Exoplanets
Atmospheres

Planets and Astrobiology (2020-2021)

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Characterization of planetary atmospheres

- Exoplanetary atmospheres can be characterized with different methods
  - Direct imaging or secondary transits

    Photometry in different spectral bands or spectroscopy of the intrisic planetary emission can constrain models of atmospheric spectra

  - Non-transiting planets in close orbits

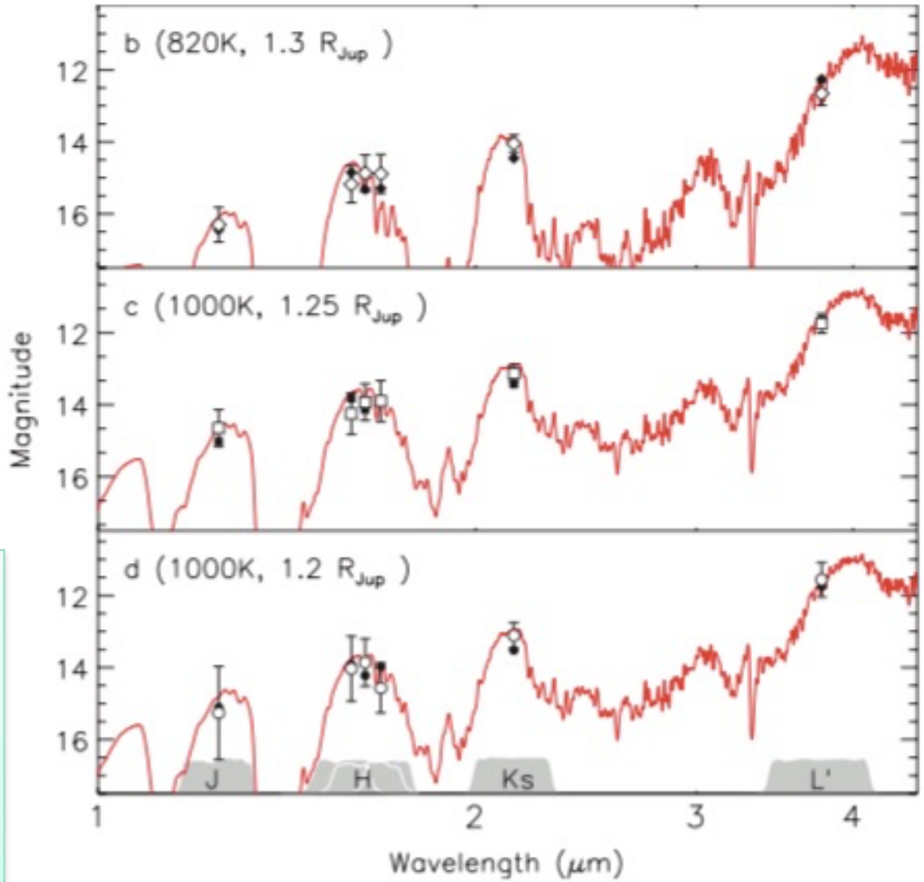
    Thermal day-side spectrum resulting from the reflection and transmission of the planetary atmosphere

  - Transmission spectroscopy during primary transits

    The atmospheric spectrum of the planet can be observed in transmission: this provides absorption spectra 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-σ 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

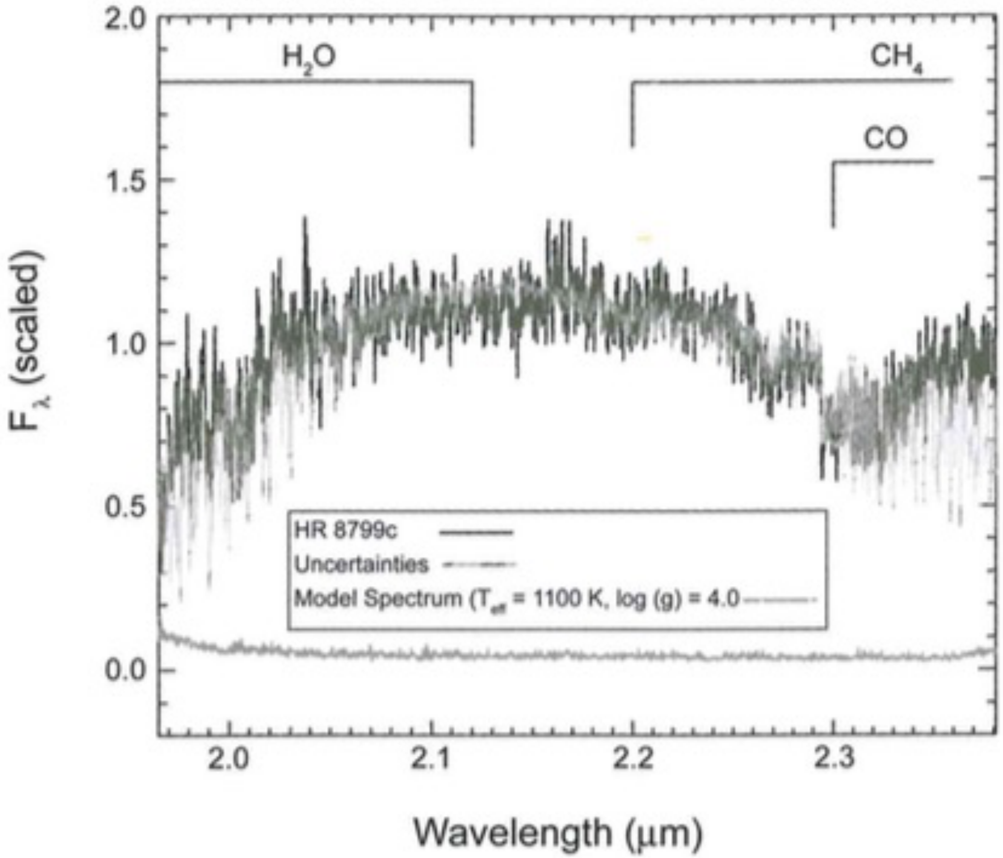
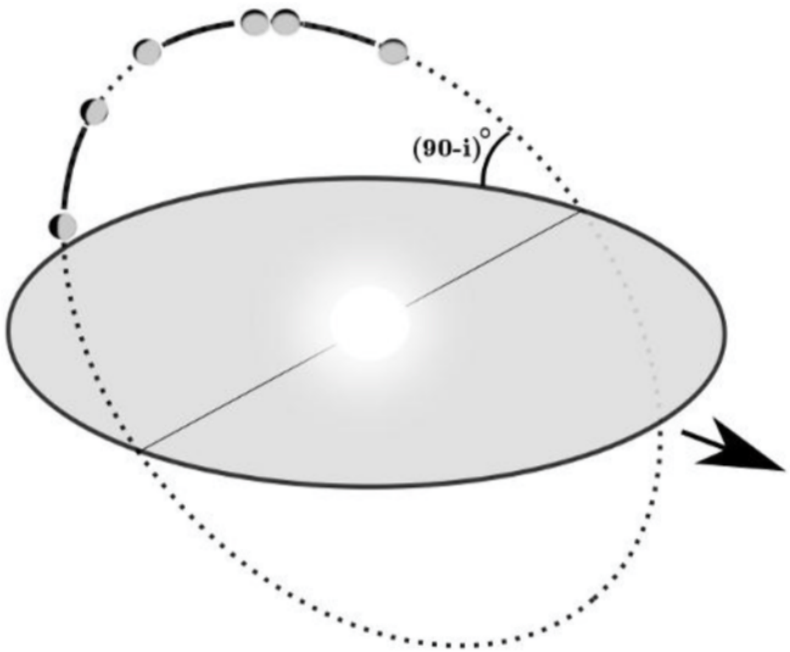


Fig. 7. High-resolution spectrum of the extrasolar planet HR 8799c taken with the OSIRIS spectrograph and the Keck adaptive optics system, reproduced from *Konopacky et al.* (2013). Residual speckle noise changes the overall spectral shape (e.g., the upturn at the long wavelength end) but does not inject narrow features; the CO break is clearly detected, as are many individual CO and H_2O lines, while methane is absent.

Atmospheric characterization of non-transiting planets

- Detection of CO in the thermal dayside spectrum of τ Boo b (Brogi et al. 2012)

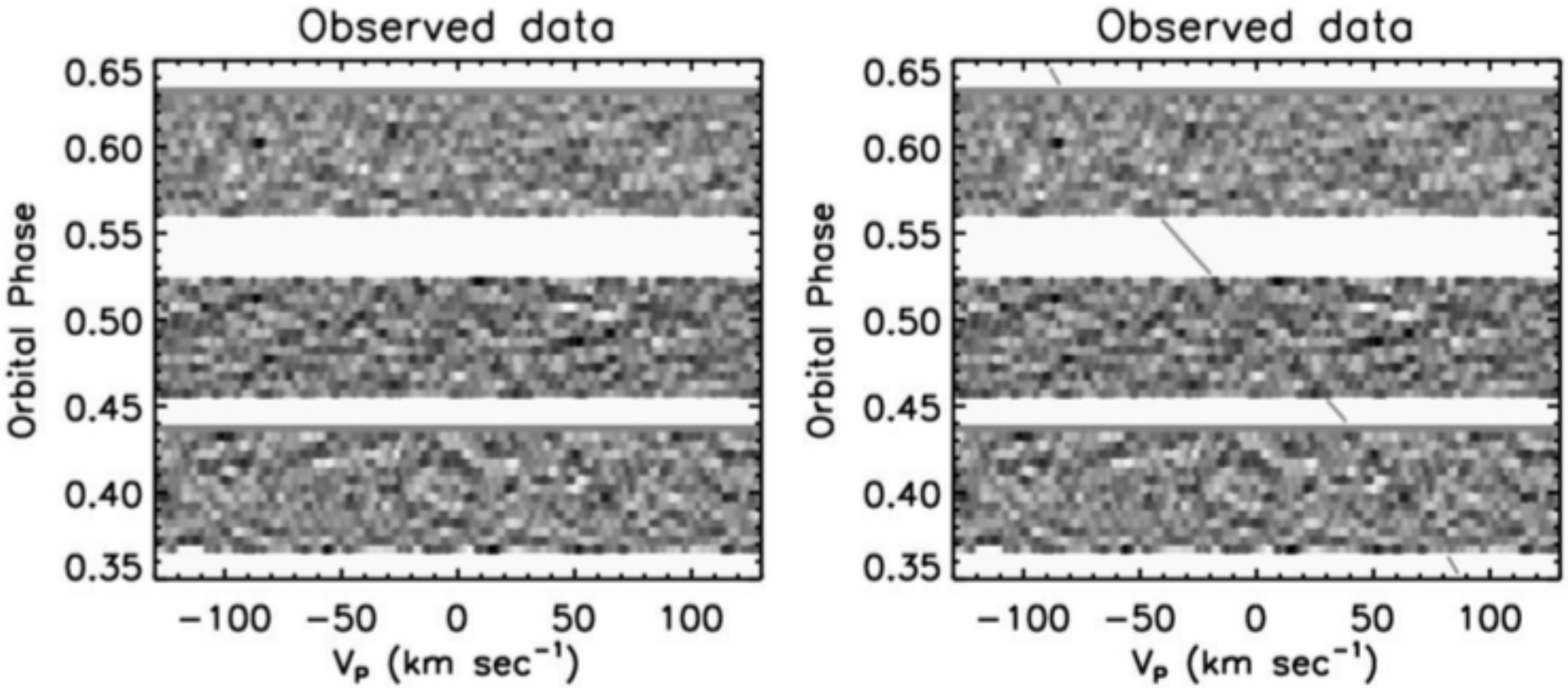
- Instrumentation
  - CRIRES, ESO VLT
  - $R \sim 10^5$ at $\lambda \sim 2.3$ nm
  - 452 spectra at orbital phases 0.37-0.63
- Methods
  - Removal of telluric lines
  - Cross-correlation of all spectra with a CO template spectrum
  - Analysis of the evolution of the cross-correlated signal as a function 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

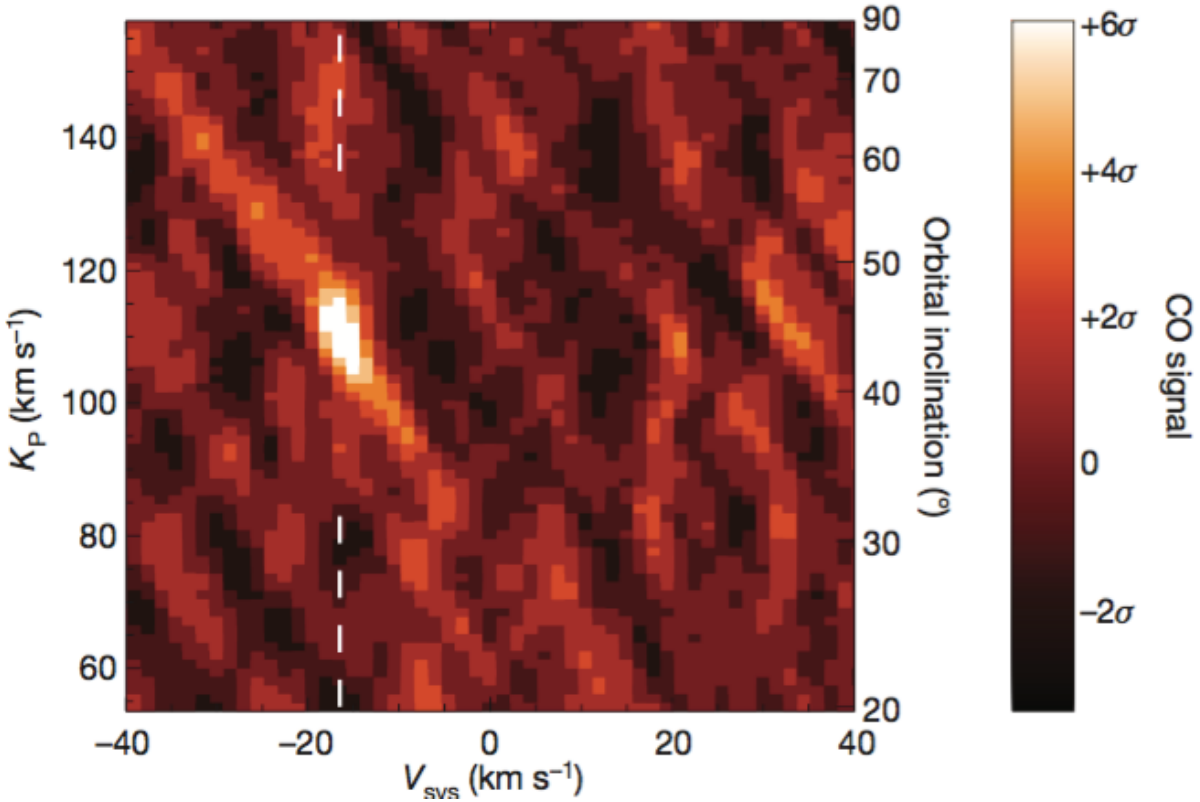
$M_p/M_* = K_p/K_*$ $\sin i = (M_p \sin i\ ) / M_p$



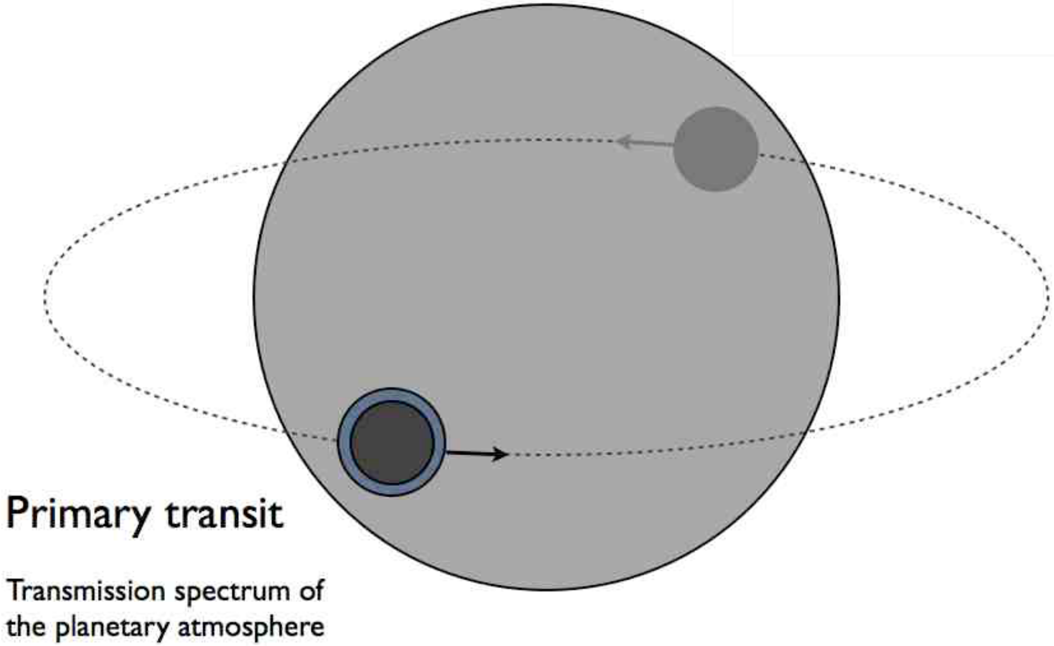
- Results for τ Boo b

  K_p=110 km/s K_*=0.46 km/s

  M_p = 5.95 M_J i = 44.5 deg



Transmission spectrum of planetary atmospheres



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

The radius is larger at wavelengths were the atmosphere is more absorbing

Thanks to this effect, it is possible to infer 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 the detection of giant planets with extended atmospheres transiting in front of stars with small radius

- Gaseous giants give the strongest signal, for a given type of star
  - e.g. Tinetti et al. (2007)

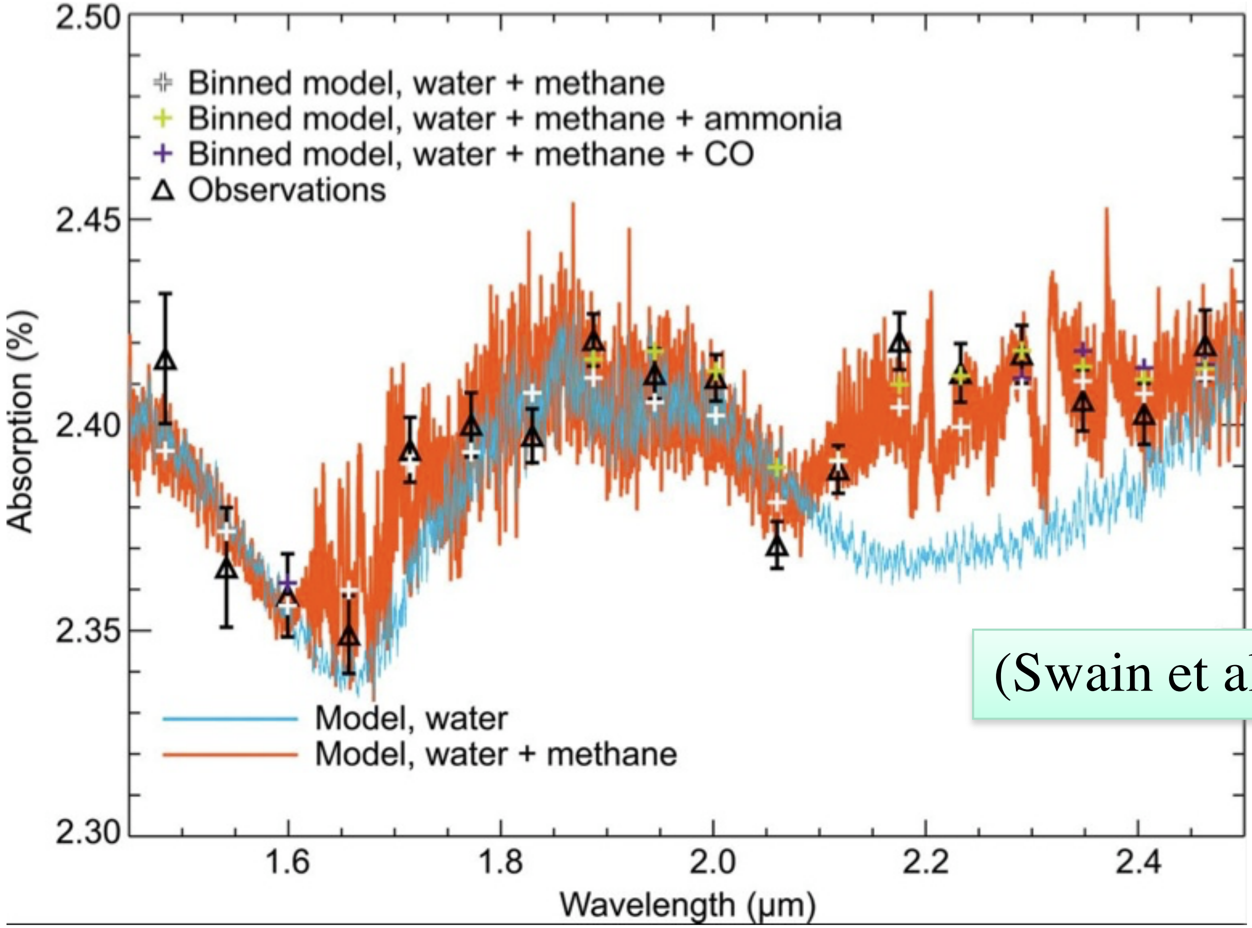
- Space-born instrumentation optimized for the infrared band is particularly important for this type of observation
  - e.g. HST, Spitzer

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



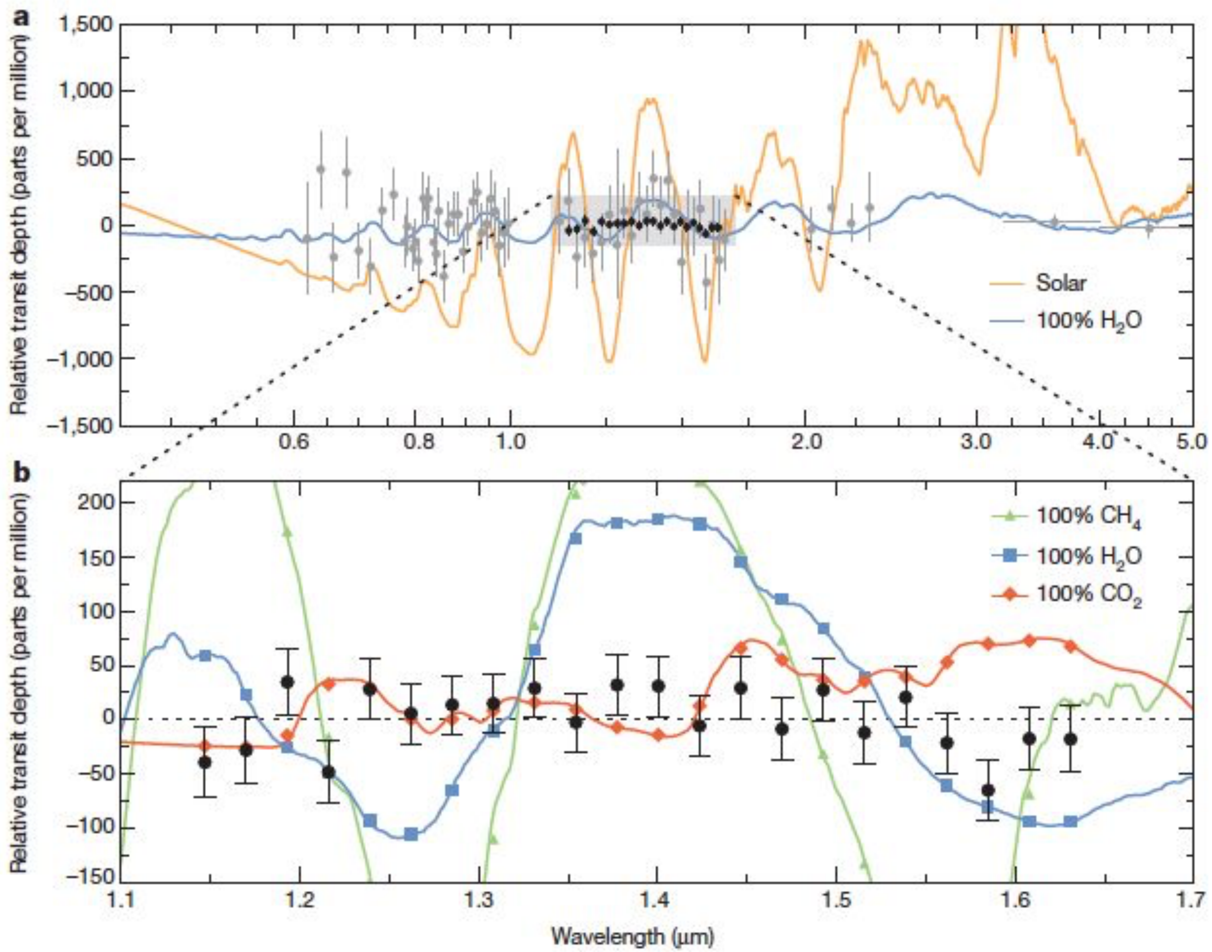
(Swain et al. 2008)

Spectroscopy of planetary atmospheres

Example of HST observations

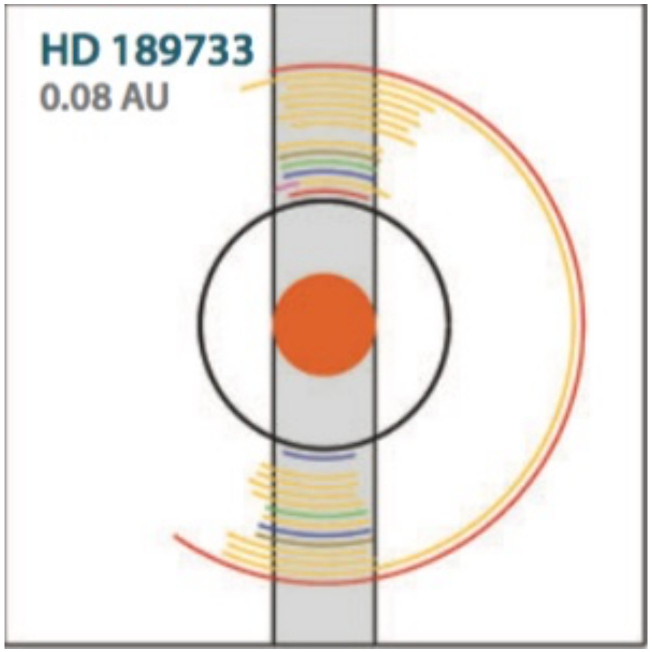
Super-Earth GJ 1214 (candidate ocean planet)

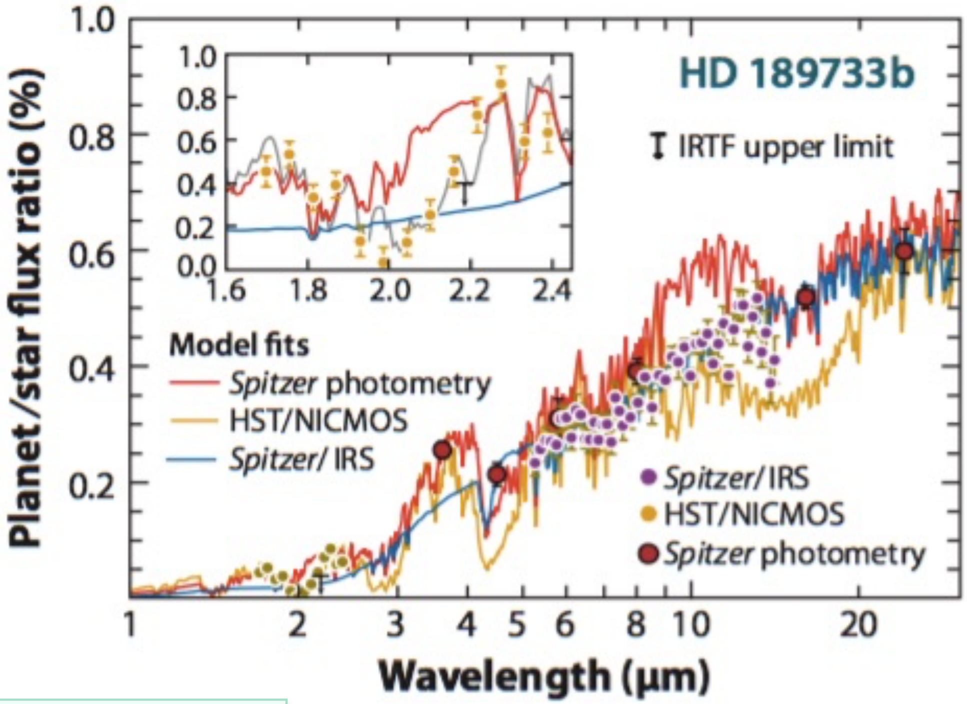
The flatness of the spectrum provides evidence for clouds (Kreidberg 2014)



Absorption spectroscopy of planetary atmospheres

Example of Spitzer observations
HD 189733 b



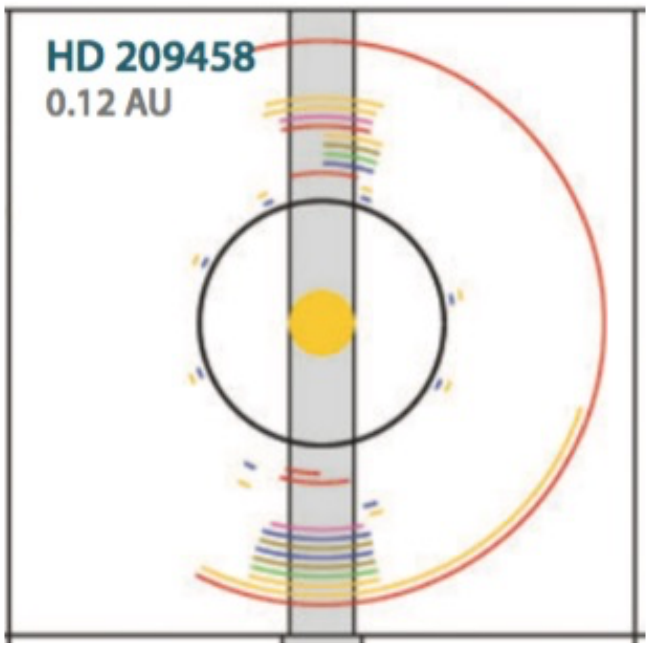


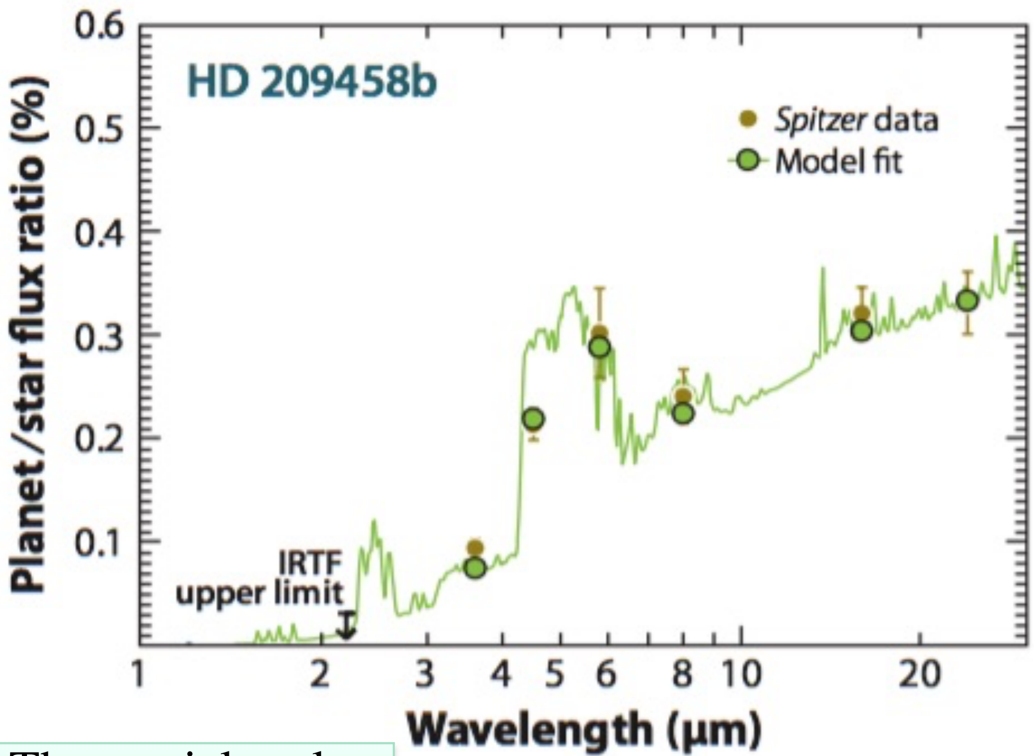
Disk: star. Black curve: planetary orbit. The spatial scale is given in AU. The stellar disk has been increased by a factor of 3 for visibility.
Arcs: Spitzer observations during primary and secondary transits in different spectral bands.
The observer is watching from below.

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)





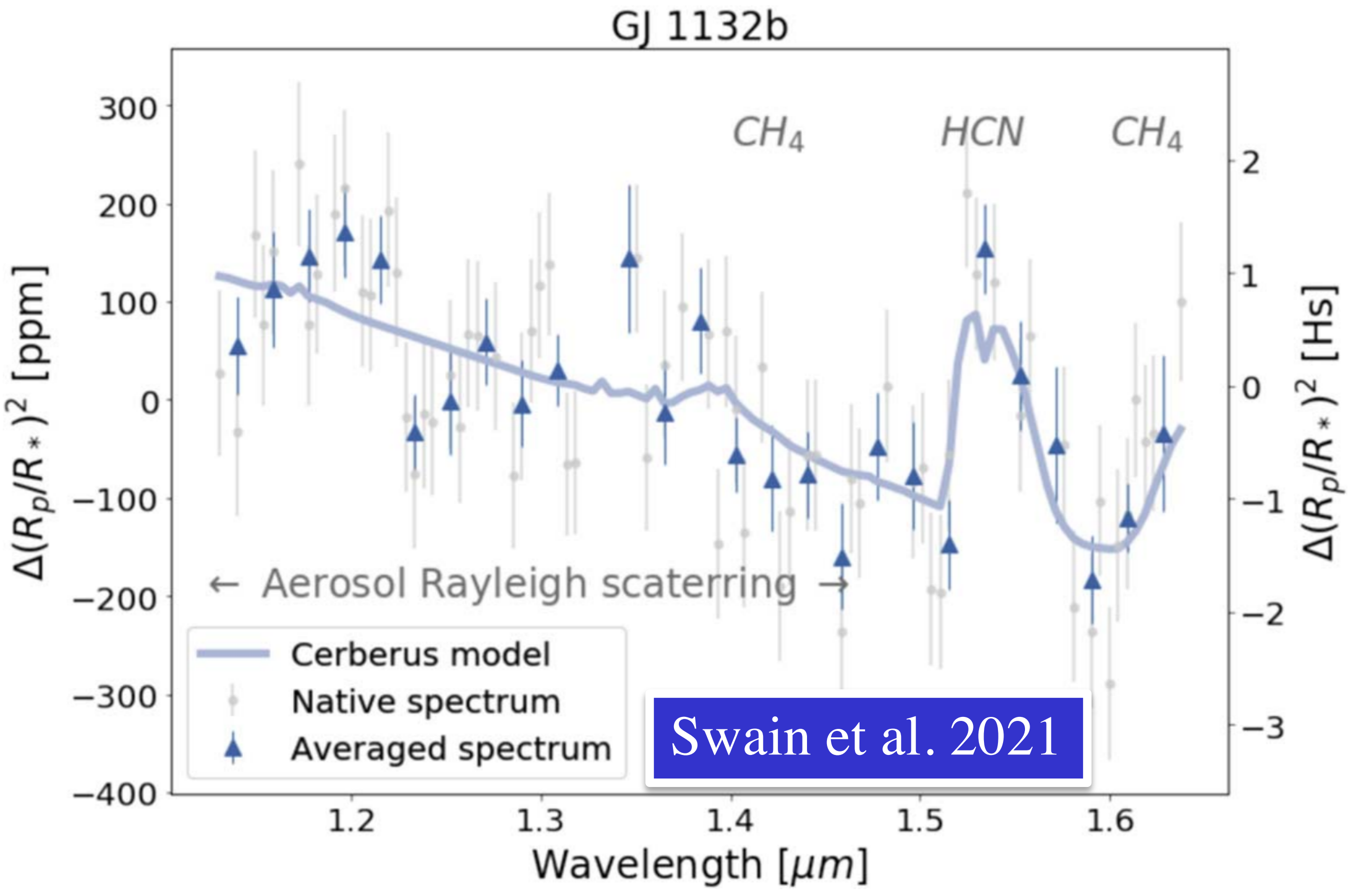
Disk: star. Black curve: planetary orbit. The spatial scale is given in AU. The stellar disk has been increased by a factor of 3 for visibility.
Arcs: Spitzer observations during primary and secondary transits in different spectral bands.
The observer is watching from below.

Spectroscopy of planetary atmospheres

Atmospheric spectrum of a rocky exoplanet using HST WFC3

GJ 1132 b (M=1.66 $M_{\oplus}$, R=1.16 $R_{\oplus}$, ρ =6.3 g/cm^3, P=1.6 days)

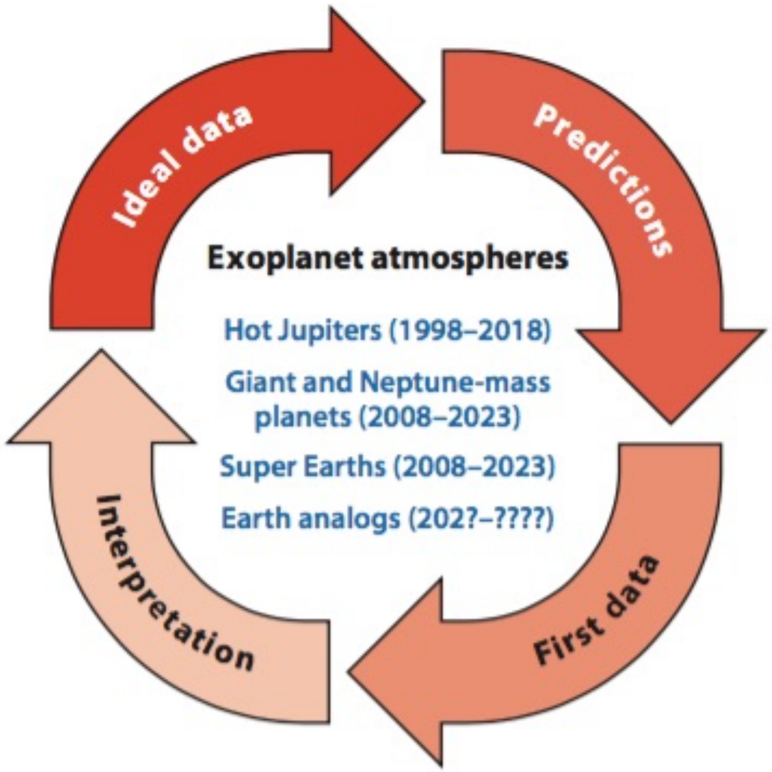
Rayleigh scattering, HCN, and CH_4 in a low mean molecular weight atmosphere



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)

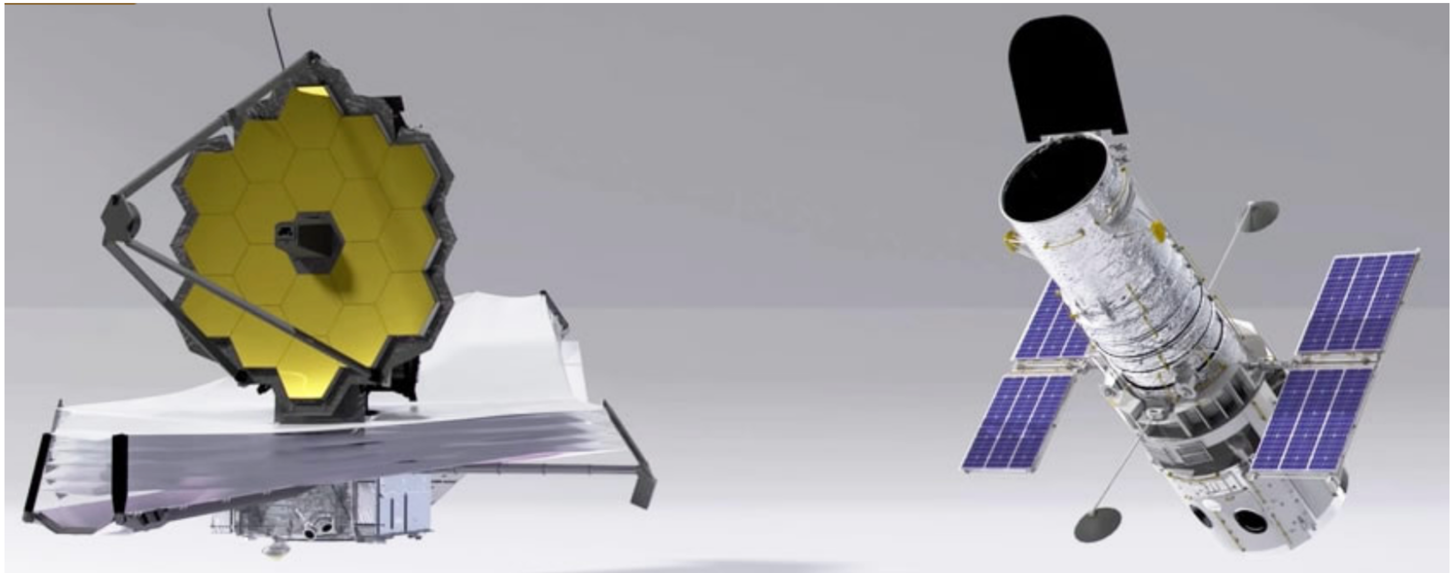
- Earth-like atmospheres are still beyond detection limit for the instrumental projects currently scheduled



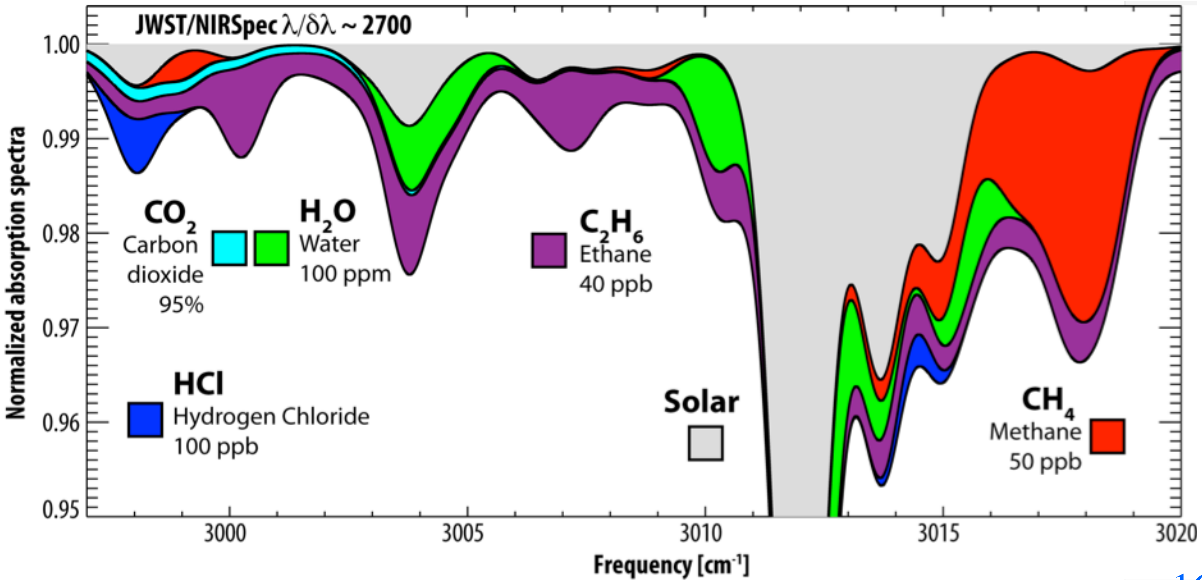
Future observations of planetary atmospheric spectra:
The James Webb telescope

Primary mirror diameter: ~ 6.5 m

Infrared range: 0.6 to 28 microns



The infrared sensitivity will allow Webb to search for trace amounts of organics in the extremely thin Martian atmosphere



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 [$\mathrm{Jm^{-2}\ s^{-1}\ Hz^{-1}}$], a beam of traveling photons; κ is the absorption coefficient [$\mathrm{m^{-1}}$], which includes both absorption and scattering out of the radiation beam; ε is the emission coefficient [$\mathrm{Jm^{-3}\ s^{-1}\ Hz^{-1}}$], 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

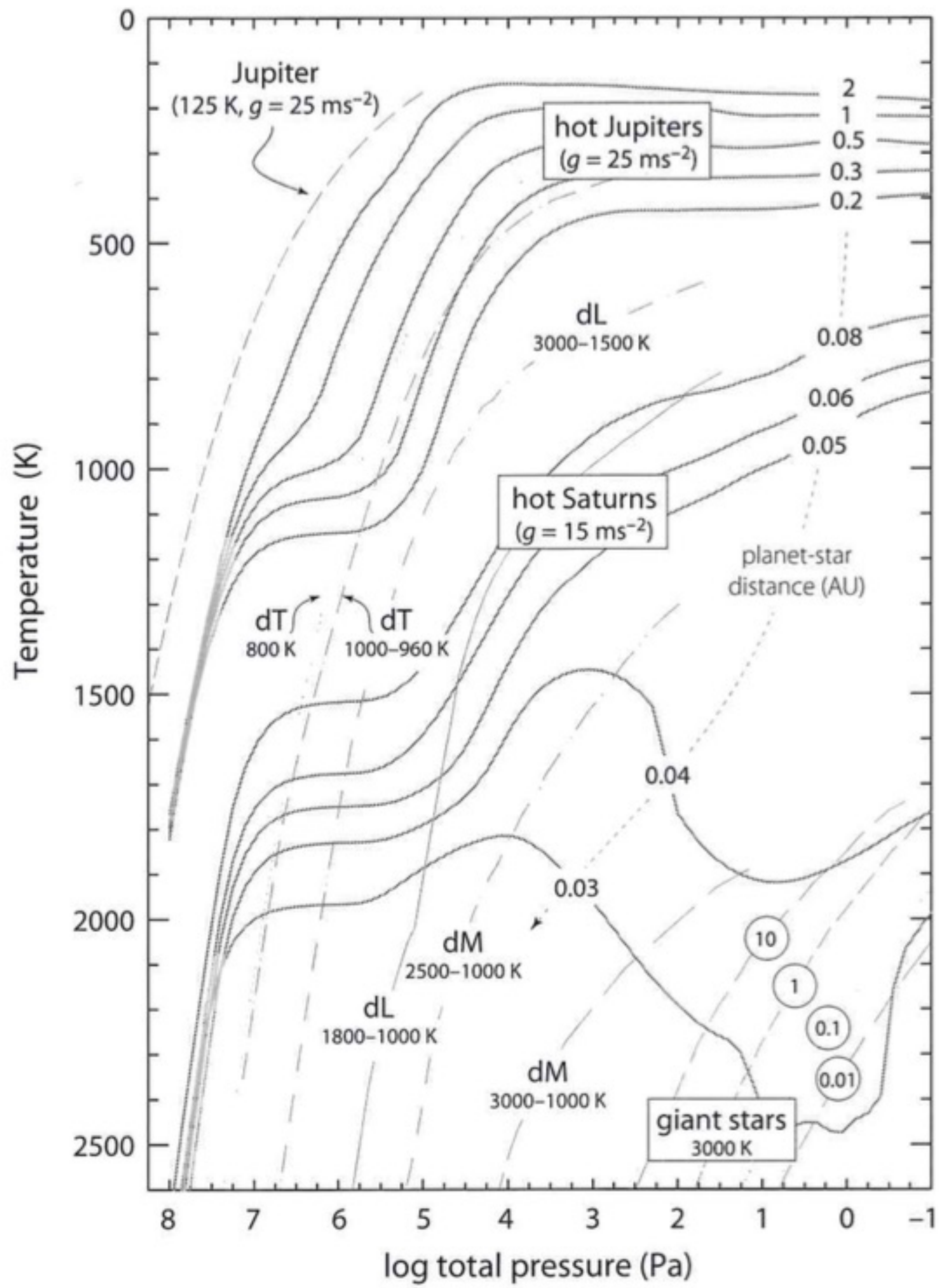
- Equilibrium chemistry
  - Network of chemical reactions taking place between atomic/molecular species, as a function of T, P and radiation

Pressure-temperature relations for model atmospheres

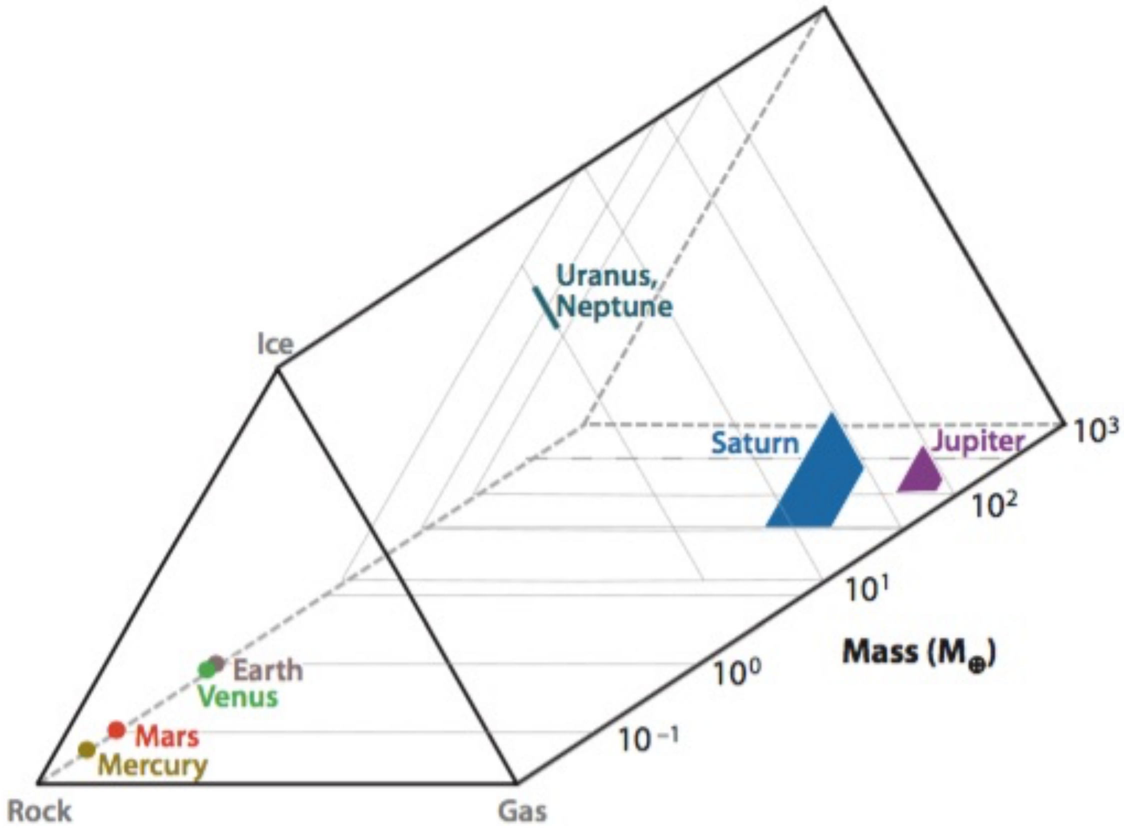
Thick lines: Jupiter- and Saturn-mass planets

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).

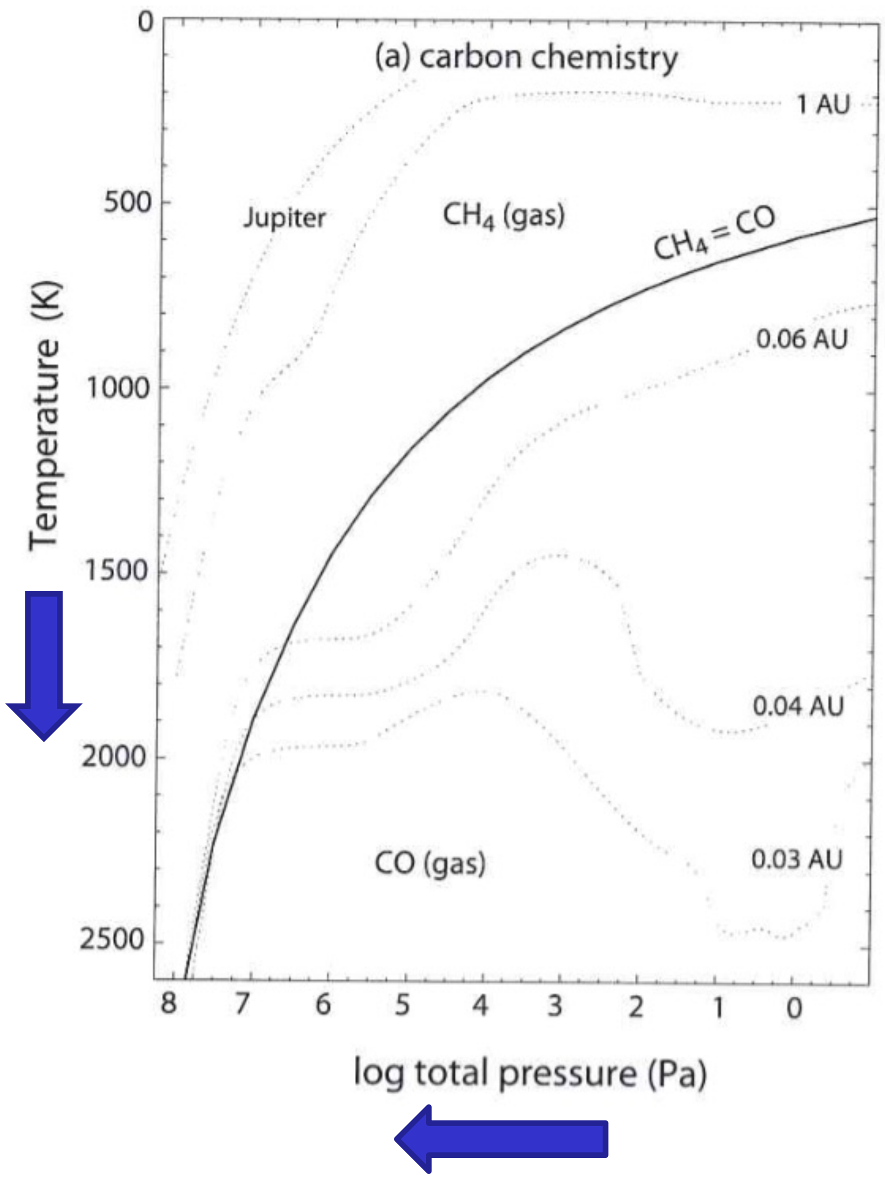
Equilibrium chemistry

- Example: carbon chemistry
  - The equilibrium distribution of C, over a large range of T and P, is controlled by the reaction between CO and CH_4

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O$$

  - 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, CH_4 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:

$$
\begin{aligned}
\mathrm{H_2} + h\nu\ (\lambda < 84.5\,\mathrm{nm}) &\rightarrow \mathrm{H} + \mathrm{H} \\
\mathrm{CH_4} + h\nu\ (\lambda < 145\,\mathrm{nm}) &\rightarrow \mathrm{CH_3} + \mathrm{H} \\
\mathrm{NH_3} + h\nu\ (\lambda < 230\,\mathrm{nm}) &\rightarrow \mathrm{NH_2} + \mathrm{H} \\
\mathrm{O_2} + h\nu\ (\lambda < 240\,\mathrm{nm}) &\rightarrow \mathrm{O} + \mathrm{O}
\end{aligned}
$$

The latter is the first step in the formation of O_3 (ozone) in the Earth's atmosphere

Models of high-resolution Transmission Spectra of Earth-like planets around FGKM host stars

Kaltenegger & Lin (2021)

- Modelling strengths of spectral features in transit that could indicate a biosphere similar to the modern Earth on exoplanets orbiting F0 to M8 stars

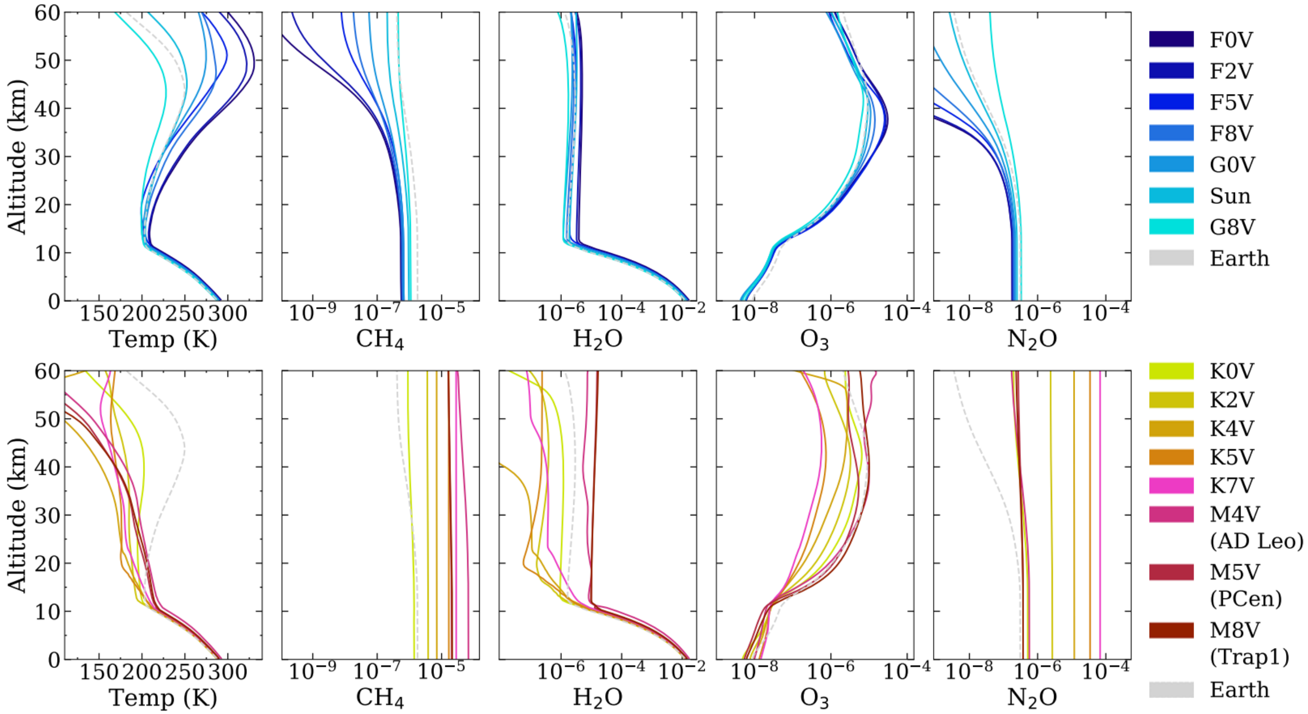


Figure 2. Temperature profile and mixing ratios for the major atmospheric gases for Earth-like planets around (top) F and G and (bottom) K and M grid host stars, with modern Earth radius, mass, pressure, and outgassing ratios (see Madden & Kaltenegger 2020a).

Models of high-resolution Transmission Spectra of Earth-like planets around FGKM host stars

Kaltenegger & Lin (2021)

- The atmospheric biosignature pairs O_2+CH_4 and O_3+CH_4—which identify Earth as a living planet—are most prominent for Sunlike and cooler host stars