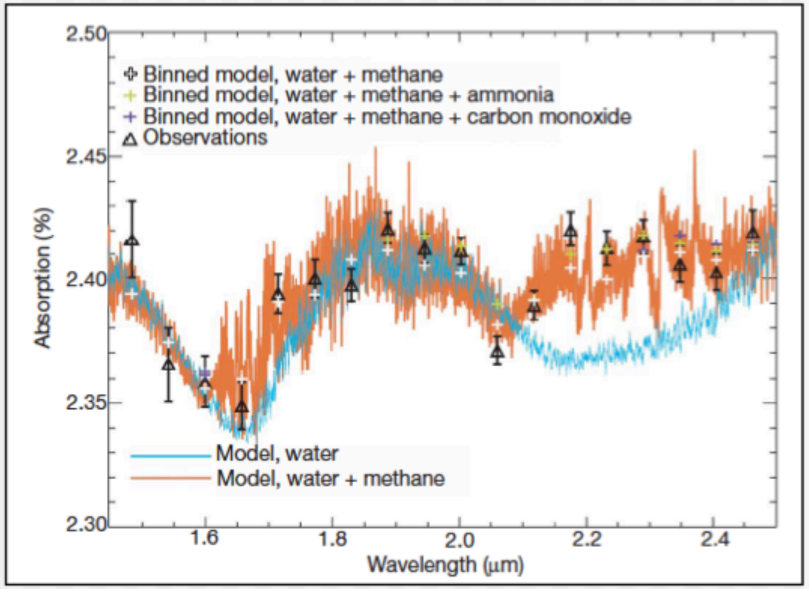
R_p is larger in the visible:
Clouds/haze?
Starspots?
Tinetti et al. (2007)



But a more thorough analysis of the data contradicts convincingly this detection *(Ehrenreich et al. 2007)*

Detection of methane in the atmosphere of HD 189733 ?

Instrument: HST/NICMOS

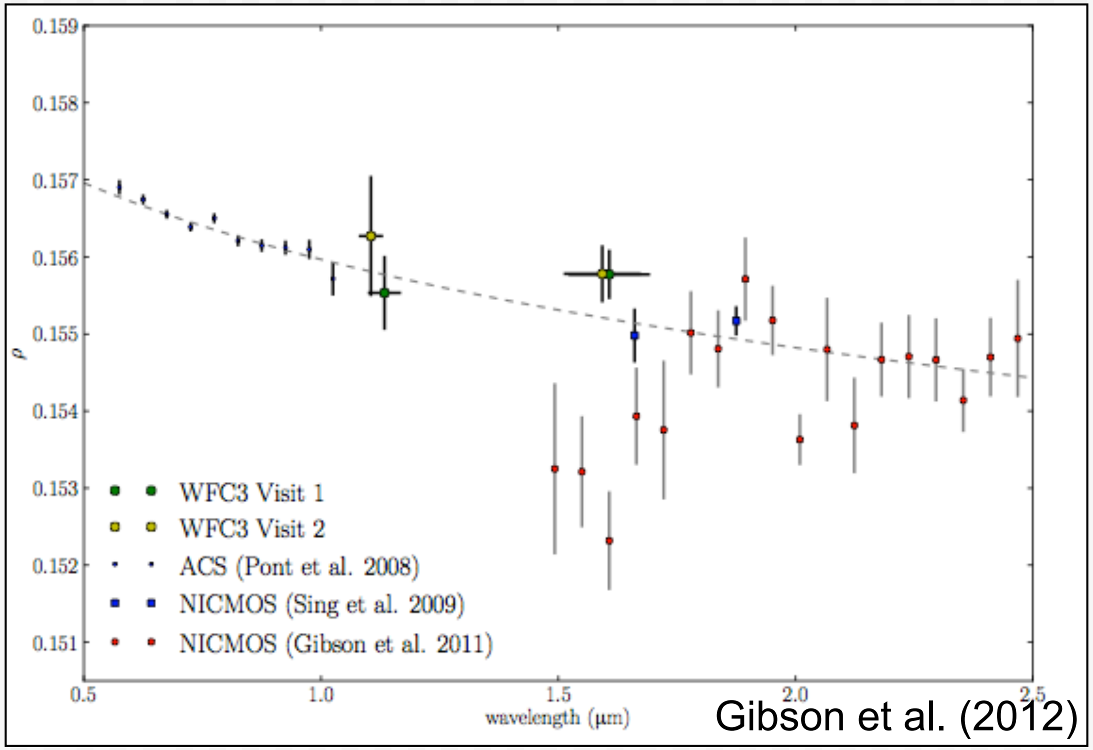


Detection of H_2O and CH_4
CO should be the dominant C-bearing molecule for
T > 1200K
->Chemical gradient?
->Photochemical mechanism?

Swain et al. (2008)

Light curve is detrended using the out-of-transit data, using a 5-variables function + wavelength correction. <error bar> ~50ppm.

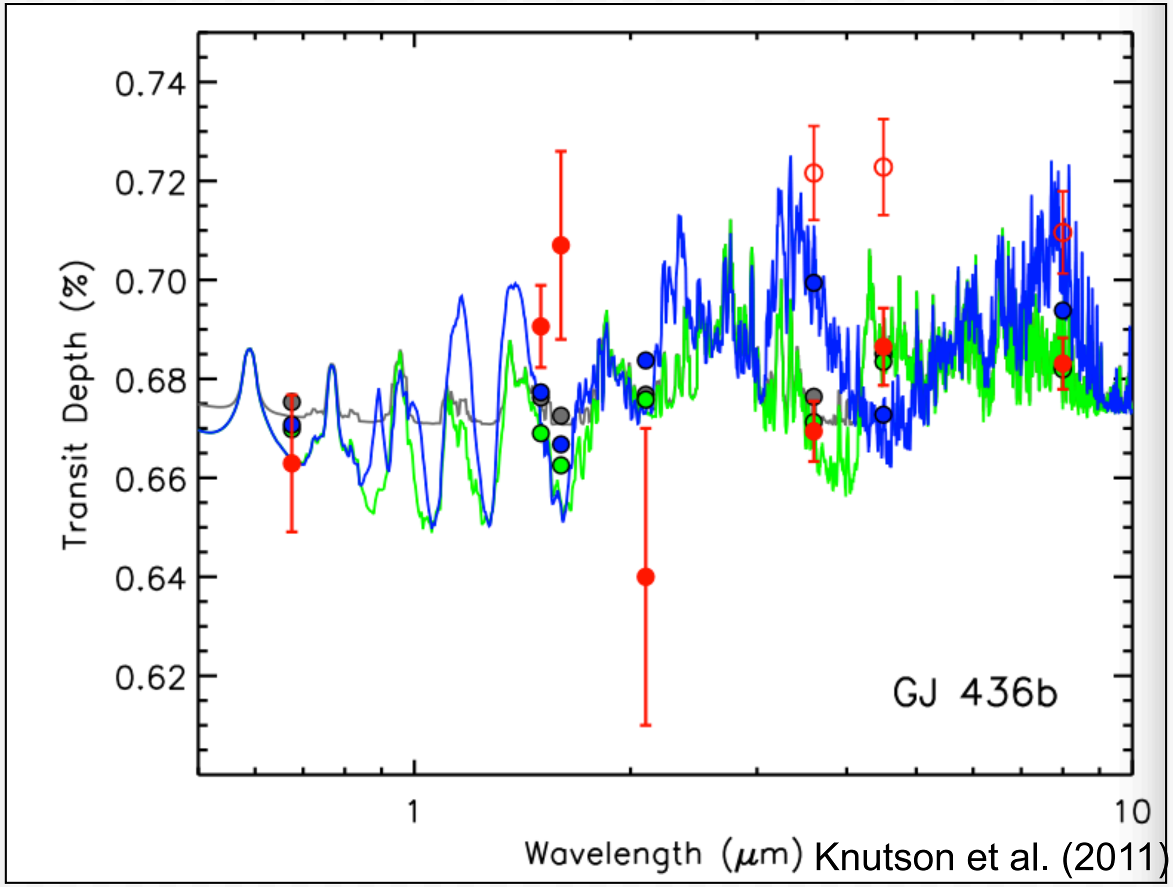
HD189733b's methane detection: too nice to be true?



Gibson et al. (2012)

Haze dominates the transmission spectrum
Spots makes the situation difficult,
NICMOS systematics make it even worst

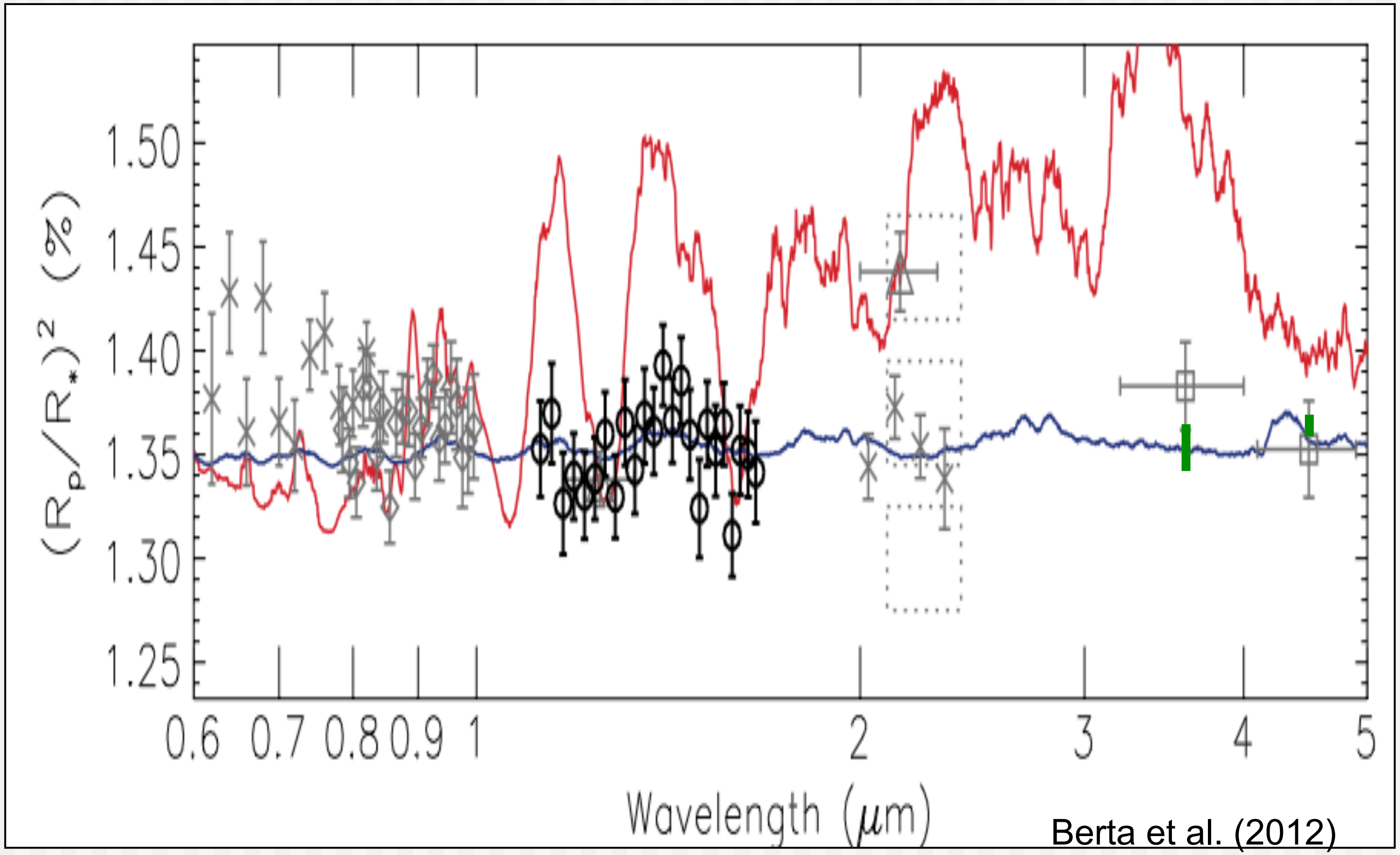
Methane depletion in a ‘cool’ Neptune atmosphere?



Knutson et al. (2011)

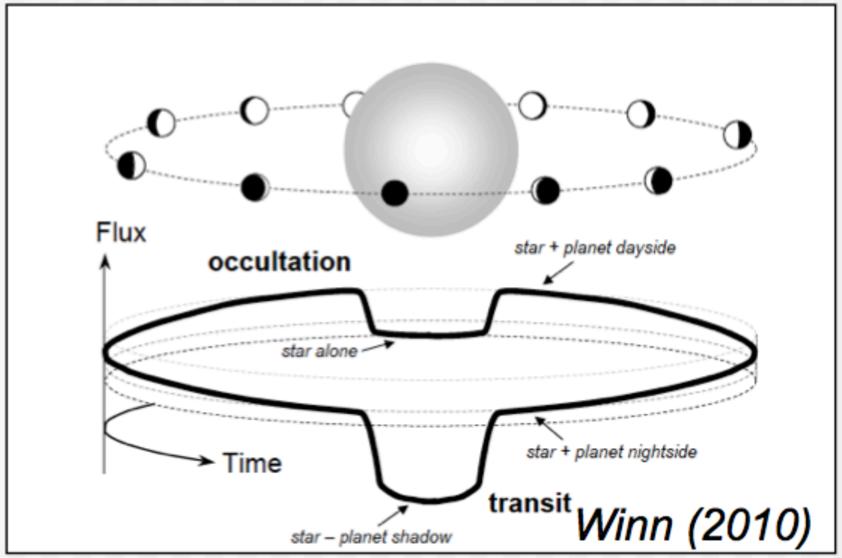
Models with enhanced CO and reduced CH_4 are favored. Spots makes difficult to draw firm conclusions…

Super-Earth GJ1214b's atmosphere: water or H_2 + clouds/haze?



+ Bean et al. (2010; 2011), Croll et al. (2011), Désert et al. (2011); de Mooij et al. (2011)

Occultation emission spectrophotometry



IR:

$$\delta_{occ}(\lambda) = k^2 \frac{B_\lambda(T_p)}{B_\lambda(T_\star)}$$

brightness temperature $T_b(\lambda)$ of the dayside hemisphere

Vis:

$$\delta_{occ}(\lambda) = A_\lambda \left(\frac{R_p}{a}\right)^2$$

Geometric albedo $A(\lambda)$

Occultation emission spectrophotometry

Reflectance signal: ~100ppm for a hot Jupiter
Thermal emission: a few 1/1000 for a hot Jupiter

$$T_p = T_* \left(\frac{R_*}{a}\right)^{1/2} [f(1 - A_\mathrm{B})]^{1/4},$$

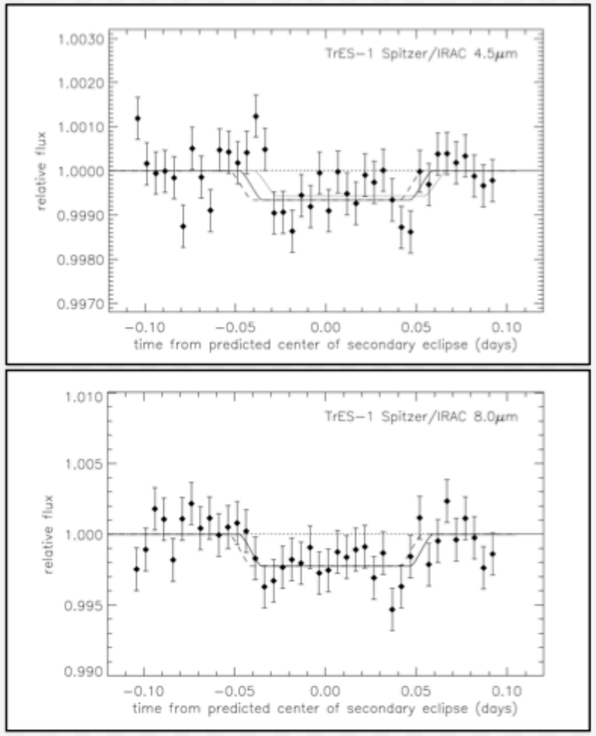
f = reradiation factor
= ¼ if incident energy is homogeneously distributed across the atmosphere
= 2/3 if incident stellar flux is directly remitted back to space
A_B = Bond albedo

T_p can be as high as 3000K!

First detections of the emission of exoplanets: TrES-I

Instrument: Spitzer/IRAC 4.5 and 8 μm

Charbonneau et al. (2005)

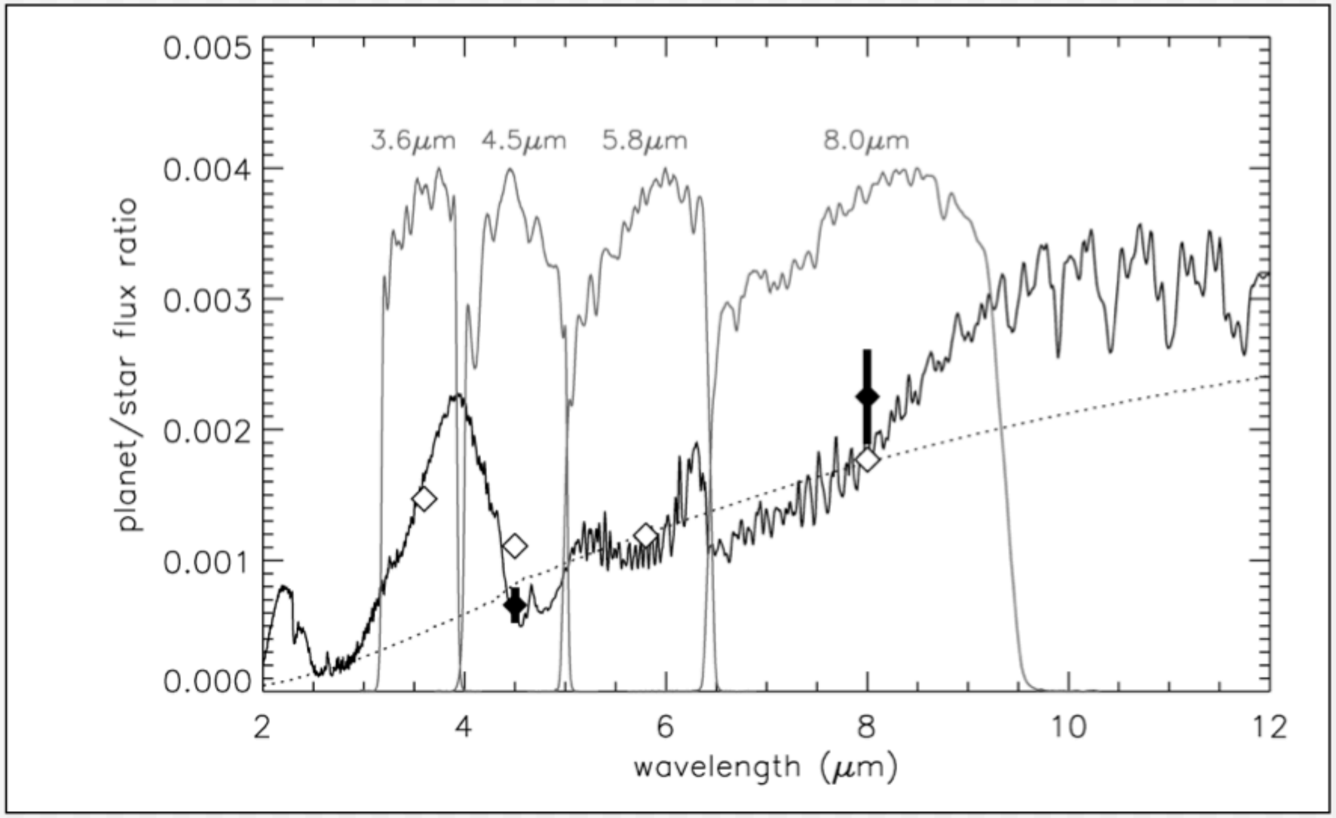


$dF_{4.5\mu m}$ = 660 ± 130 ppm
$dF_{8\mu m}$ = 2250 ± 360 ppm

$T_{b,4.5\mu m}$ = 1010 ± 60 K
$T_{b,8\mu m}$ = 1230 ± 110 K
T_p = 1060 ± 50 K
➔ **A_B = 0.31 ± 0.14 for f=1/4**

But of course, the planet does not emit like a blackbody, and *f* is unknown

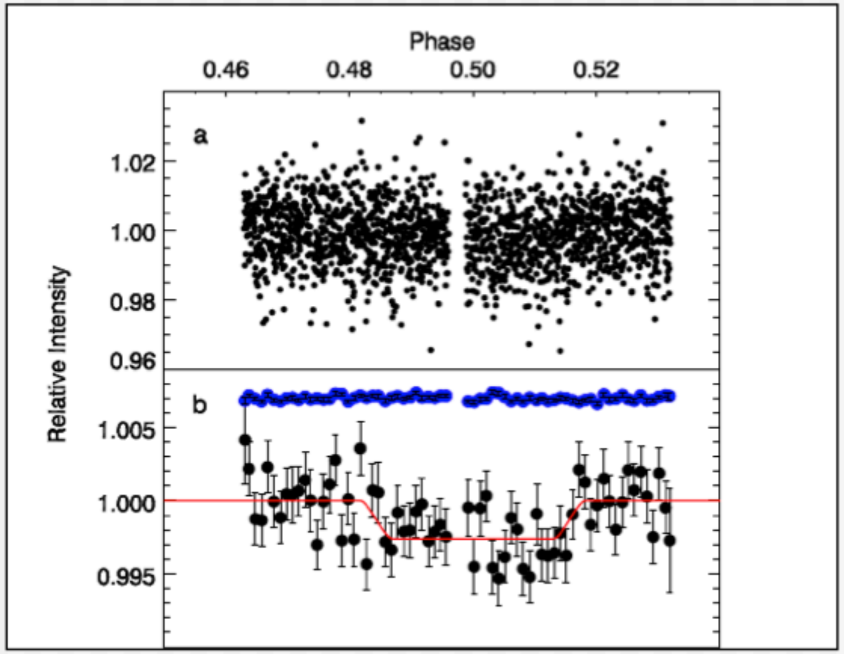
First detections of the emission of exoplanets: TrES-1 b



Sudarsky et al. (2003) model for 51 Peg b, rescaled

First detections of the emission of exoplanets: HD 209548 b

Instrument: Spitzer/MIPS 24 μm
Deming et al. (2005)



$dF_{24\mu m} = 0.26 \pm 0.05$ %
$T_{b,24\mu m} = 1130 \pm 150$ K

A few words about emission spectrum models

1-D plane-parallel radiative transfert code. Solves equations of radiative transfert, radiative and hydrostatic equilibrium to get P(z), T(z) and radiation field R(z,λ).
Boundary conditions: stellar flux and interior entropy.

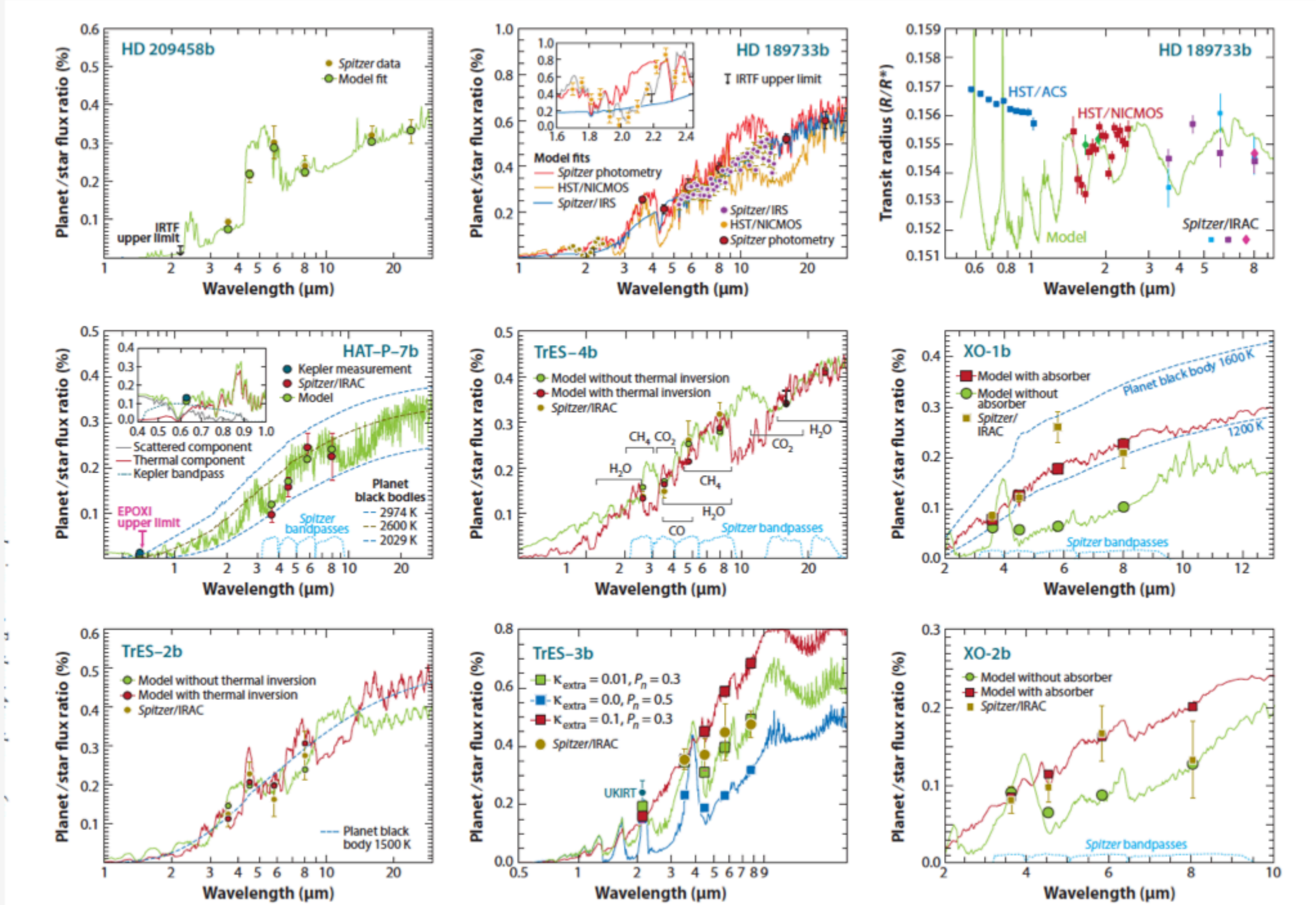
Parameters:

- **Interior entropy**
- **Opacities**
- **Choice of atomic & molecular species to include**
- **Abundances**
- **Chemical equilibrium or not** (CO, N_2)
- **Clouds**
- **Heat distribution efficiency**

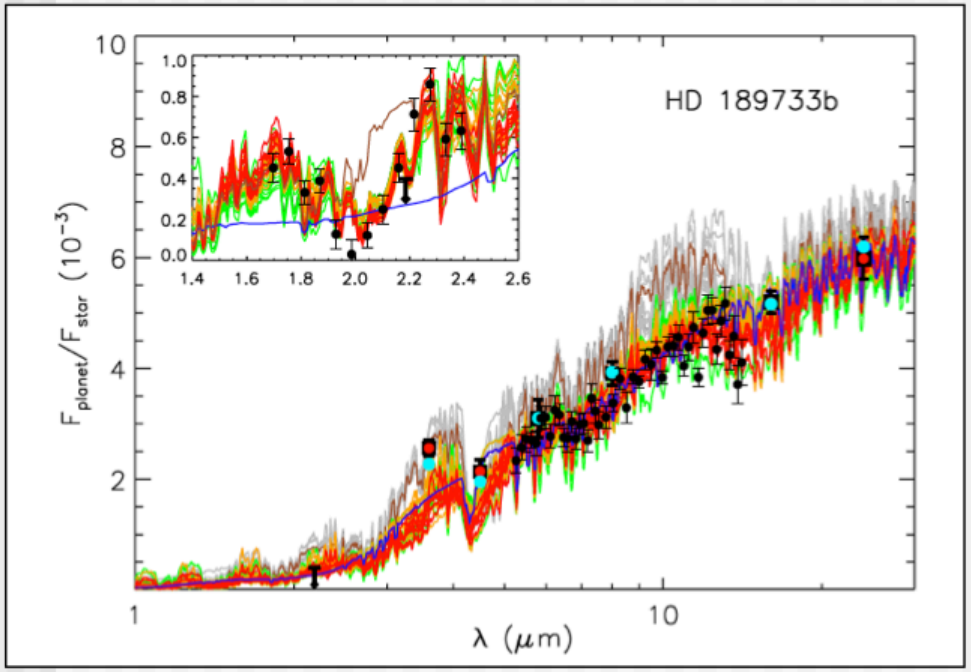
Atmospheric circulation (e.g. hot Jupiters): 3D models based on fluid dynamic equations

The Spitzer Legacy

Seager & Deming (2010)



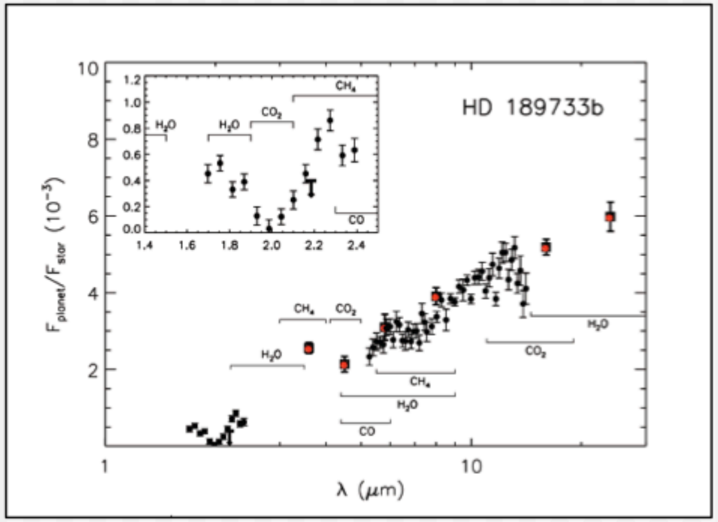
Occultation spectrophotometry: the hot Jupiter HD 189733 b



Madhusudhan & Seager (2009)

MIPS 24μm
IRS 16μm
IRS spectrum 5 – 14μm
IRAC 3.6, 4.5, 5.8, 8μm
NICMOS 1.7-2.5μm
Ground upper-limit 2.2μm

No model can fit all the data
The best-fit models for Spitzer do not fit at all NICMOS



Occultation spectrophotometry: the hot Jupiter HD 189733 b

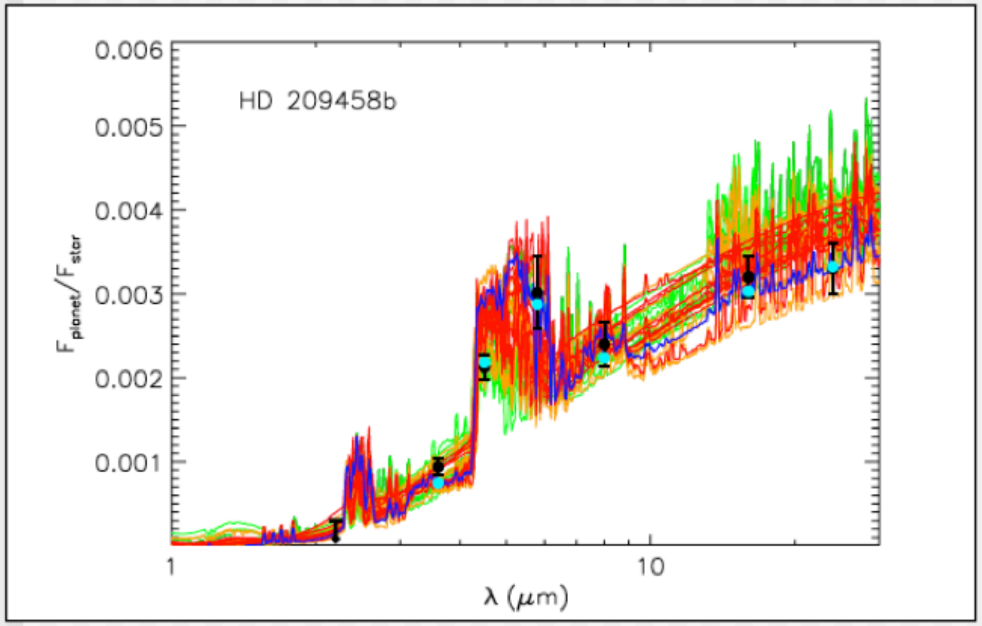
IRS: models with moderately efficient distribution to the night sides are allowed. No thermal inversion. No constraint on abundances.

IRAC/IRS/MIPS photometry: favors poorly efficient heat distribution and no thermal inversion, and gives some constraints on abundances. CO_2 detection.

NICMOS: many constraints on abundances. No CH_4. Strong CO_2 absorption feature, not in agreement with Spitzer.

The agreement between all these data sets is weak, so, at face value, we have to admit a variability of the atmospheric properties.

Occultation spectrophotometry: the hot Jupiter HD 209458 b

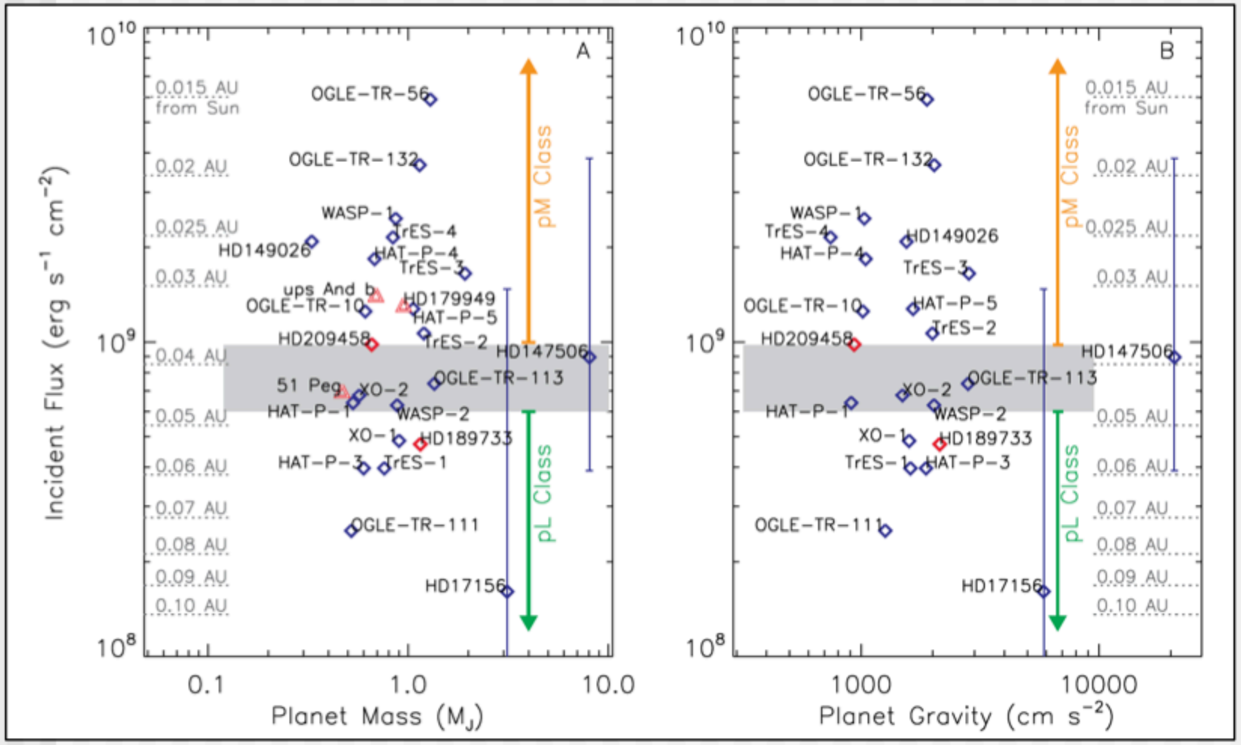


MIPS 24μm
IRS 16μm
IRAC 3.6, 4.5, 5.8, 8μm
Ground upper-limit 2.2μm

Madhusudhan & Seager (2009)

Unavoidable thermal inversion
Presence of CO, CO_2, H_2O and CH_4
Efficient heat distribution

Thermal inversions: two classes of hot Jupiter?



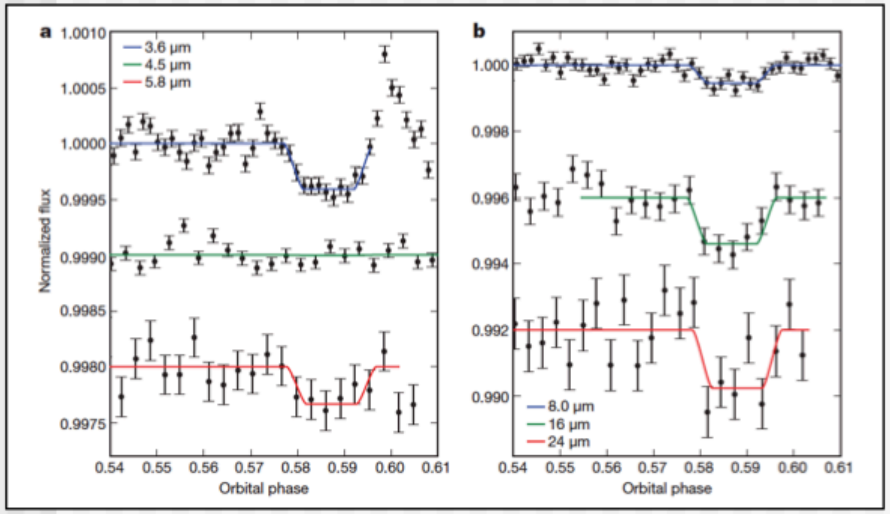
Fortney et al. (2008)

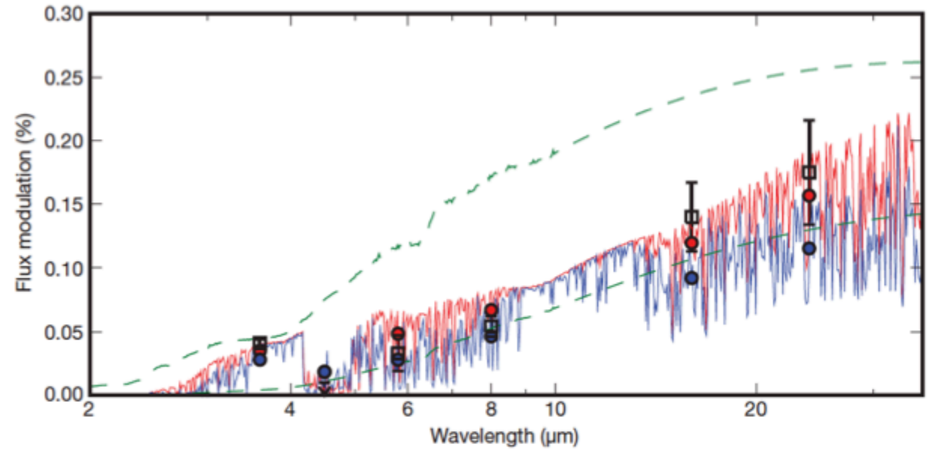
Planets with Teff > 2700K have lower albedo and/or heat transport efficiency
(Cowan & Agol 2011)

But the inference of thermal inversion is not always secure (Madhusudhan & Seager 2010)

Some 'pM' planets do not show inversion… *(e.g. Fressin et al. 2009, Gillon et al. 2009)*

The broadband thermal emission spectrum of the hot Neptune GJ 436 b





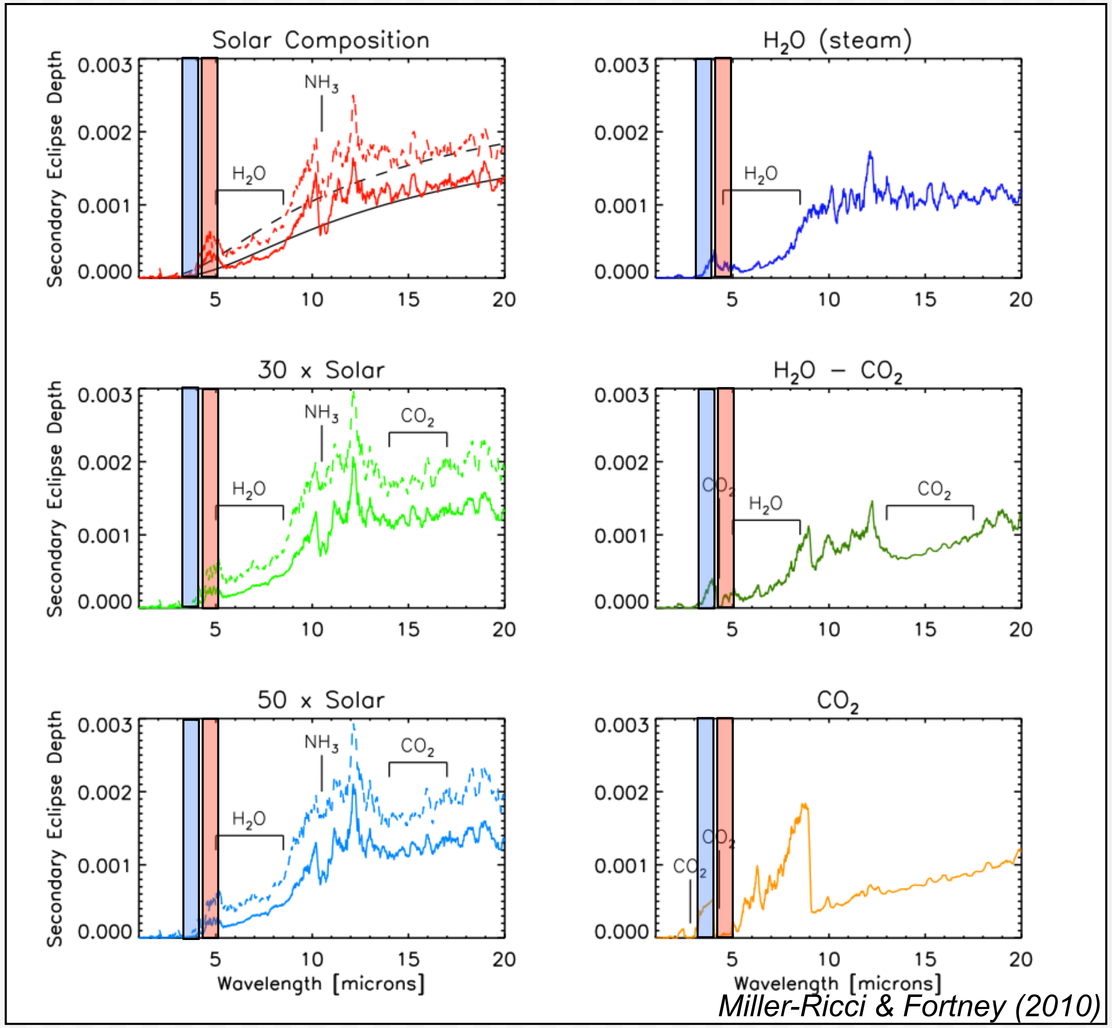
High CO abundance, deficiency in CH_4

CH_4-to-CO ratio at least 10^5 times smaller than predicted

Disequilibrium processes? (vertical mixing, CH_4 polymerization)

Stevenson et al. (2010)

Measuring the thermal emission of a super-Earth: GJ1214b



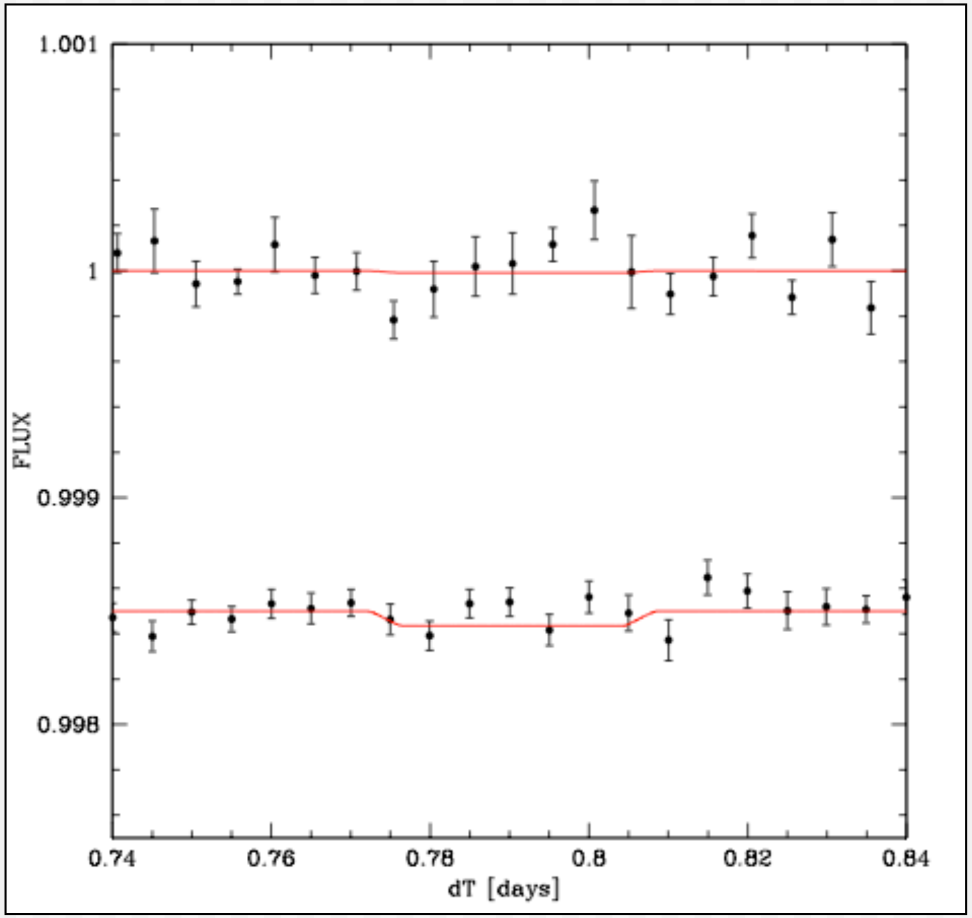
- Teq ~ 560K
- Spitzer program 70049 (PI D. Deming): 42h at 3.6μm and 460h at 4.5μm
- Global analysis of all Spitzer data (3 programs,17 transits + 20 occultations)
- Expected occultation depths: from <50 to ~300 ppm

Measuring the thermal emission of a super-Earth: GJ1214b

- Depth 3.6µm
  30 (-20,+35) ppm
  <122 ppm (95%)

- Depth 4.5µm
  47 (-28,+35) ppm
  <115 ppm (95%)

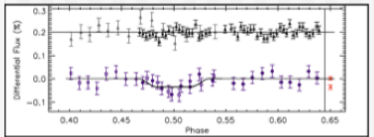
Still under analysis…



Gillon et al. (in prep.)

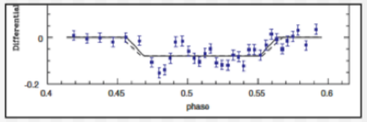
Ground-based occultation measurements

OGLE-TR-56b z'



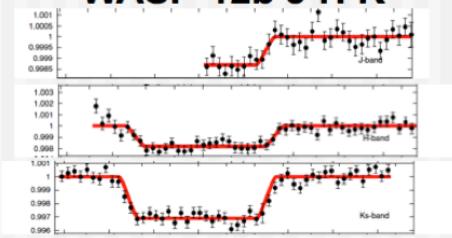
Sing & Lopez-Morales (2009)

WASP-12b z'



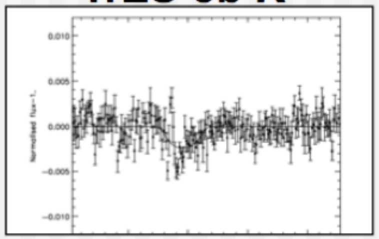
Lopez-Morales et al. (2010)

WASP-12b J H K



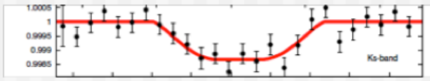
Croll et al. (2011)

TrES-3b K



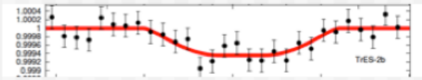
De Mooij & Snellen (2009)

TrES-3b K



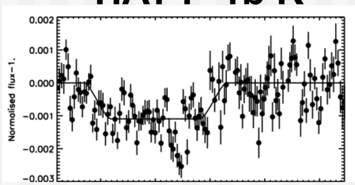
Croll et al. (2010b)

TrES-2b K



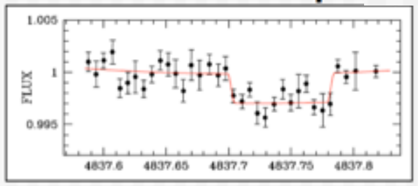
Croll et al. (2010a)

HAT-P-1b K



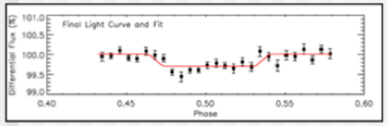
De Mooij et al. (2011)

CoRoT-1b 2.09 µm



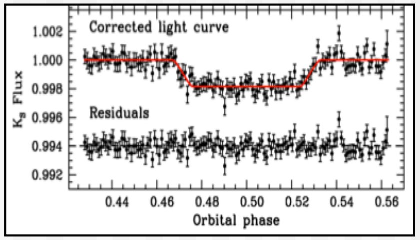
Gillon et al. (2009)

CoRoT-1b K



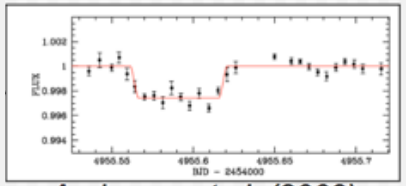
Rogers et al. (2010)

WASP-4b K



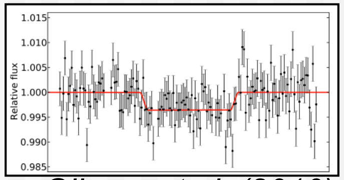
Caceres et al. (2011)

WASP-19b H



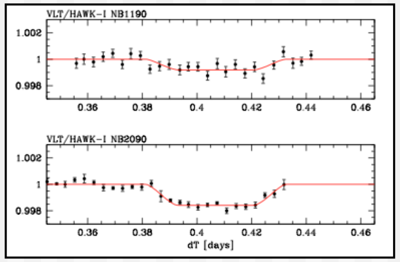
Anderson et al. (2009)

WASP-19b 2.09 µm



Gibson et al. (2010)

WASP-43b 1.19 & 2.09 µm

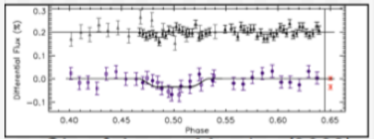


Gillon et al. (2012)

Ground-based occultation measurements

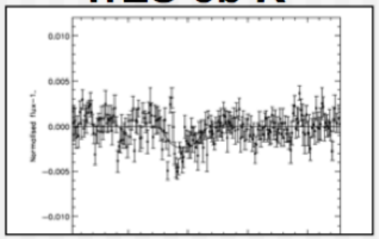
VLT/HAWK-I

OGLE-TR-56b z'



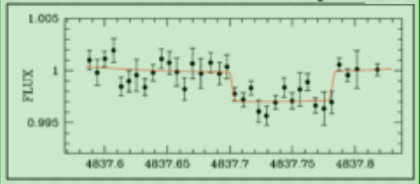
Sing & Lopez-Morales (2009)

TrES-3b K



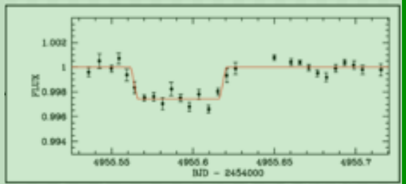
De Mooij & Snellen (2009)

CoRoT-1b 2.09 µm



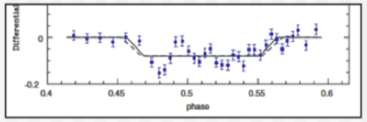
Gillon et al. (2009)

WASP-19b H



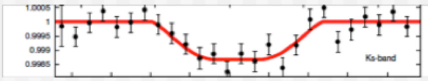
Anderson et al. (2009)

WASP-12b z'



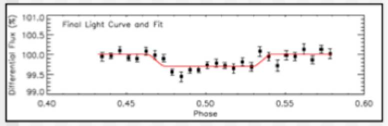
Lopez-Morales et al. (2010)

TrES-3b K



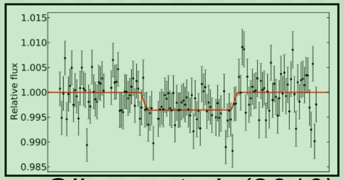
Croll et al. (2010b)

CoRoT-1b K



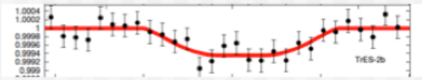
Rogers et al. (2010)

WASP-19b 2.09 µm



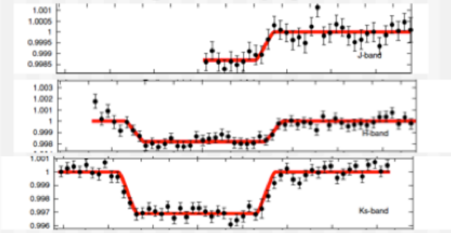
Gibson et al. (2010)

TrES-2b K



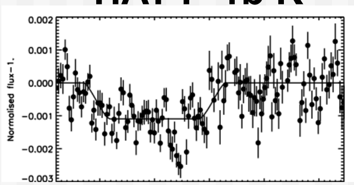
Croll et al. (2010a)

WASP-12b J H K



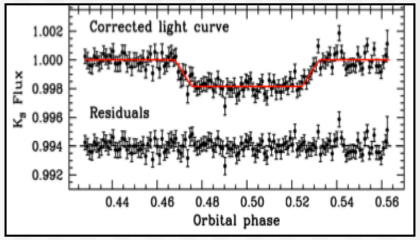
Croll et al. (2011)

HAT-P-1b K



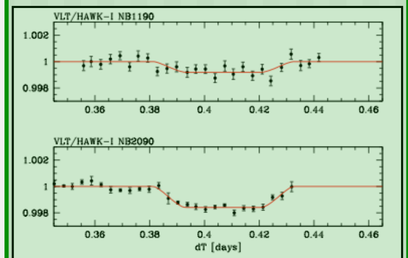
De Mooij et al. (2011)

WASP-4b K



Caceres et al. (2011)

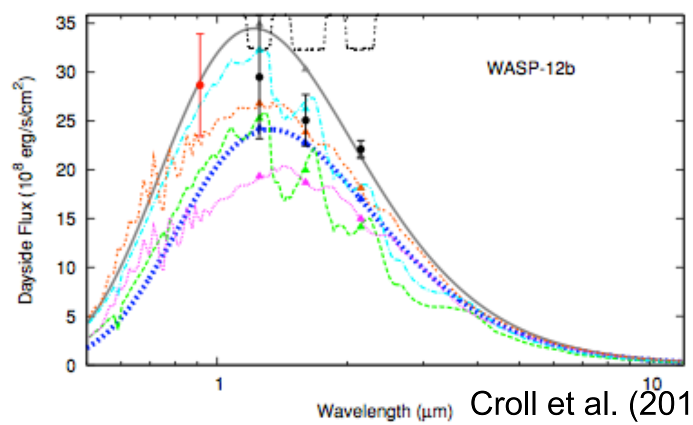
WASP-43b
1.19 & 2.09 µm



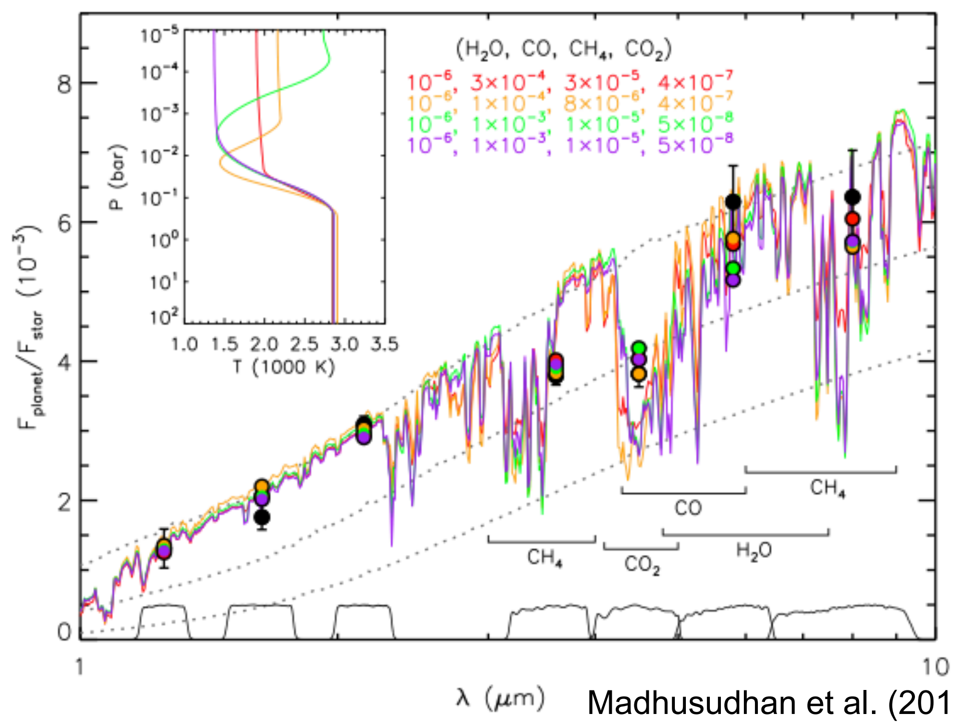
Gillon et al. (2012)

Ground-based occultations: complementary to Spitzer

Near-IR = peak of SED for hot Jupiters



Croll et al. (2011)



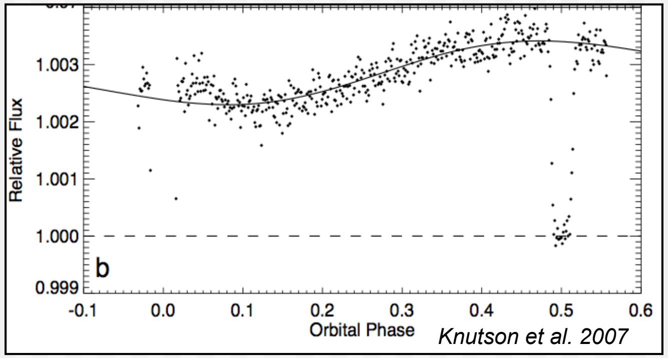
Madhusudhan et al. (2011)

WASP-12b: a ‘pM’ planet without a strong thermal inversion and with a high C/O ratio

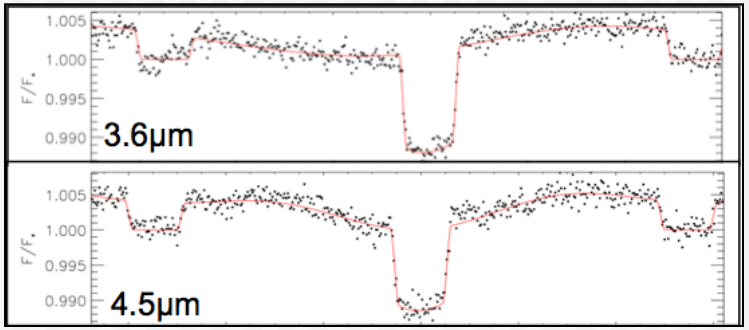
Phase curve of transiting planets: measuring the heat transport efficiency

Degeneracy heat transport/albedo broken by optical (albedo) or IR (heat transport) full orbit curves.

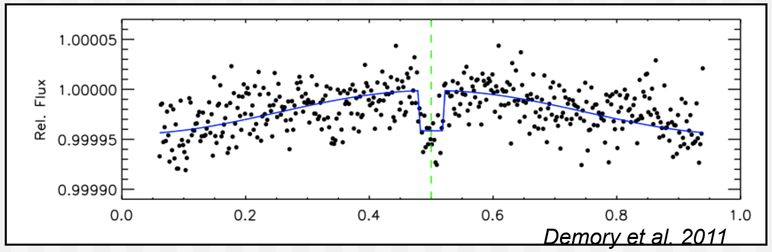
Eccentric orbit: constraints on radiative time constant, tidal heating and pseudo-synchronisation rotation (HD 80606, e=0.93, Laughlin et al. 2007)



HD189733b 8μm photometry with Spitzer: Efficient heat distribution & hot spot shifted East

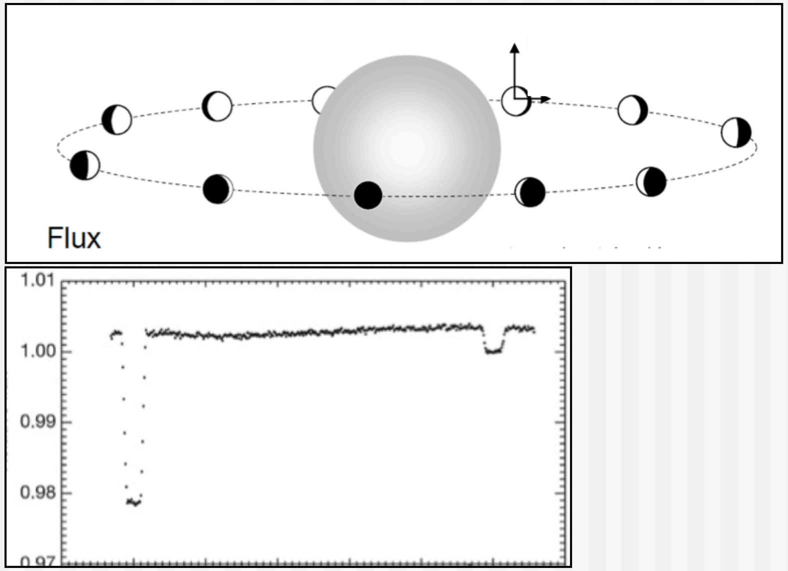


WASP-12b 3.6/4.5μm photometry with Spitzer: Inefficient heat distribution and non-zero albedo

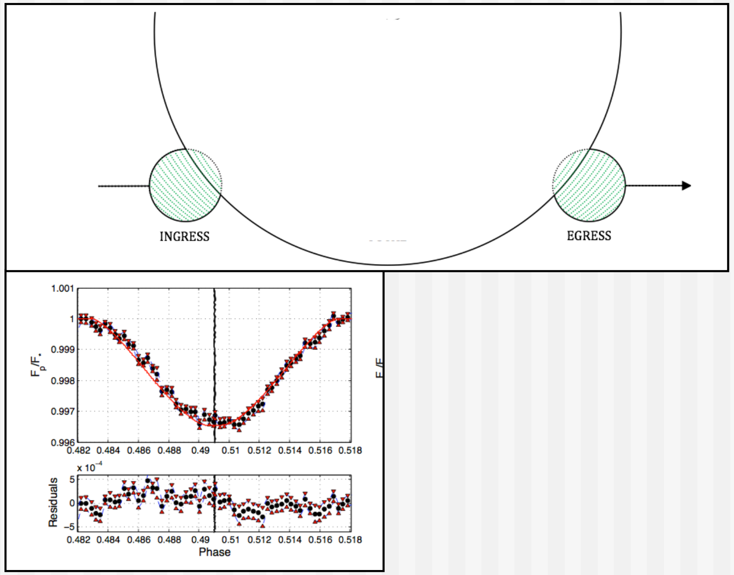


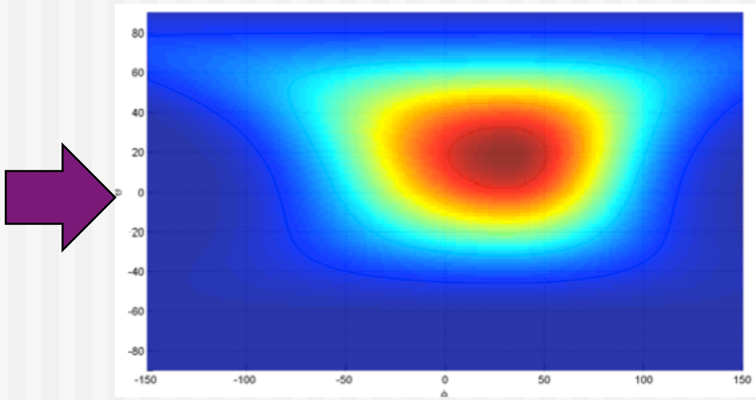
Kepler-7b optical photometry with Kepler: a high albedo hot Jupiter (A_g~0.3)

Phase curves + eclipse scanning: 2D emission maps



+



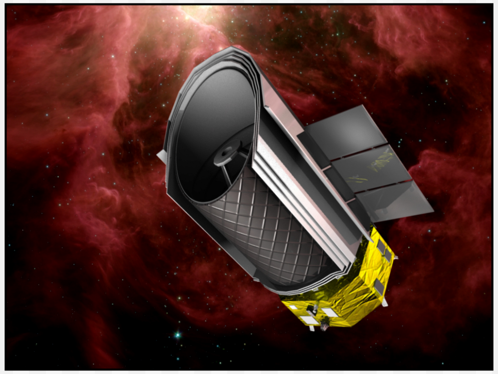


HD189733b
Global analysis of Spitzer data
e < 0.0081 (95% level)
Hot spot at 24±11 °E, 17±10 °N

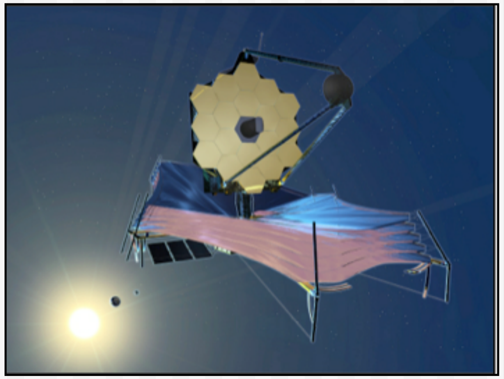
de Witt et al. (2012)
see also Majeau et al. (2012)

The future of transiting planets atmospheric characterization

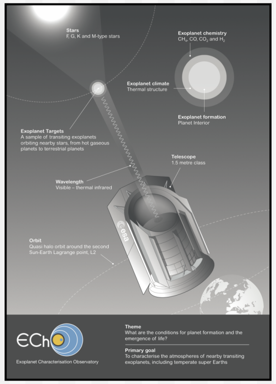
1/ Space-based visible + infrared spectroscopy/photometry



SPICA
JAXA/ESA – 3.5m
3.5 to 210µm
Launch: 2017



JWST
NASA+ESA/CSA – 6.5m
0.6 to 23µm
Launch: 2018 - 2020



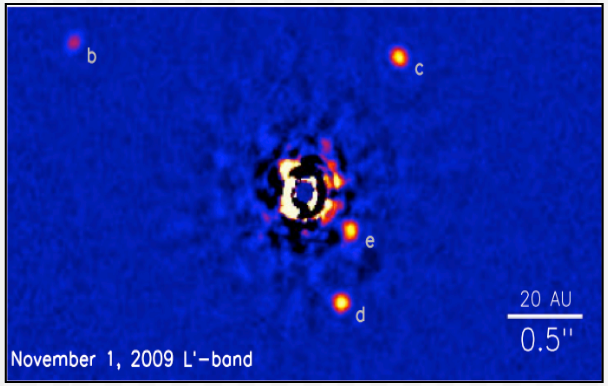
EChO
ESA – 1.4m
0.4 to 16µm
Launch: 2022 (?)

2/ Ground-based visible + near-IR instruments

Certainly, but need “wide” FOV (comp stars)

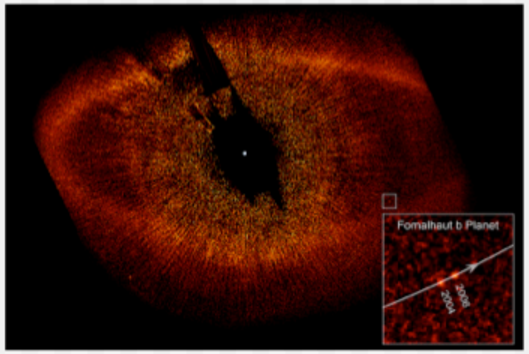
Direct spectroscopy of extrasolar planets

HR 8799



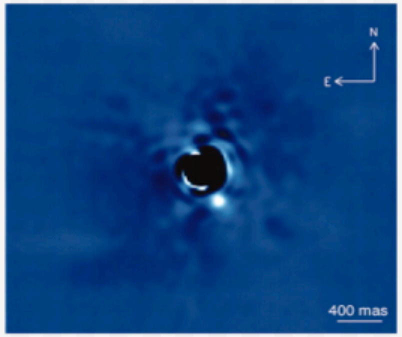
Marois et al. (2011)

Fomalhaut



Kalas et al. (2008)

β Pictoris

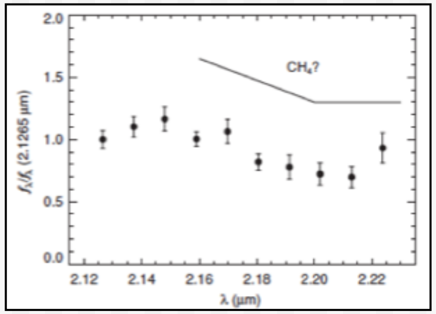


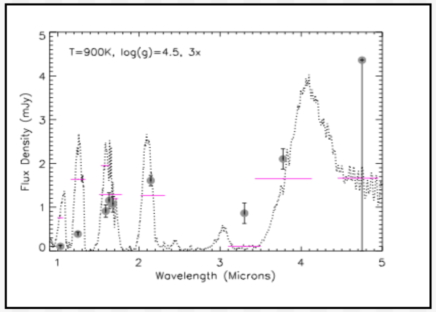
Lagrange et al. (2010)

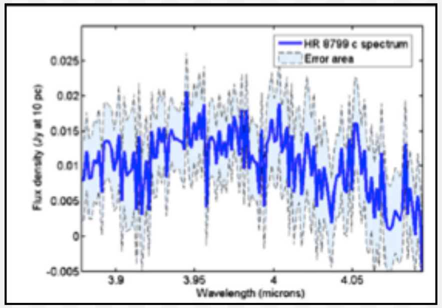
Nearby young A stars, large period massive planets still in contraction

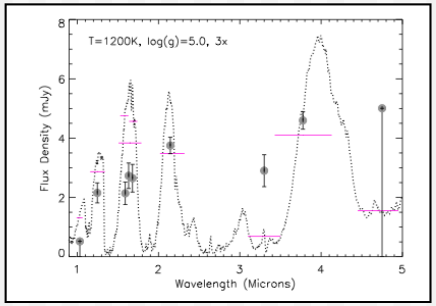
Direct spectroscopy of HR8799 planets

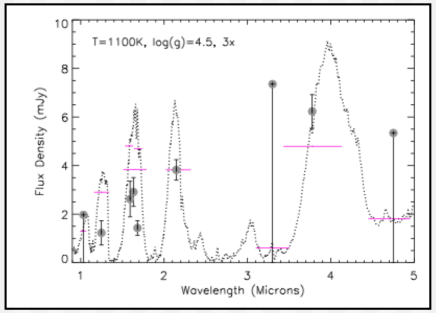
HR 8799b	**HR 8799c**	**HR 8799d**









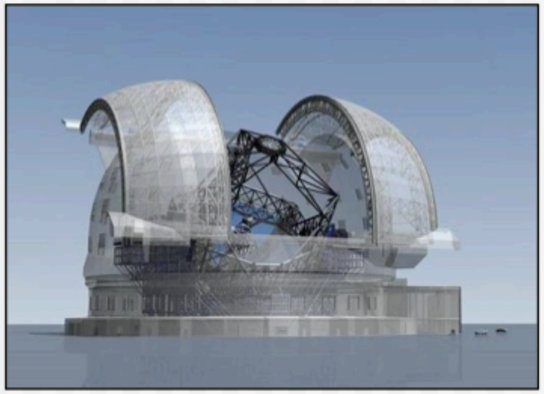


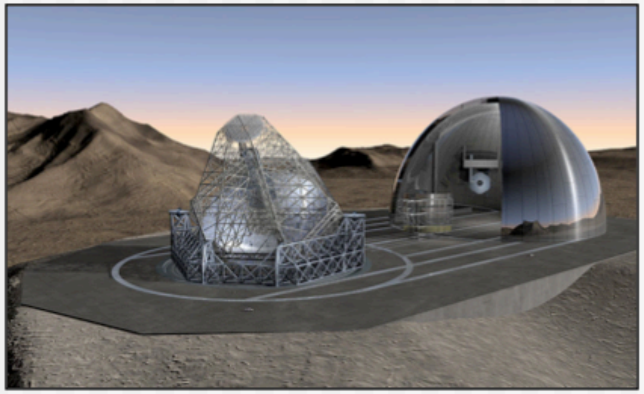
Janson et al. (2010)
Bowler et al. (2010)
Currie et al. (2011)

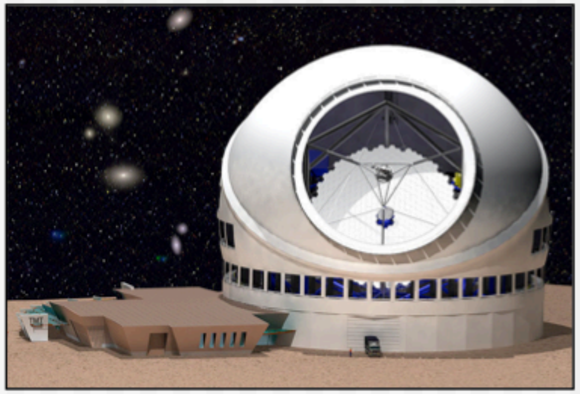
Similar to BD spectra, but only to some extent.
Discrepancies in colors/magnitudes explained by thicker cloud coverage.
Origin: gravity? Metallicity?

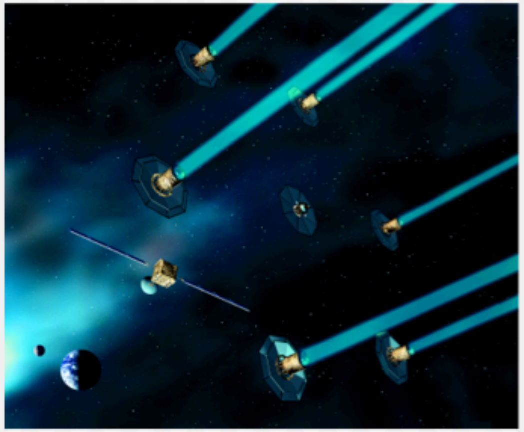
The future for spatially resolved exoplanet characterization

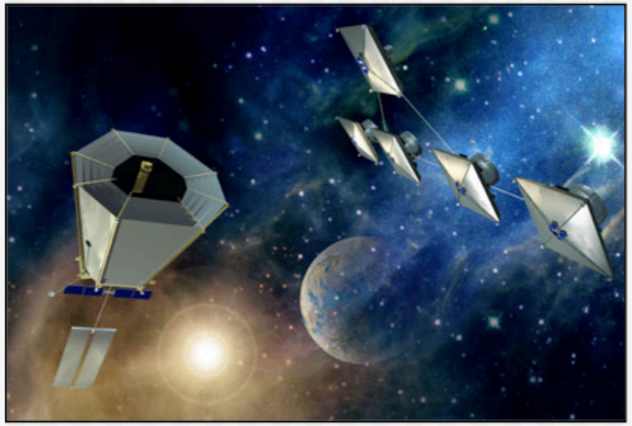
Extremely large ground-based telescopes and …







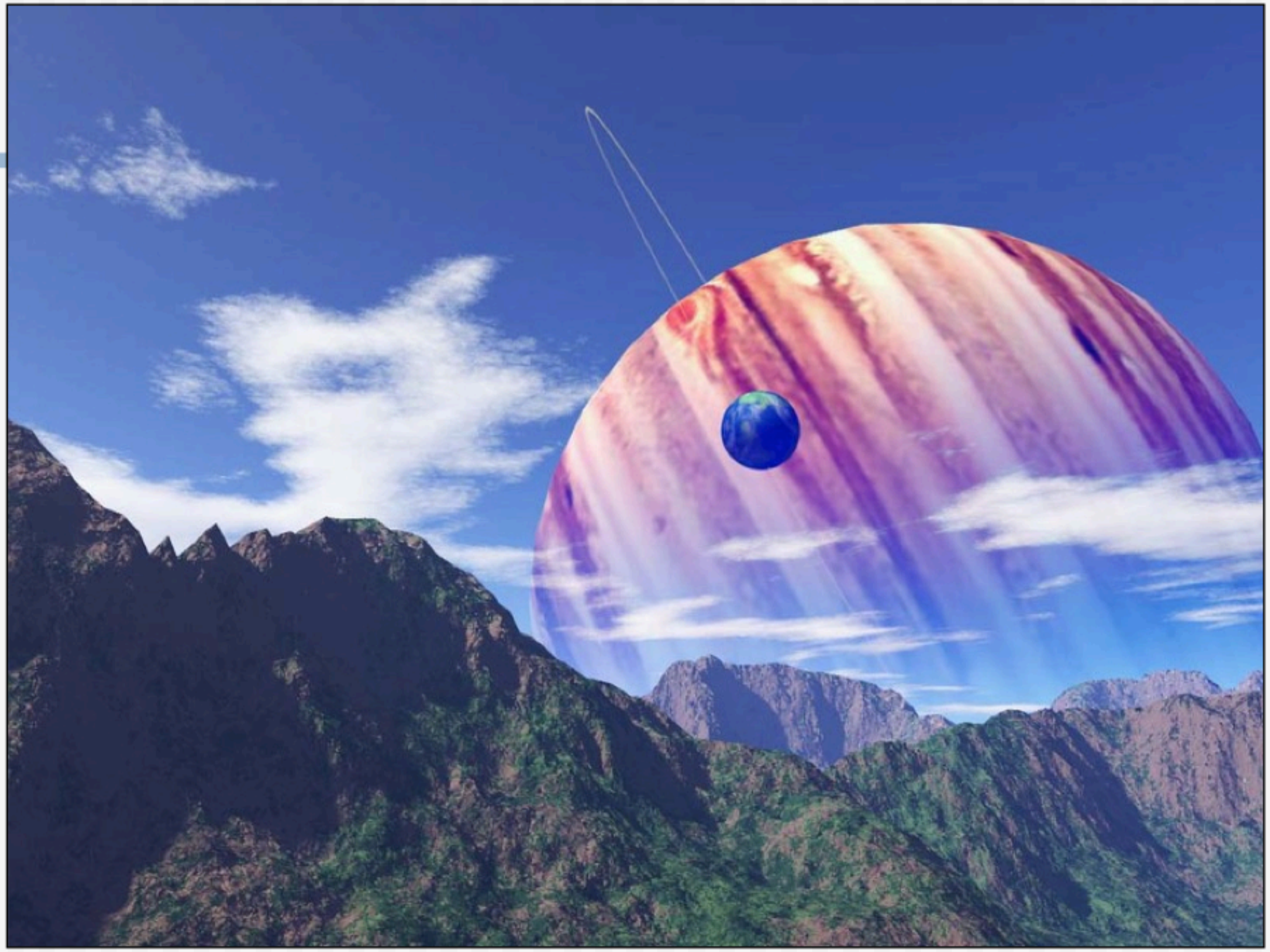




… space-based coronography & interferometry

Conclusions

- **The era of atmospheric characterization of exoplanets has started**: thermal profile, heat transport, clouds/haze, emission map, composition.
- **Transiting planets** makes possible **thorough atmospheric studies** without the need for spatial resolution of the planet.
  - * Transmission spectra: very challenging – very promising
  - * Emission spectra: well established method for photometry – also possible from the ground
  - * Phase curves + occultations: 2D maps!
- **Direct detection of exoplanets ➔ spatially resolved spectroscopy** for young massive giant planets at large orbital distances. First spectra: similar to BDs, but only to some extent.



Thank you for your attention!