

Exoplanets Atmospheres

Planets and Astrobiology (2019-2020)

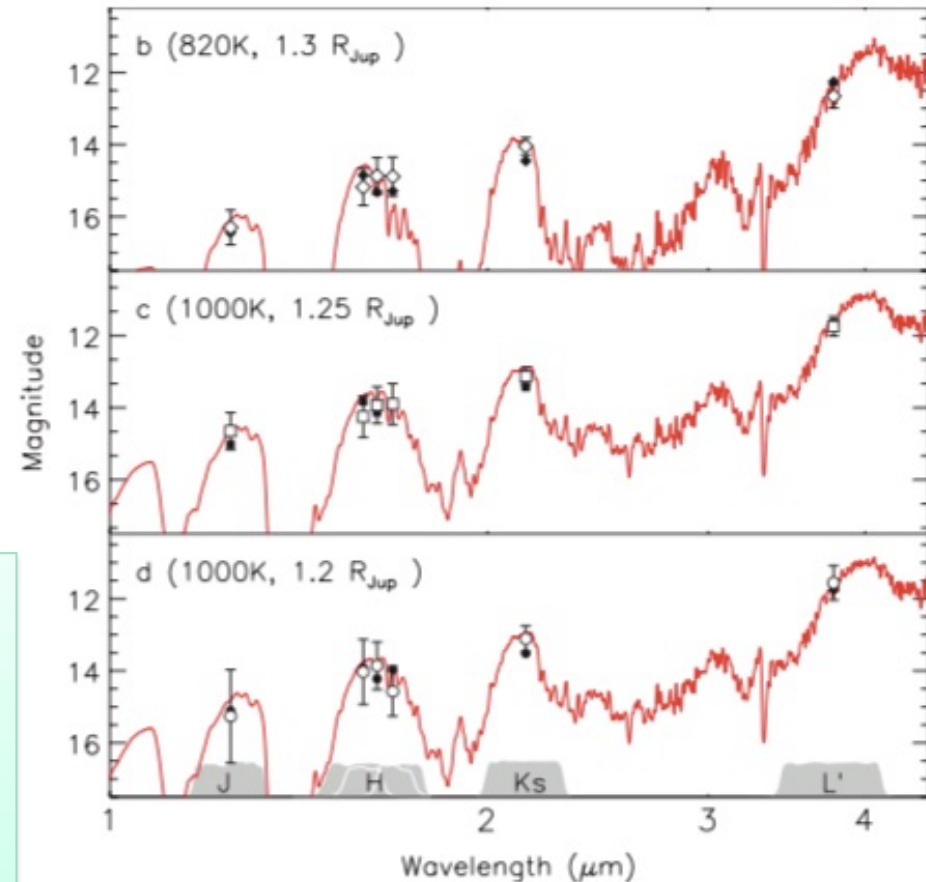
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Characterization of planetary atmospheres

- The characterization of planetary atmospheres can be performed with different methods
 - Direct imaging and secondary transits
 - Photometry in different spectral bands or spectroscopy of the intrinsic planetary emission can constrain models of atmospheric spectra
 - Transmission spectroscopy during primary transits
 - The atmospheric spectrum of the planet can be observed in transmission: this provides the possibility of performing absorption spectroscopy of the planetary atmosphere
 - Non-transiting planets in close orbits
 - Thermal day-side spectrum resulting from the reflection and transmission of the planetary atmosphere

Photometry of planetary atmospheres from direct imaging

Fig. 5. Synthetic spectra from model atmospheres containing clouds located between 10 and 0.1 bar of pressure are compared to the measured fluxes (with $3\text{-}\sigma$ error bars) for HR 8799 b, c, and d. Response curves for each filter band pass are indicated along the x axis. The predicted magnitudes from the synthetic spectra, averaged over the filter passbands, are shown by the filled symbols.



Example: planetary system detected
with direct imaging
HR 8799 b, c, d (Marois et al. 2008)
 $M = 7, 10, 10 M_J$ - $a = 68, 38, 24$ AU

Infrared bands

Spectroscopy of planetary atmospheres from direct imaging

Example:

HR 8799 c

$M = 10 M_J$ - $a = 38$ AU

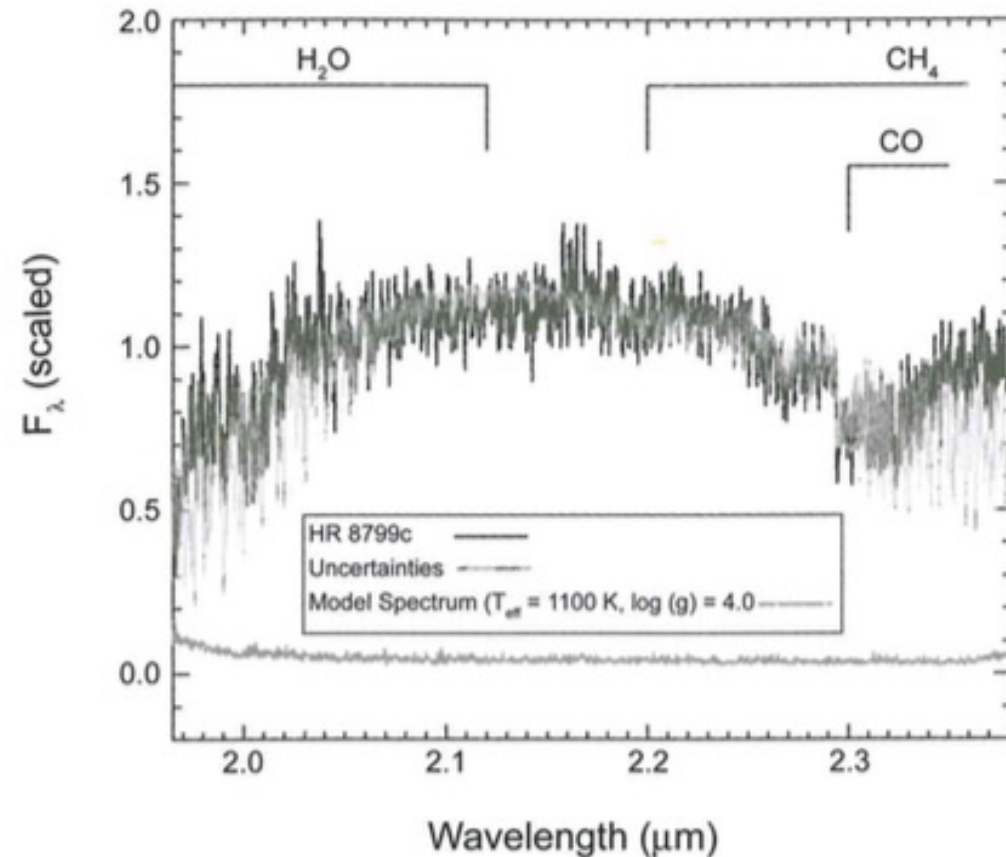
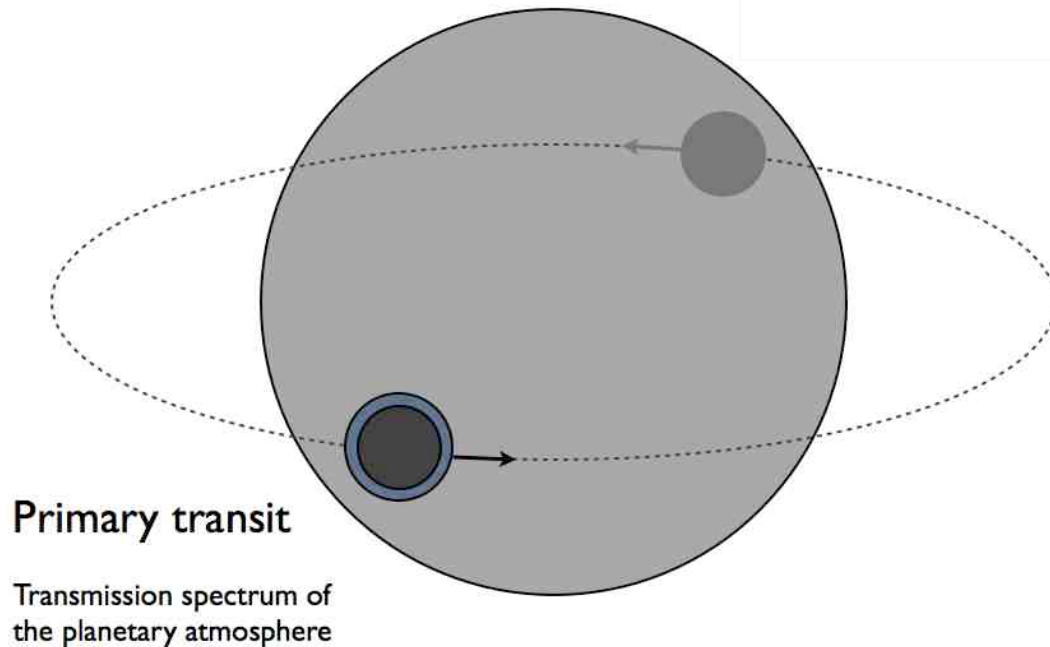


Fig. 7. High-resolution spectrum of the extrasolar planet HR 8799c taken with the OSIRIS spectrograph and the Keck adaptive optics system, reproduced from *Konopacky et al. (2013)*. Residual speckle noise changes the overall spectral shape (e.g., the upturn at the long wavelength end) but does not inject narrow features; the CO break is clearly detected, as are many individual CO and H₂O lines, while methane is absent.

Transmission spectrum of planetary atmospheres

Due to the spectral dependence of the atmospheric absorption, the radius of the planet (measured with the transit method) will vary as a function of wavelength



The radius will be larger at wavelengths where the atmosphere is more absorbing

In this way, it is possible to obtain an atmospheric transmission spectrum from the observed wavelength dependence of the radius, $R_p = R_p(\lambda)$

Absorption spectroscopy of planetary atmospheres

- The atmospheric absorption signal scales with the scale-height of the atmosphere, h , and the planet radius, R_p

$$\delta I \sim \frac{2 h R_p}{R_*^2}$$

- Detection bias favours stars with smaller radii
- Gaseous giants give the strongest signal, for a given type of star
 - e.g. Tinetti et al. (2007)
- Space-born instrumentation optimized for the infrared band is particularly important for this type of observation
 - e.g. HST, Spitzer

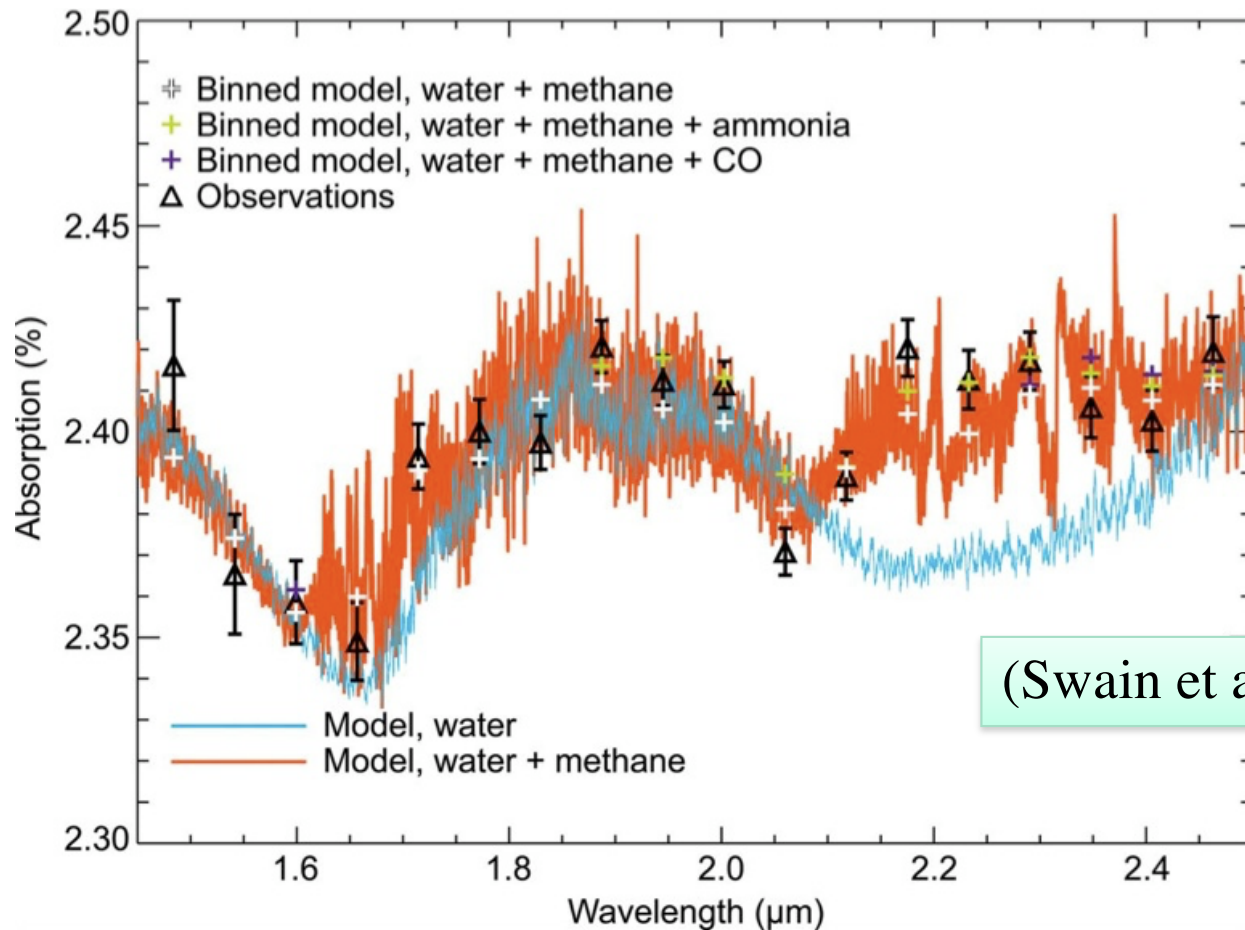
Spectroscopy of planetary atmospheres

Absorption spectroscopy with primary transits:

molecular detections in HD 189733 b ($M_p=1.15 M_J$, $a=0.03$ AU)

H_2O , CH_4 , CO_2 , CO

Triangles: HST/NICMOS observations – Other symbols: binned models

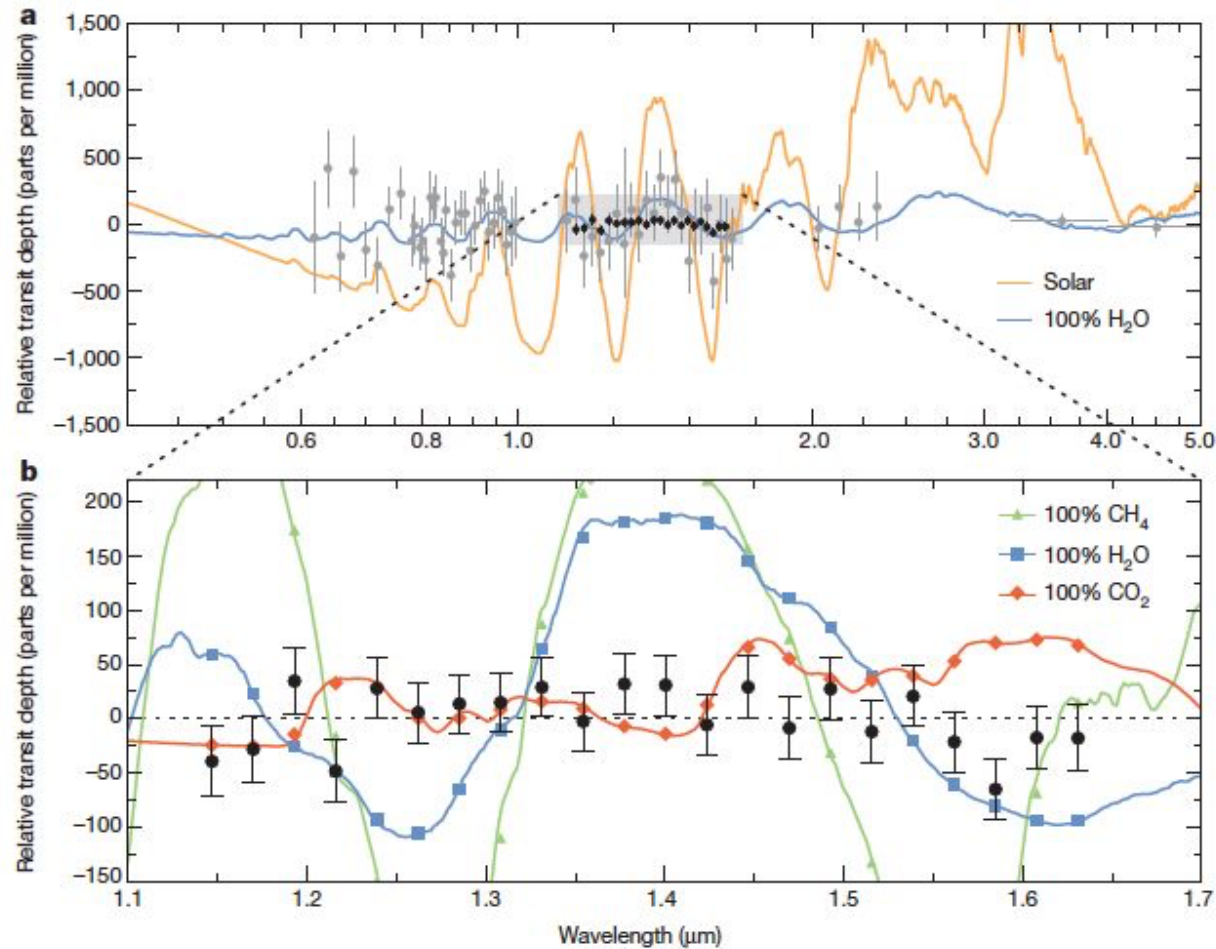


Spectroscopy of planetary atmospheres

Example of HST observations

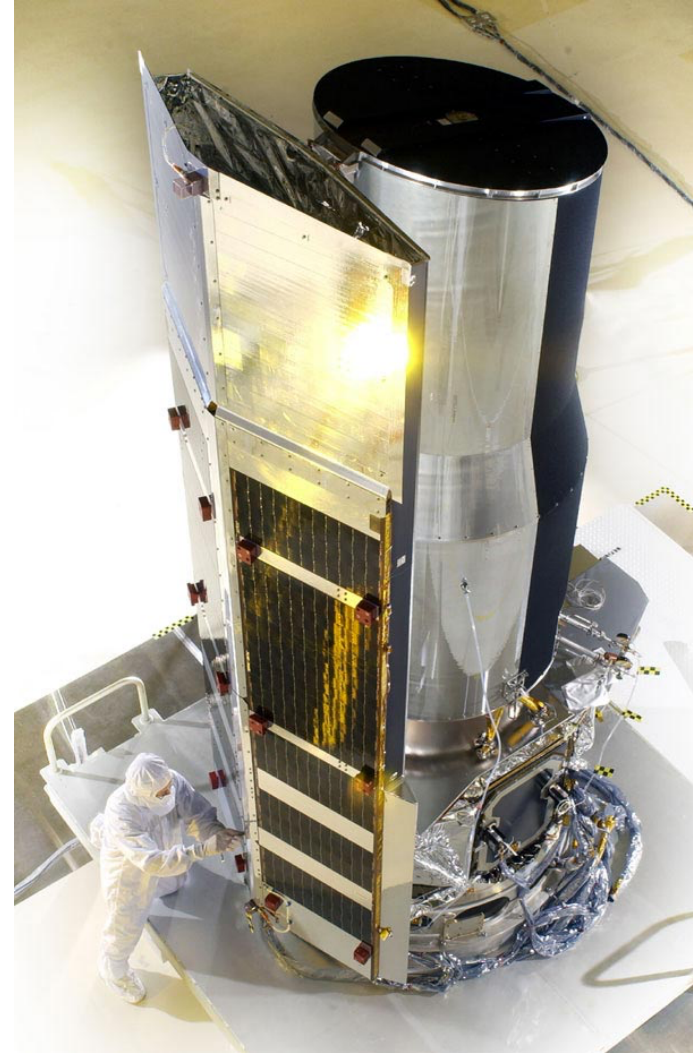
Super-Earth GJ 1214 (candidate ocean planet)

The flatness of the spectrum provides evidence for clouds (Kreidberg 2014)



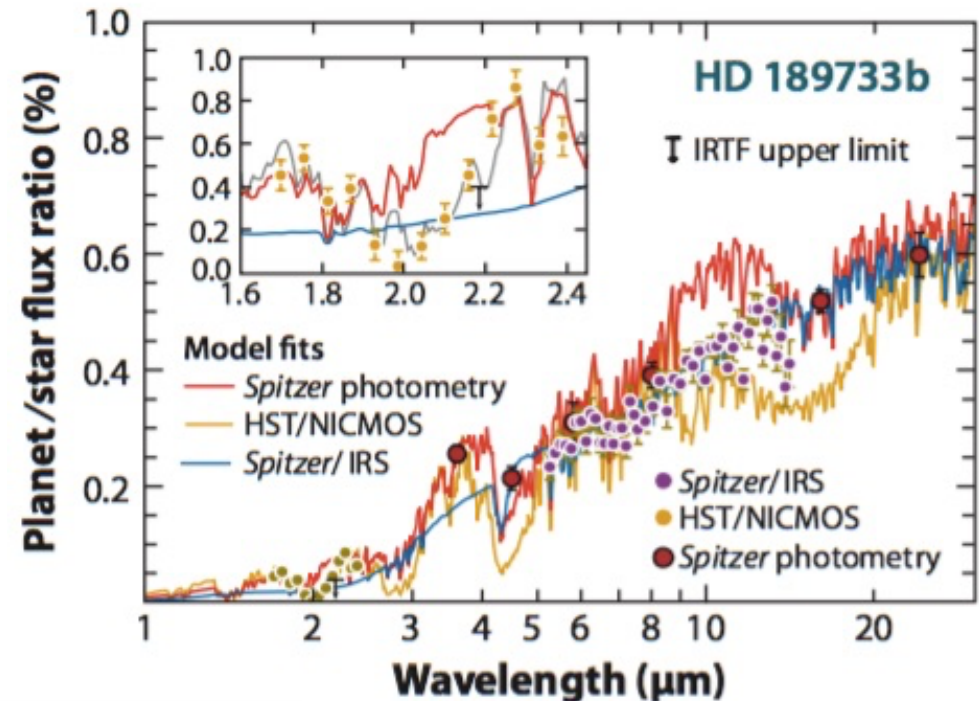
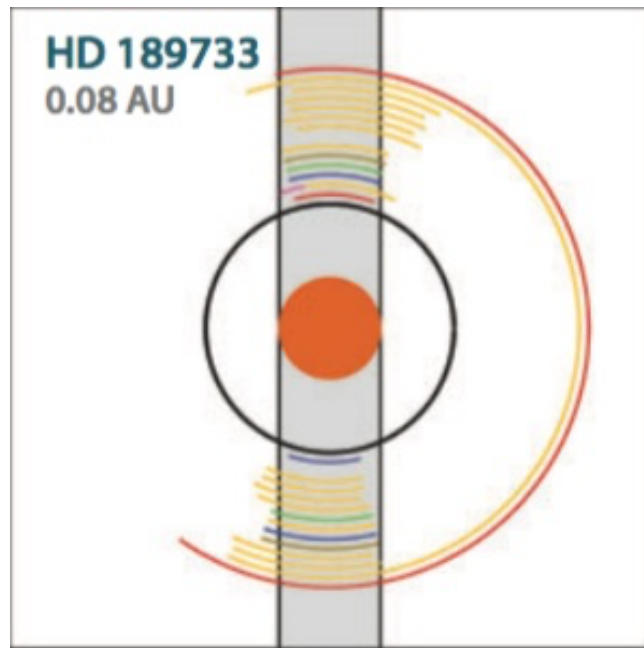
Spitzer Space Telescope (NASA)

- Space-borne, cryogenically-cooled infrared observatory capable of studying objects ranging from the Solar System to the distant Universe
- Wavelength Coverage: 3 - 180 microns
- Telescope: 85 cm diameter, f/12
- Science Capabilities:
 - Imaging / Photometry, 3-180 microns
 - Spectroscopy, 5-40 microns
 - Spectrophotometry, 50-100 microns



Absorption spectroscopy of planetary atmospheres

Example of Spitzer observations HD 189733 b



Disk: star. Black curve: planetary orbit. The spatial scale is given in AU. The stellar disk has been increased by a factor of 3 for visibility.

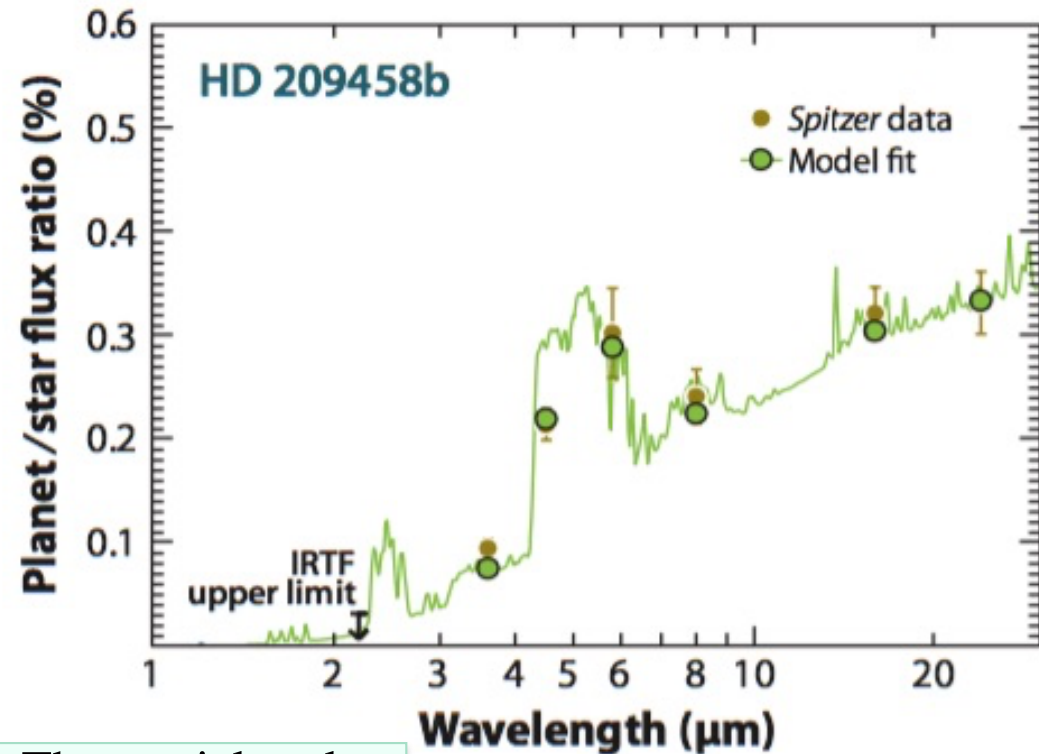
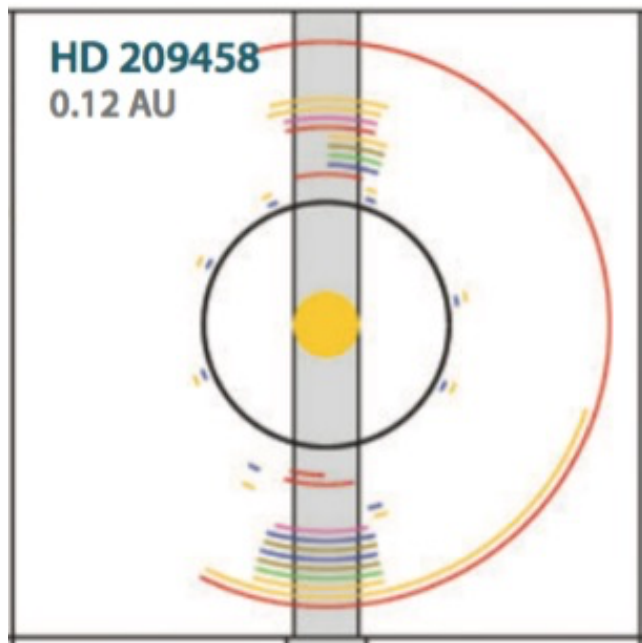
Arcs: Spitzer observations during primary and secondary transits in different spectral bands.

The observer is watching from below.

Spectroscopy of planetary atmospheres

Example of Spitzer observations

HD 209458 b ($M=0.64 M_J$, $R=1.4 R_J$, $a=0.048$ AU)



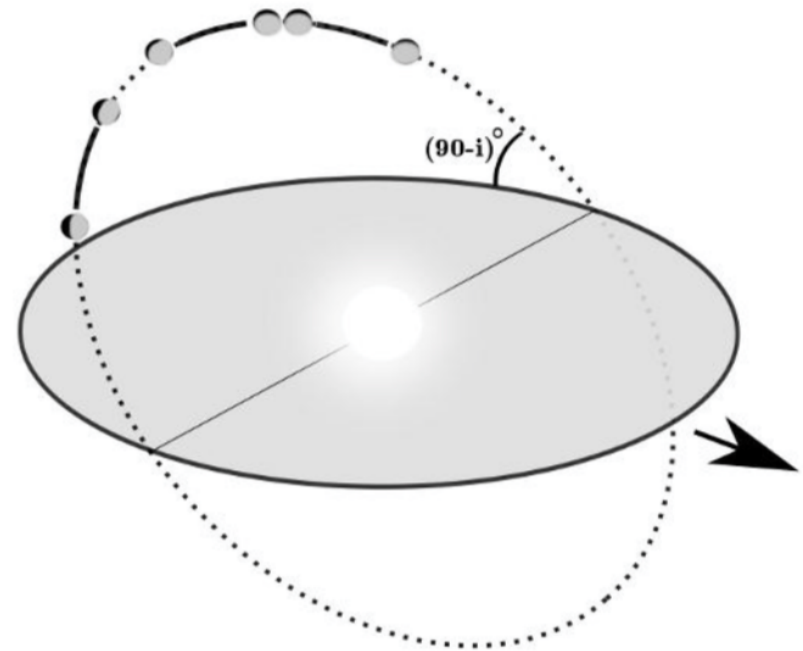
Disk: star. Black curve: planetary orbit. The spatial scale is given in AU. The stellar disk has been increased by a factor of 3 for visibility.

Arcs: Spitzer observations during primary and secondary transits in different spectral bands.

The observer is watching from below.

Atmospheric characterization of non-transiting planets

- Detection of CO in the thermal dayside spectrum of τ Boo b (Brogi et al. 2012)
- Instrumentation
 - CRIRES, ESO VLT
 - $R \sim 10^5$ at $\lambda \sim 2.3$ μm
 - 452 spectra at orbital phases 0.37-0.63
- Methods
 - Removal of telluric lines
 - Cross-correlation of all spectra with a CO template spectrum
 - Analysis of the evolution of the cross-correlated signal as a function of orbital phase (time)

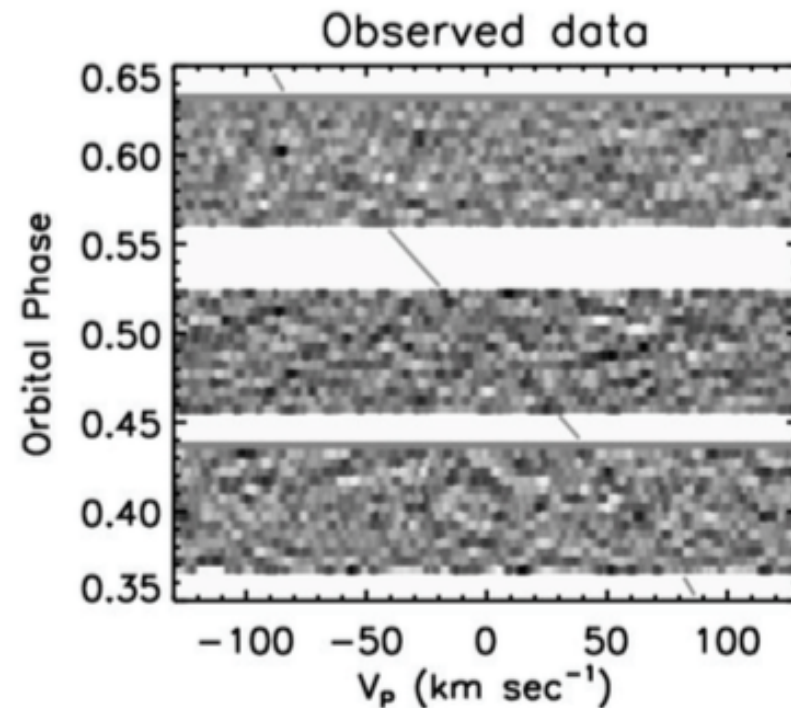
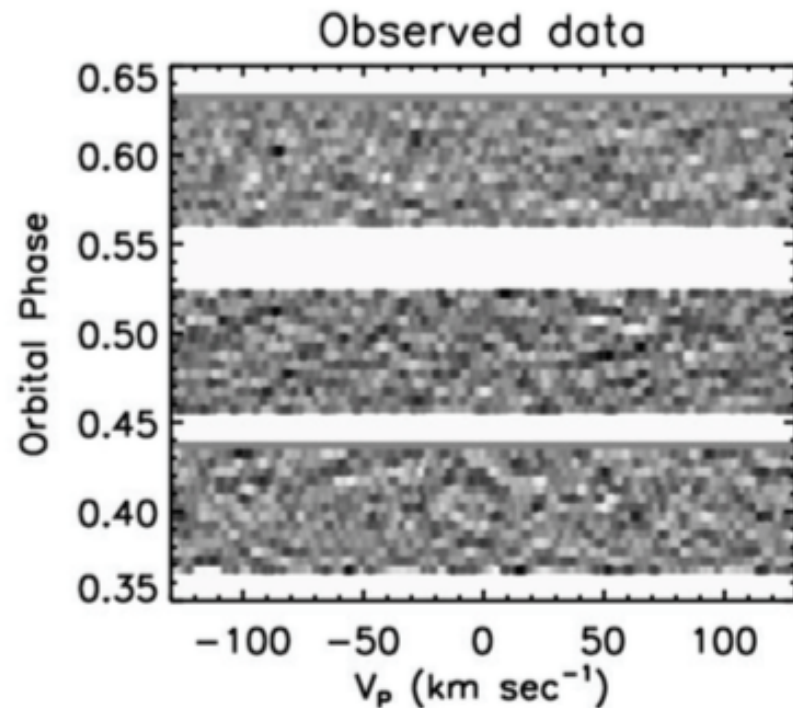


Atmospheric characterization of non-transiting planets

- Detection of an orbital trail of CO absorption
 - Planetary radial velocity signal with $K_p=110$ km/s
- Measurement of the planet mass and orbital inclination

$$M_p/M_* = K_p/K_*$$

$$\sin i = (M_p \sin i) / M_p$$

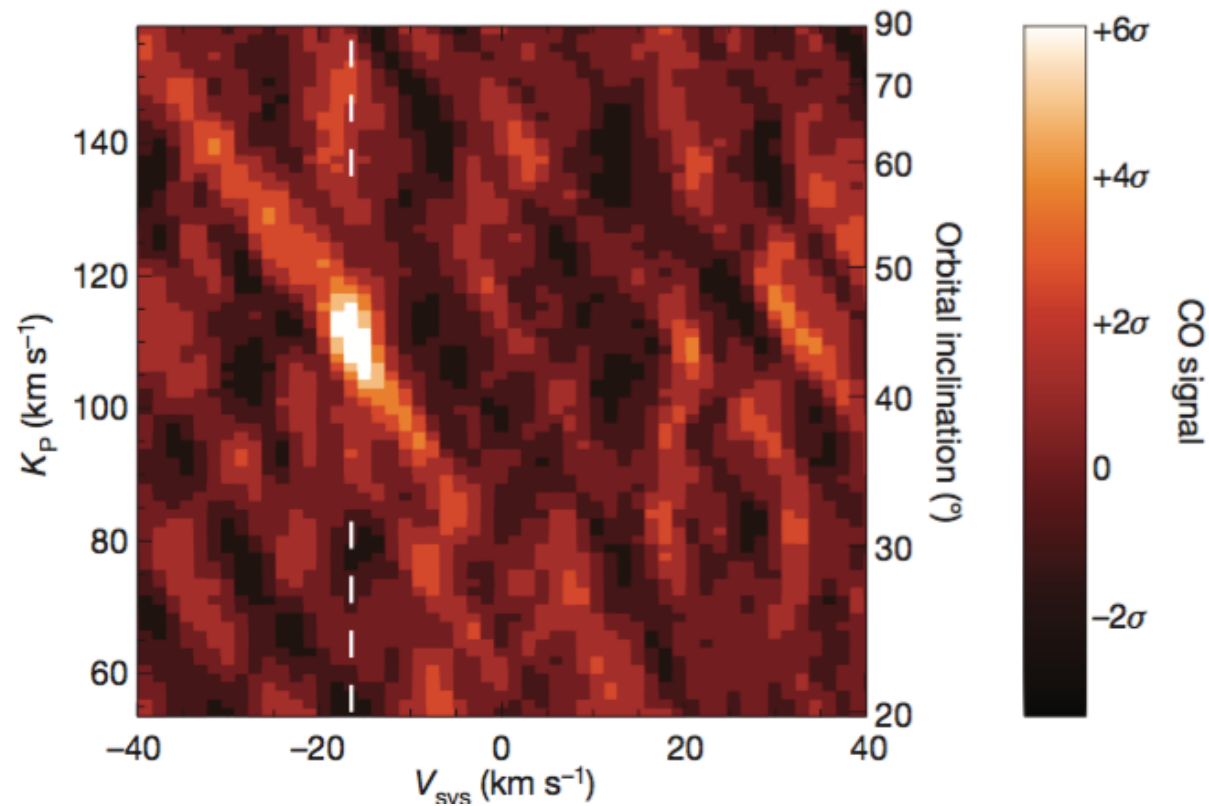


Atmospheric characterization of non-transiting planets

- Results for τ Boo b

$$K_p = 110 \text{ km/s} \quad K_* = 0.46 \text{ km/s}$$

$$M_p = 5.95 M_J \quad i = 44.5 \text{ deg}$$



Models of planetary atmospheres

- Main ingredients
- Radiative transfer equation

$$\mu \frac{dI(z, \nu, \mu, t)}{dz} = -\kappa(z, \nu, t)I(z, \nu, \mu, t) + \varepsilon(z, \nu, \mu, t)$$

Here, I is the intensity [$\text{Jm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$], a beam of traveling photons; κ is the absorption coefficient [m^{-1}], which includes both absorption and scattering out of the radiation beam; ε is the emission coefficient [$\text{Jm}^{-3} \text{s}^{-1} \text{Hz}^{-1}$], which includes emission and scattering into the beam; $\mu = \cos \theta$, where θ is the angle away from surface normal; and z is vertical altitude, where each altitude layer has a specified temperature and pressure.

- Boundary conditions different from stellar atmospheres:
 - Incident stellar radiation & clouds

Models of planetary atmospheres

- Main ingredients: opacities

$$\kappa(\lambda, T, P) = n(T, P)\sigma(\lambda, T, P)$$

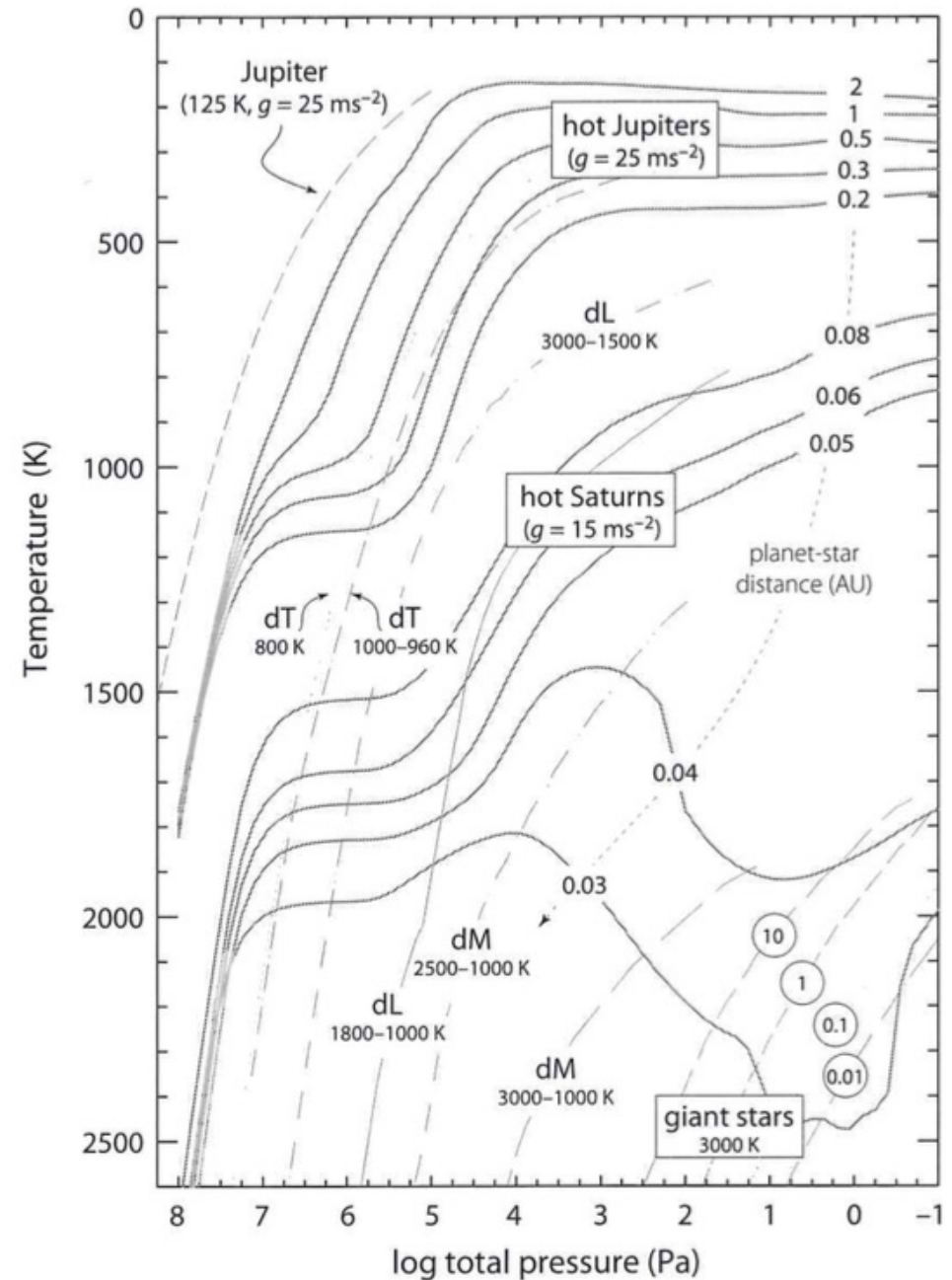
- Ingredients to calculate opacities
 - Chemical abundances of molecular species
 - Database of molecular cross-sections
 - Temperature-pressure profile as a function of z
- Equilibrium chemistry
 - Network of chemical reactions taking place between atomic/molecular species, as a function of T, P and radiation

Pressure-temperature relations for model atmospheres

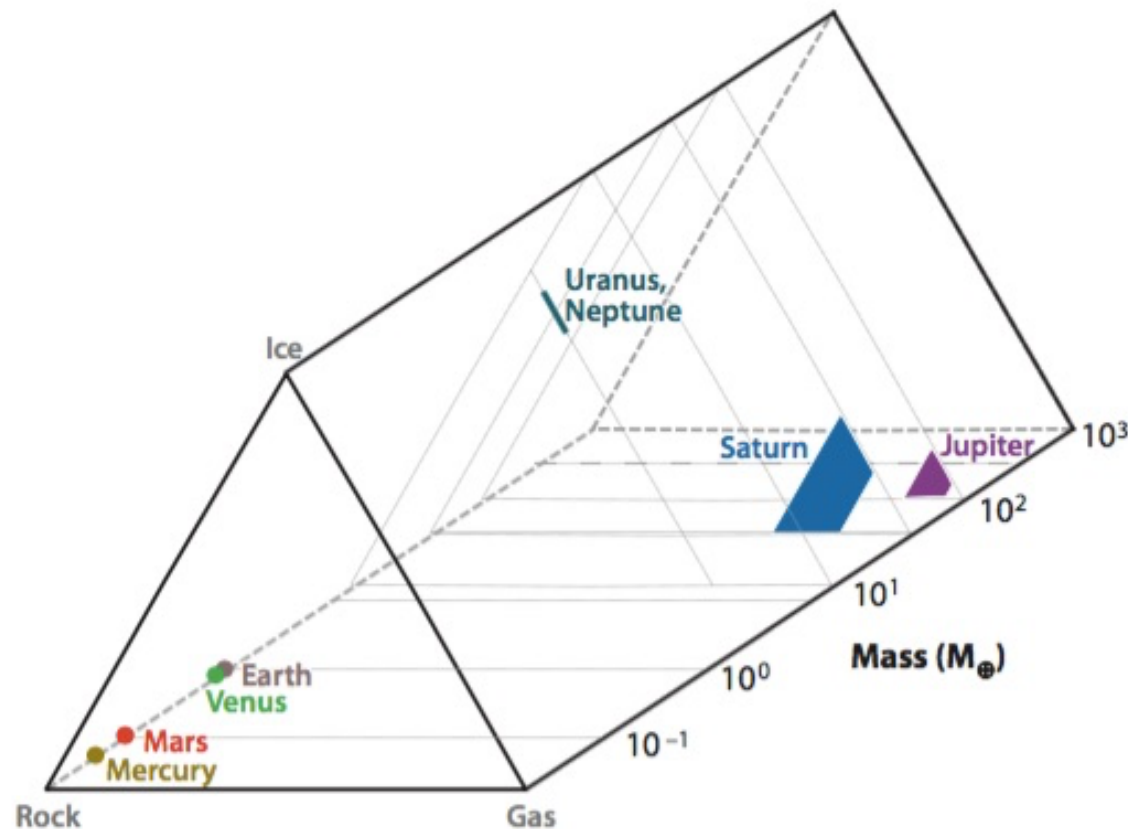
Thick lines: Jupiter- and Saturn-mass planets

Thin lines: Jupiter, dwarf stars and giant stars

(Lodders 2010)



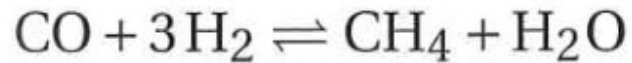
Chemical composition



Schematic diagram illustrating the range of possible planet primordial bulk compositions for planets. In this figure, gas refers to primordial H and He accreted from the nebula, ice refers to ice-forming materials, and rock refers to refractory materials. Constraints on the current compositions of the Solar System planets are plotted in colors. Exoplanets might appear anywhere in this diagram. Adapted from Rogers & Seager (2010) and Chambers (2010).

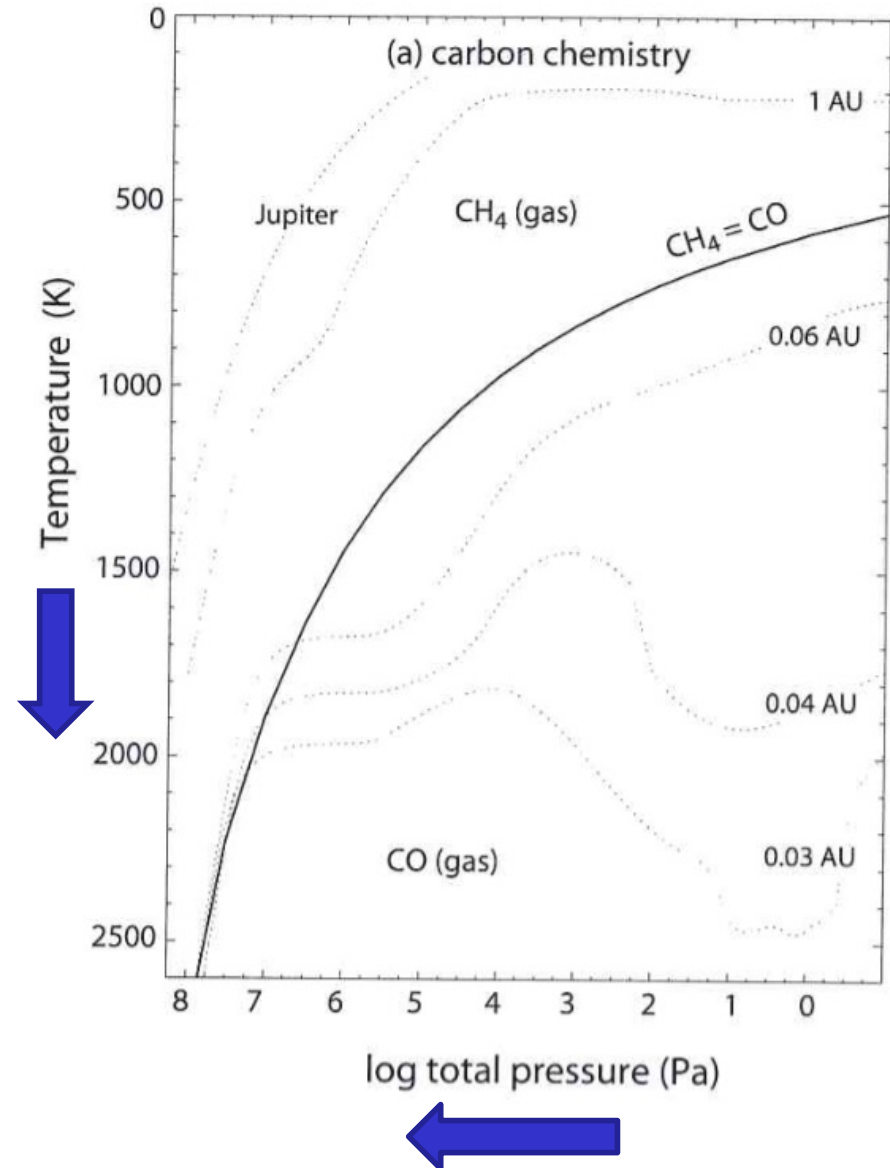
Equilibrium chemistry

- **Example: carbon chemistry**
 - The equilibrium distribution of C, over a large range of T and P , is controlled by the reaction between CO and CH₄



- As shown in the figure (Lodders 2010), at high T and low P , CO is the major C-bearing gas, while at low T and higher P , CH₄ dominates

Dotted lines: distance from the host star



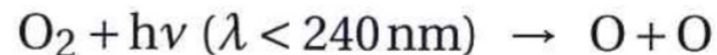
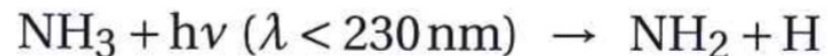
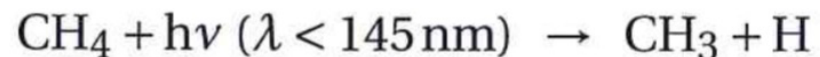
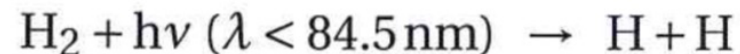
Photochemistry and photolysis

Photochemistry, which refers to all aspects of the interaction between light and atoms and molecules, plays an essential role in planetary atmospheres

Photolysis concerns, more specifically, the breakdown of molecules as a result of photon interactions

Atmospheric photochemistry is driven by the more energetic stellar photons (ultraviolet, extreme ultraviolet and, in principle, X-rays and gamma rays) and, in a more general use of the term, by energetic electrons

Atmospheric dissociation by the absorption of the incident radiation is usually relevant in the high atmosphere. Examples:



The latter is the first step in the formation of O₃ (ozone) in the Earth's atmosphere

Future observations of planetary atmospheres

- Atmospheres of super-Earths are starting to become feasible and will be common with next generation instrumentation
 - A large variety of bulk and atmospheric composition not found in the Solar System is expected (e.g., ocean planets)
- Earth-like atmospheres are beyond detection limit even for the most advanced instrumental projects currently scheduled

