Exoplanets
Characterization

Planets and Astrobiology (2022-2023)

Giovanni Vladilo & Paolo Simonetti

Exoplanets characterization

- Study of the physical properties of individual planets
  - Direct imaging can provide experimental data useful to characterize individual planets
  - When not available, the next best way is to combine data from different methods (e.g. transit + Doppler)
  - From this combination of experimental data, with the aid of modelization, we can derive information on
    - Planetary interiors
    - Planetary atmospheres
    - Planet-star interaction

Combination of different observational methods

- Doppler + transit methods
  - Combines the mass obtained from the Doppler method with the radius obtained with the transit method
  - The degeneration of the orbital inclination **sin i** is solved

  Method already applied to a large number of cases

- Doppler + astrometric methods
  - Given the minimum mass **M sin i** from the Doppler method, one can in principle estimate **sin i** with the astrometric method; in this way one can obtain the mass, rather than the minimum mass

  Currently limited due to the difficulty of astrometric observations

Estimate of planetary masses from Transit Timing Variations

Technique that can be applied to multiple planetary systems discovered with the transit method

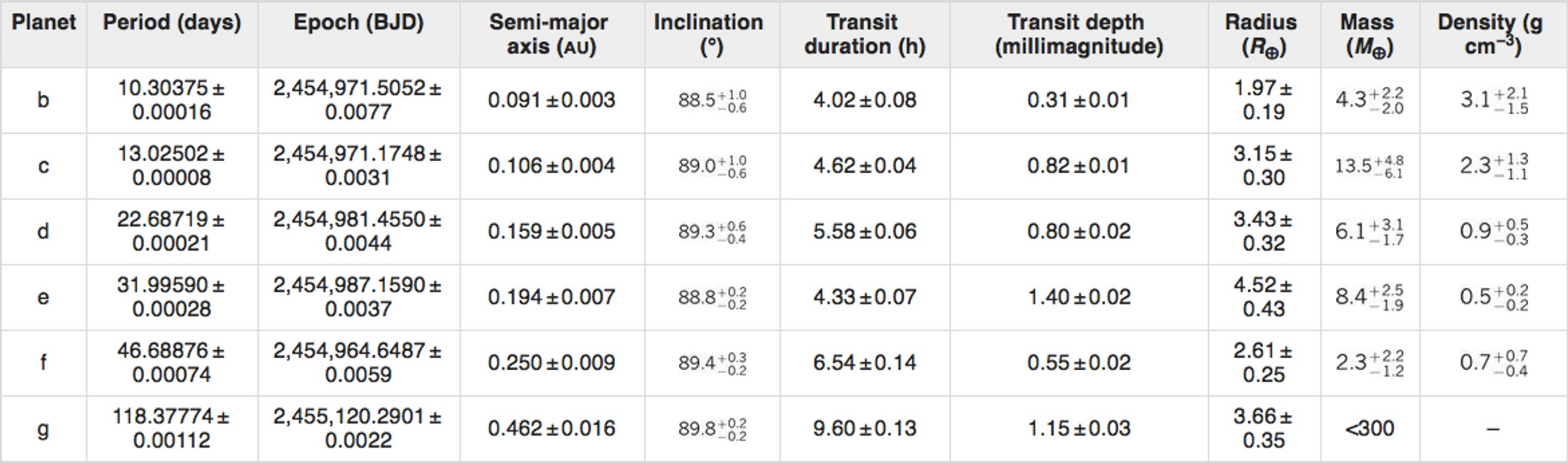
In a planetary system with many planets in nearby orbits, gravitational perturbations will induce small variations in the timing of the transits

- From a detailed analysis of the transit timings it is possible to deduce the mass of the planets, even without radial velocity observations

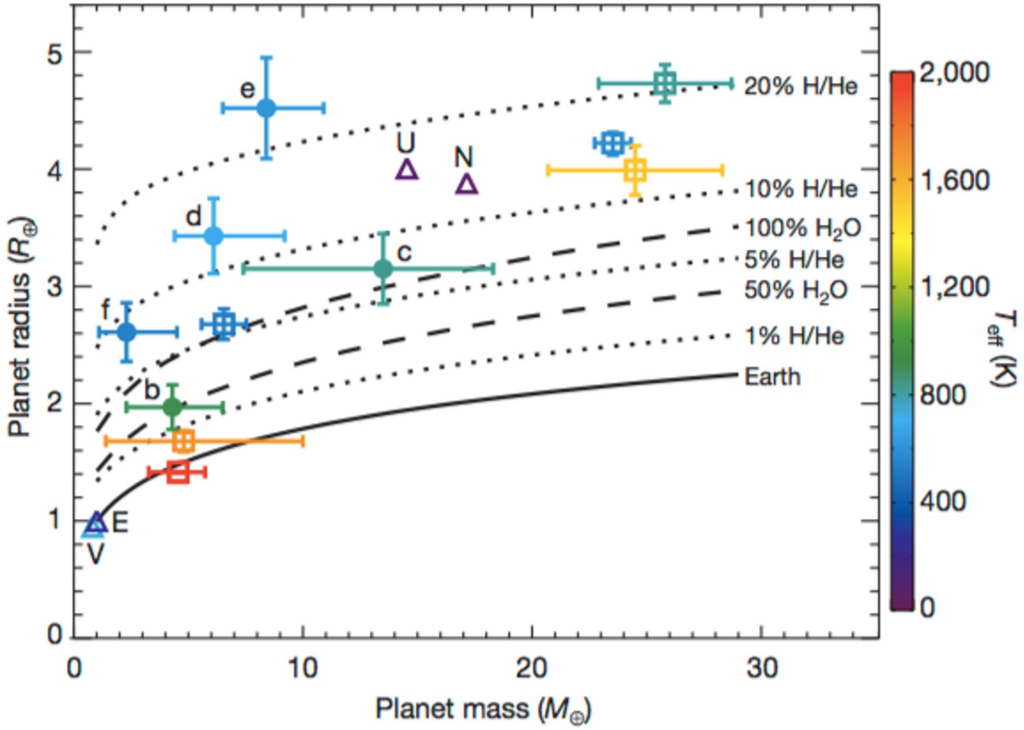
Examples:

- Kepler-11 (Lissauer et al. 2011)
- Trappist 1 (Gillon et al. 2017)

Kepler-11 (Lissauer et al. 2011)



Planet	Period (days)	Epoch (BJD)	Semi-major axis (AU)	Inclination (°)	Transit duration (h)	Transit depth (millimagnitude)	Radius ($R_\oplus$)	Mass ($M_\oplus$)	Density (g cm^{-3})
b	10.30375 ± 0.00016	2,454,971.5052 ± 0.0077	0.091 ± 0.003	$88.5^{+1.0}_{-0.6}$	4.02 ± 0.08	0.31 ± 0.01	1.97 ± 0.19	$4.3^{+2.2}_{-2.0}$	$3.1^{+2.1}_{-1.5}$
c	13.02502 ± 0.00008	2,454,971.1748 ± 0.0031	0.106 ± 0.004	$89.0^{+1.0}_{-0.6}$	4.62 ± 0.04	0.82 ± 0.01	3.15 ± 0.30	$13.5^{+4.8}_{-6.1}$	$2.3^{+1.3}_{-1.1}$
d	22.68719 ± 0.00021	2,454,981.4550 ± 0.0044	0.159 ± 0.005	$89.3^{+0.6}_{-0.4}$	5.58 ± 0.06	0.80 ± 0.02	3.43 ± 0.32	$6.1^{+3.1}_{-1.7}$	$0.9^{+0.5}_{-0.3}$
e	31.99590 ± 0.00028	2,454,987.1590 ± 0.0037	0.194 ± 0.007	$88.8^{+0.2}_{-0.2}$	4.33 ± 0.07	1.40 ± 0.02	4.52 ± 0.43	$8.4^{+2.5}_{-1.9}$	$0.5^{+0.2}_{-0.2}$
f	46.68876 ± 0.00074	2,454,964.6487 ± 0.0059	0.250 ± 0.009	$89.4^{+0.3}_{-0.2}$	6.54 ± 0.14	0.55 ± 0.02	2.61 ± 0.25	$2.3^{+2.2}_{-1.2}$	$0.7^{+0.7}_{-0.4}$
g	118.37774 ± 0.00112	2,455,120.2901 ± 0.0022	0.462 ± 0.016	$89.8^{+0.2}_{-0.2}$	9.60 ± 0.13	1.15 ± 0.03	3.66 ± 0.35	<300	–



Planets with measurements of masses and radii

- From mass and radius measurement we obtain

- mean density $\varrho \sim M/R^3$

  Casts light on the internal structure/composition of the planet

- surface gravity $g \sim M/R^2$

  Important for the modelization of the atmosphere and climate

- escape velocity $v_\mathrm{e} \sim (M/R)^{1/2}$

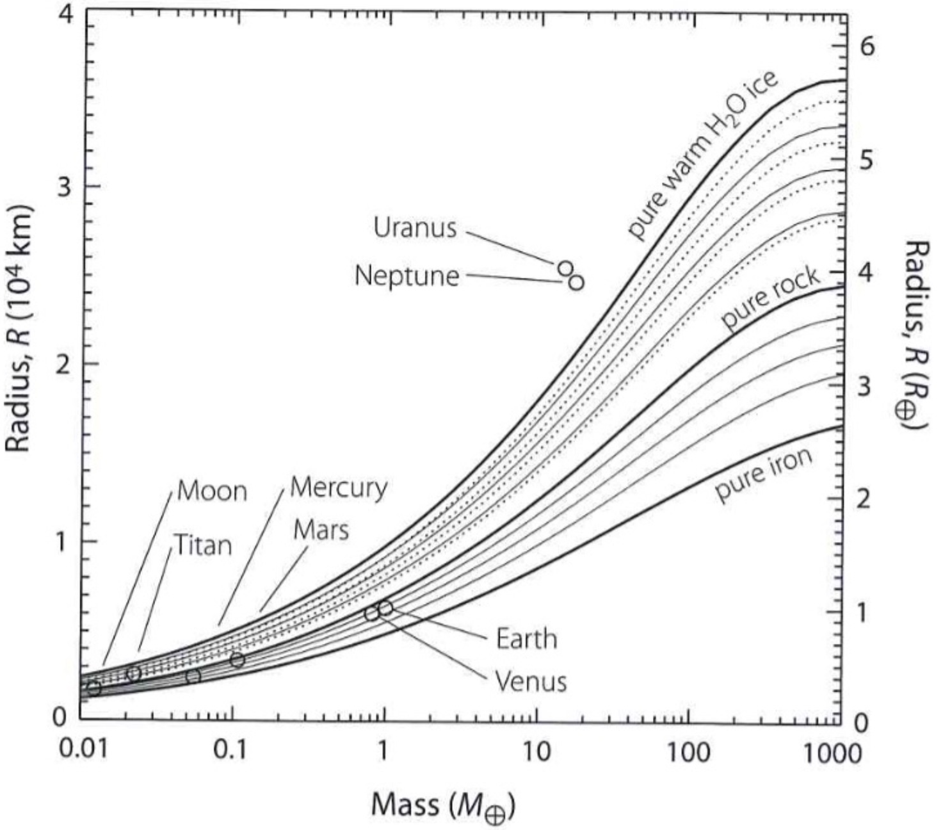
  Indicates the capacity for the planet to maintain an atmosphere

Mass versus radius:
theoretical relations for planets of low mass

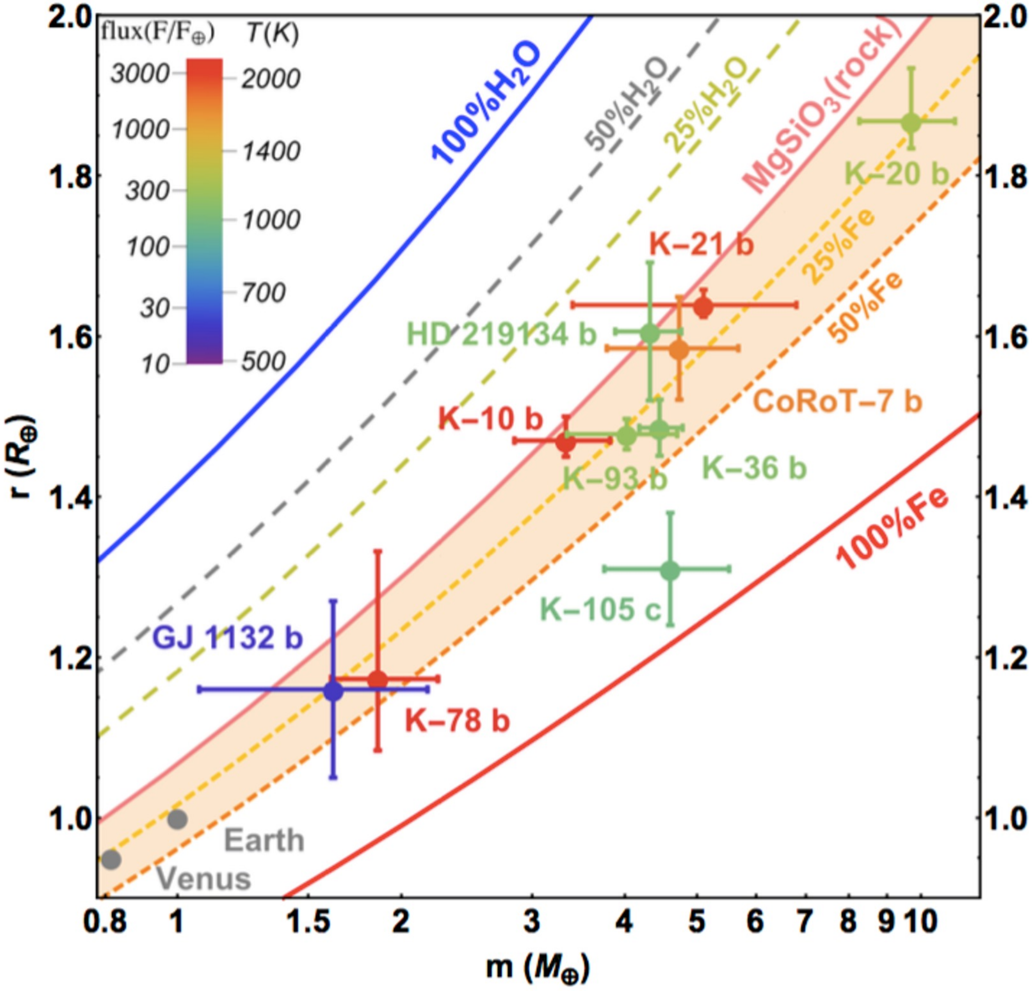
Mass versus radius for planets composed of H_2O ice, rock (Mg_2SiO_4), and iron

Thin curves are calculated for different values of fractional composition and different temperatures

From Fortney et al. 2007)



Zeng et al. (2017)



Mass-radius plots showing selected rocky planets

Curves show models with different compositions

Planets are color coded according to their incident stellar flux

Ocean planets

The large variety of exoplanet properties suggests that planets with masses in the range between Earths and super-Earths may have bulk composition dominated by volatiles such as H_2O ice, rather than rocky material

Such objects, called ocean planets, could form at large orbital distances, beyond the snow line

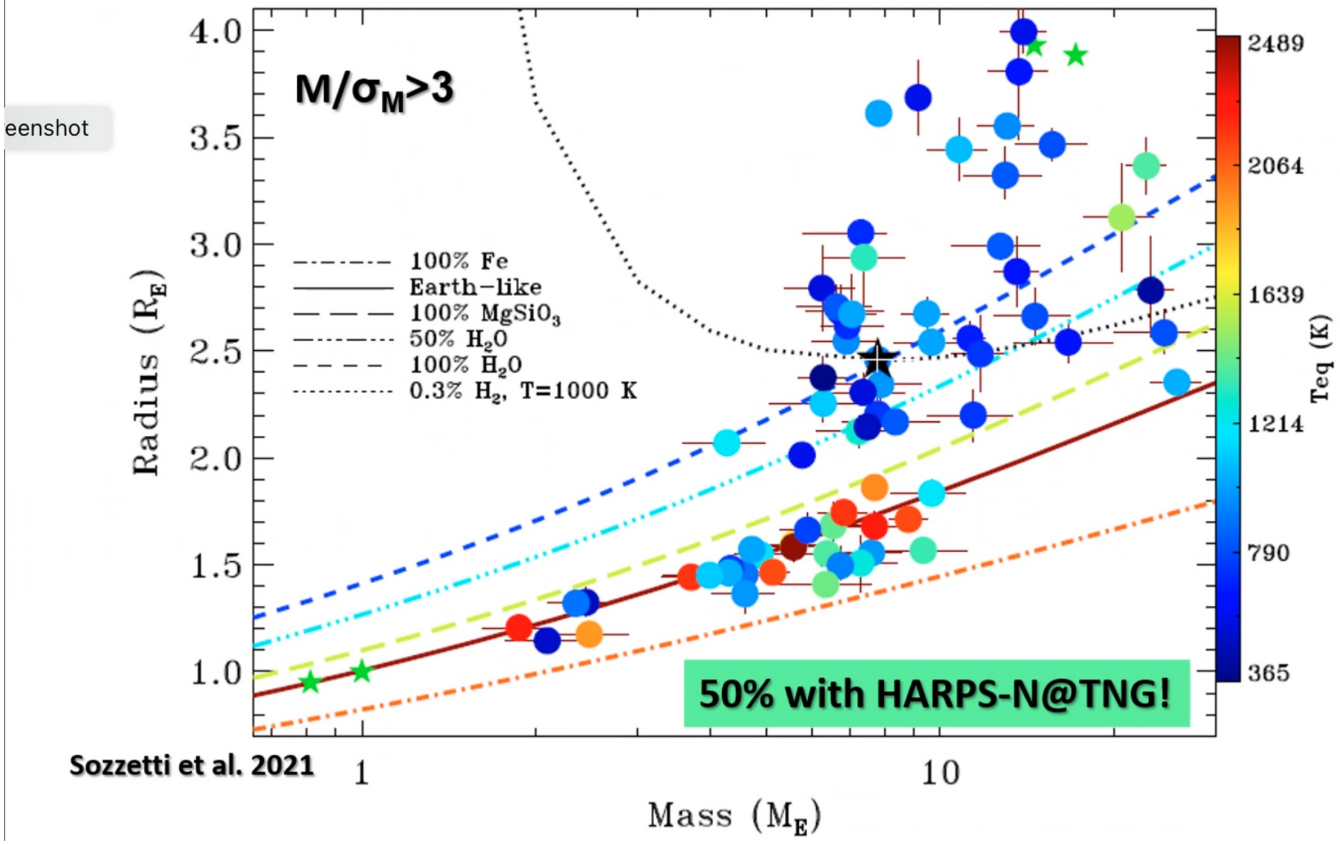
In the range 1- 10 Earth masses they are not expected to accumulate a large H/He envelope (at variance with icy/gaseous giants of the Solar System)

A fraction of such planets could have migrated inwards, in a region where water can be in liquid phase, leading to the existence of "water worlds"

Candidate ocean planet:

example: GJ 1214 b (d=13 pc, M=6.6$M_\oplus$, R=2.7$R_\oplus$, ϱ=1.9 g cm^{-3})

M-R Relation: Small Planets



$M/\sigma_M>3$

50% with HARPS-N@TNG!

Sozzetti et al. 2021

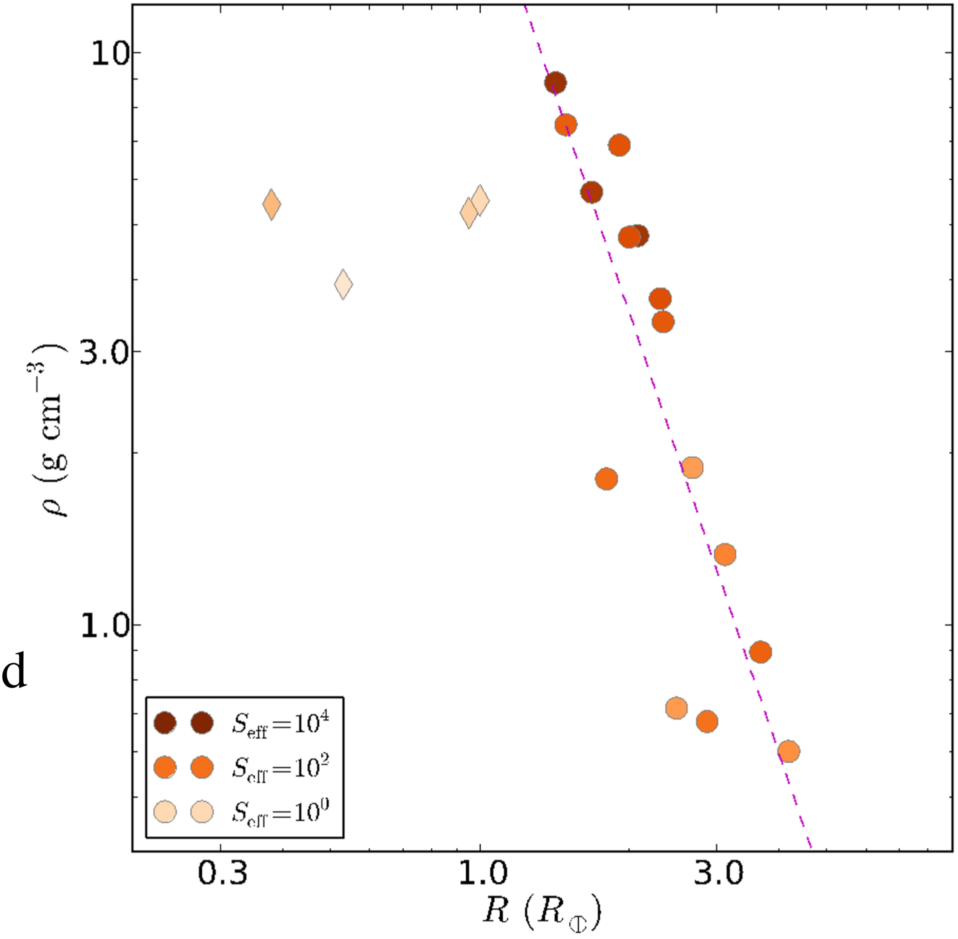
Mass-radius plots showing selected rocky planets
Curves show models with different compositions
Planets are color coded according to their equilibrium temperature

Mean density versus radius and insolation

Sample of planets with
$M < 10$ Earth masses
and reliable measurements of M and R

Circles: exoplanets
Diamonds: Solar System planets
Color coding: insolation

- The uncorrected mean density decreases with increasing planet size (dashed line)
- The level of insolation tends to decrease with decreasing density
  - This implies that the insolation plays an important role in the process of planetary accretion
  - Possible interpretation: at high level of insolation only dense, refractory material is accumulated



Mean density versus radius and insolation

Sample of planets with $M < 10$ Earth masses and reliable measurements of M and R

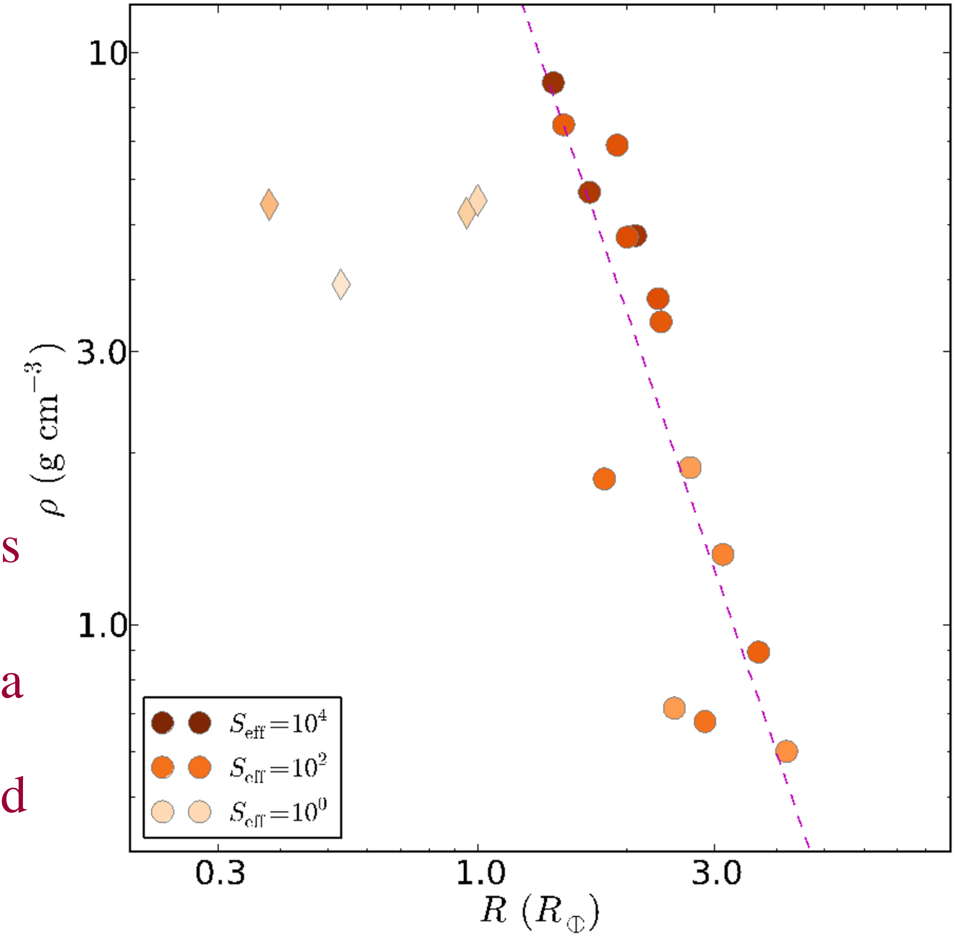
Circles: exoplanets

Diamonds: Solar System planets

Color coding: insolation

- Solar System planets do not follow the experimental trend observed in exoplanets
- At a given density and radius, their level of insolation is much lower
- Current samples of exoplanets are not representative of Solar System conditions, even when we consider planets with similar radii and densities

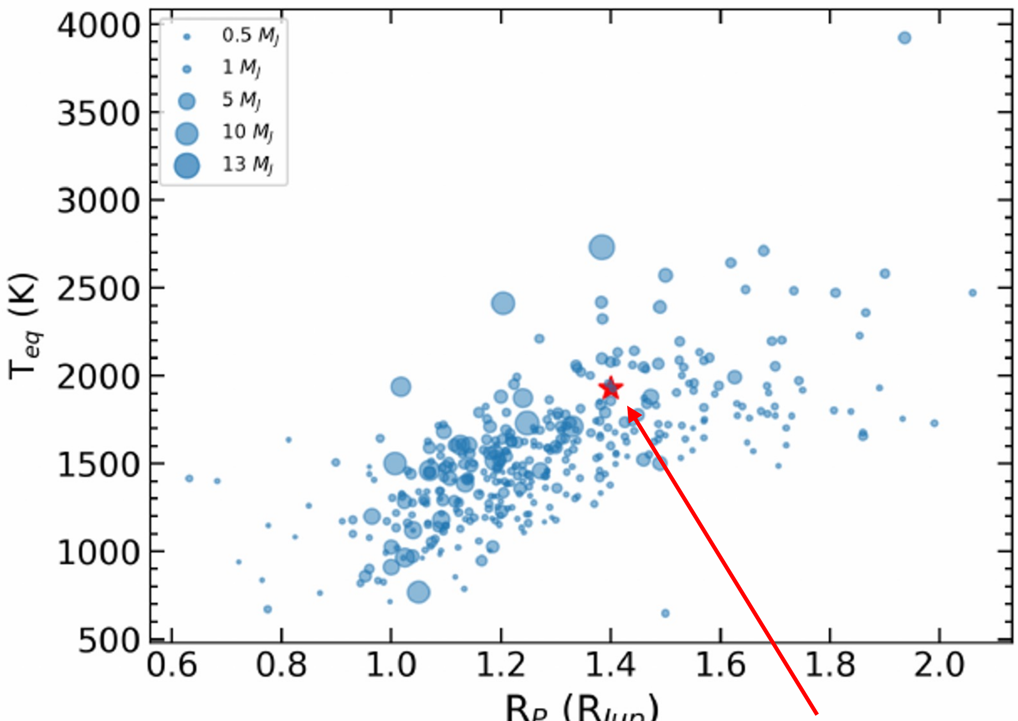
- This situation will change when data of terrestrial-type planets with lower level of insolation will be accumulated



Radius vs insolation: Hot Jupiters

- Maximum expected radius of a non-young Jupiter-type planet: 1.1 R_J
- Tens of planets known with considerably larger radii
- Simple irradiation from the star cannot explain their size: a mechanism efficiently heating up their interiors is needed
- Possible mechanisms: tides excited by the star (Bodenheimer et al. 2001), kinetic heating (Guillot & Showman 2002), <u>ohmic dissipation</u> (Batygin & Stevenson 2010)

Khandelwal et al. (2021)

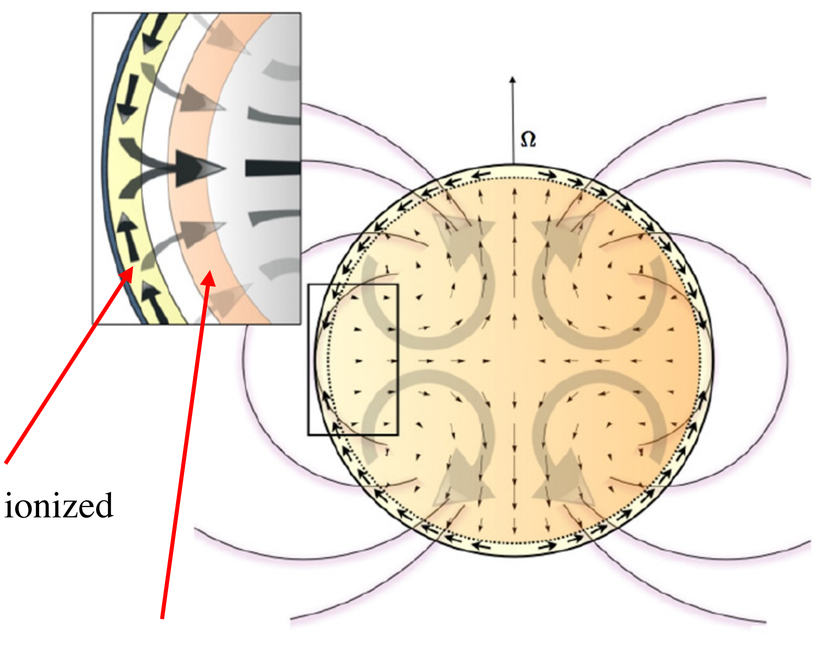


TOI-1709b

Radius vs insolation: Hot Jupiters

Ohmic dissipation:

- Metals in the Hot Jupiters atmospheres are partially ionized
- Hot Jupiters are (most probably) tidally locked: very strong winds (~ km s^{-1}) redistributing heat
- Induction of currents in the outer mantle of the planet, whose dissipation releases heat
- Characteristic efficiency profile with a decrease at very high temperatures (above 2200 K) due to the winds being braked by the planetary magnetic field



Partially ionized winds

Region into which energy is transferred (via induced currents)

Exoplanet characterization:
observations of radiation emitted by the planet

- The faint radiation emitted by planets has two contributions
  - Intrinsic thermal emission

    The study of the thermal emission is carried out in the infrared band

    Provides direct information on the planet surface temperature and the atmospheric properties of the outer layers
  - Reflected stellar radiation

    The study of the stellar light reflected by the planet is carried out in the visible band

    Provides information on the albedo properties of the outer layers

Exoplanet characterization: observations of planet radiation

- Methods to measure the exoplanet radiation
  - Direct imaging

    If the image of the planet is solved, the thermal emission can be directly measured

    In this case, however, the planet-star separation will be quite high and, as a result, the stellar light reflected by the planet cannot be measured

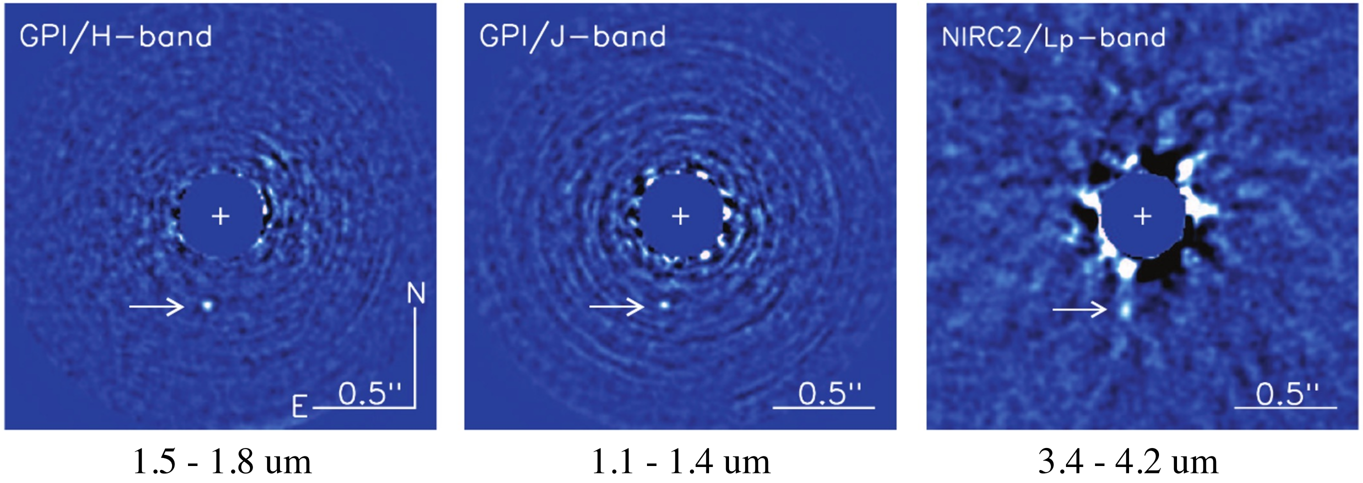
  - Secondary transits

    By studying the light curve at the epoch in which the planet is hidden by the star ("secondary transit")

Exoplanet characterization: observations of planet radiation

Direct imaging

- Opportunity to retrieve low-resolution spectra by observing a planet in different bands
- These spectra can then be fitted to directly obtain the effective temperature of the planet
- Currently possible only with young Jupiter-like planets
- The large orbital distances prevent observations of non-self-luminous (due to formation heat) objects



1.5 - 1.8 um

1.1 - 1.4 um

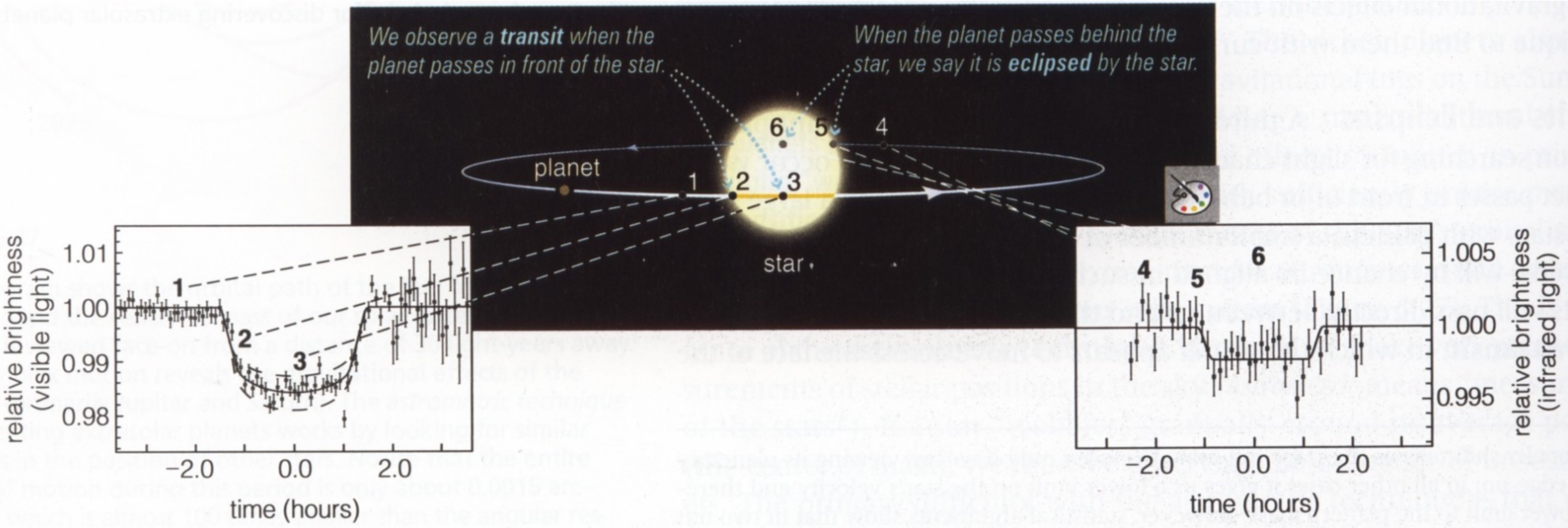
3.4 - 4.2 um

51 Eridani b (Macintosh et al. 2015)

Secondary transits

- Transit of the planet behind the star (the planet is eclipsed by the star)

  With a proper geometric configuration of the orbits



Secondary transits

Light curve of the secondary transit

- Out of the transit: we observe the sum of the stellar+planetary emission
- During the transit: we only observe the stellar light, as a result there is a small dip in the light curve

Importance of the secondary transit

- The difference of the fluxes during and out of the transit provides a direct measurement of the planetary emission
- The effect is stronger in the infrared and allows us to study the infrared emission of the planet
- In the Rayleigh-Jeans limit, valid at long wavelengths, the emission scales linearly with T, and the depth of the secondary eclipse is given by

$$\Delta F \simeq \frac{T_p}{T_\star}\left(\frac{R_p}{R_\star}\right)^2$$

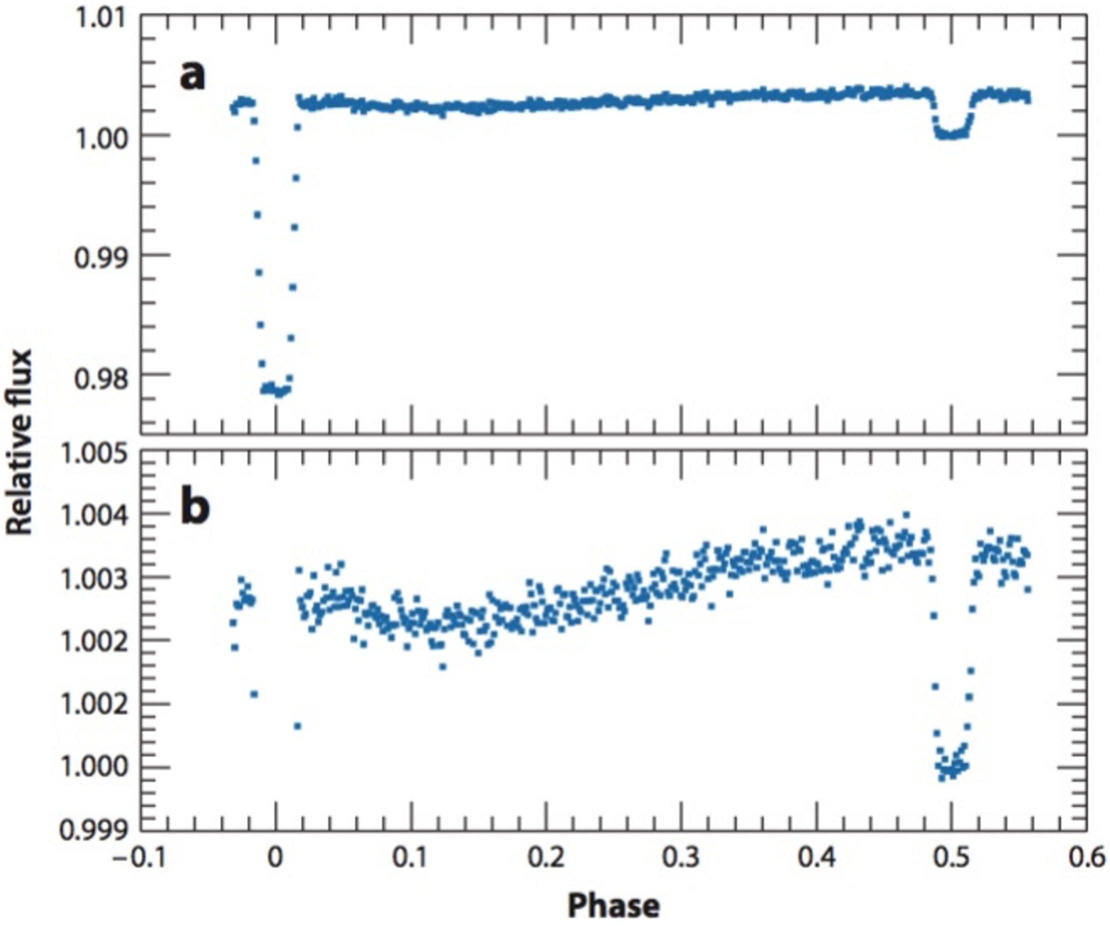
Secondary transits

Example:

Infrared light curve of HD 189733Ab (K1-K2 star at 19 pc, M_p=1.15 M_J, a=0.03 AU)

The first dip (left) is the transit and the second dip the secondary eclipse

Bottom panel: a zoom of the top panel



Surface temperature distribution of tidally-locked Hot Jupiters

- For transiting Hot Jupiters the light curves of primary and secondary transits can be combined to derive information on the light emitted by the planet at different orbital phases

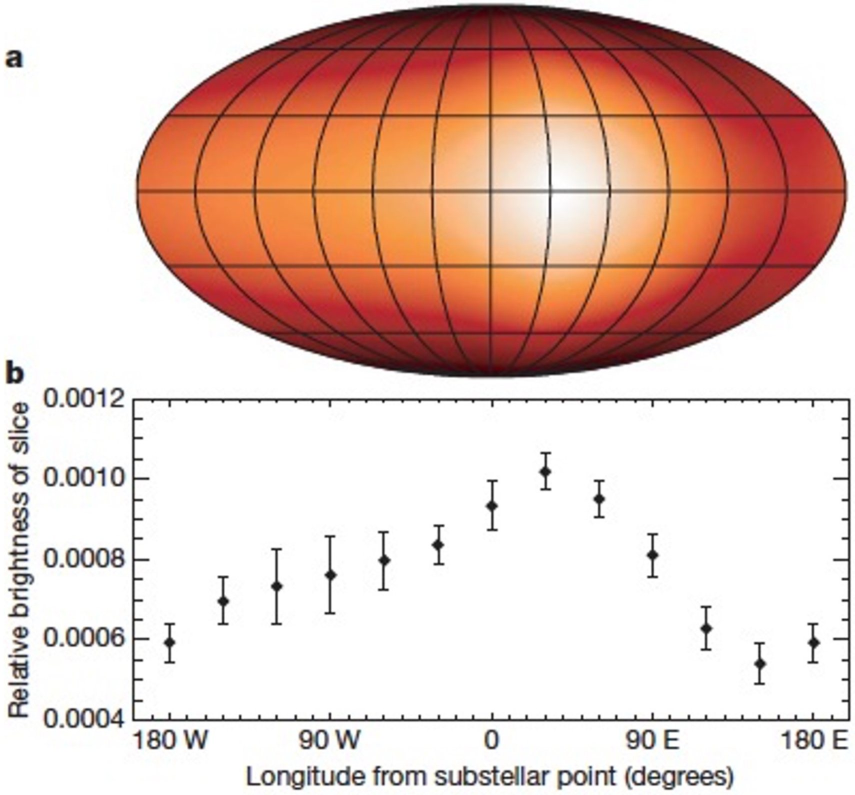
- Assuming that the planet is tidally locked, the orbital phase can be converted in phase of planetary rotation

- In this way it is possible to reconstruct the surface emissivity as a function of planet longitude

1-bar temperature distribution of tidally-locked Hot Jupiters

Example:

- HD 189733b observed in the IR with Spitzer-IRAC (Knutson et al. 2007)
- The longitudinal variation of the surface temperature is not very high, in spite of the tidal locking
- The relatively small temperature variation suggests the existence of an efficient mechanism of heat diffusion along the planet surface
- There is an offset between the sub-stellar point and the longitude of maximum temperature



Interaction between planet and star

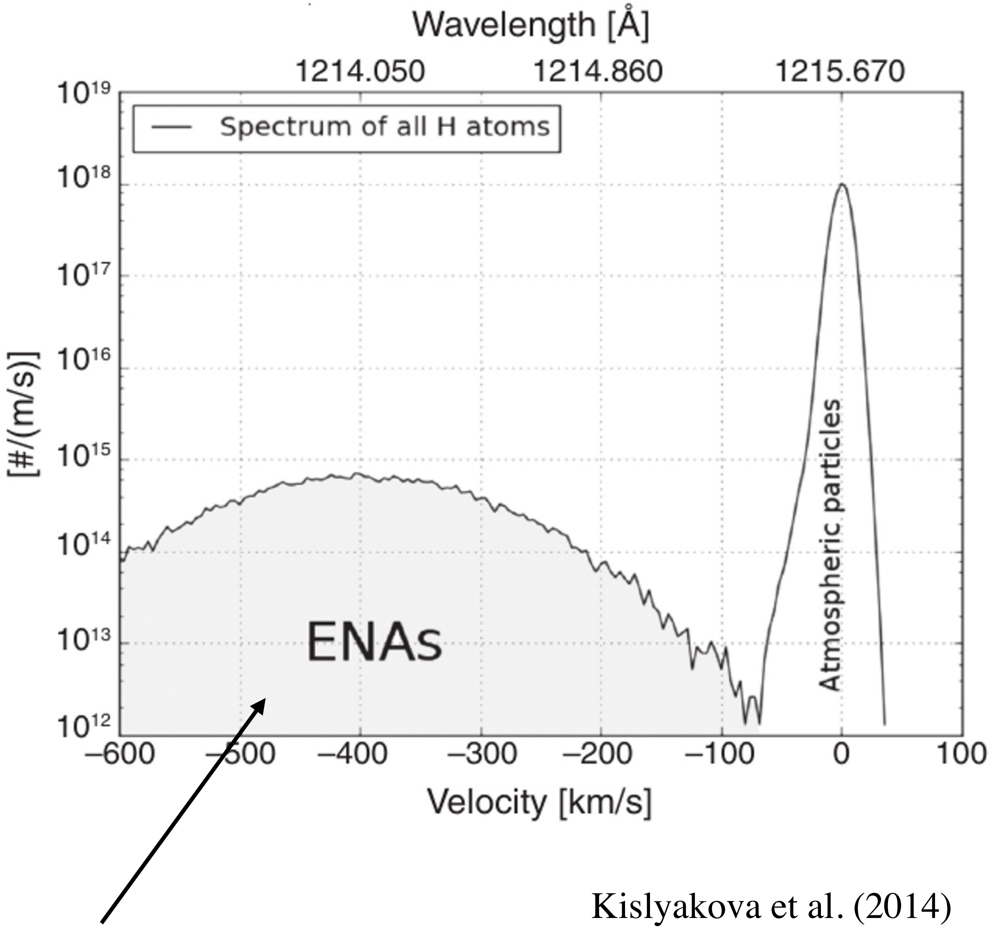
Detection of atoms from the planet's atmosphere accelerated away towards us along the line of sight

Possible production mechanisms:

- acceleration via radiation pressure
- charge exchange processes due to wind-magnetosphere-atmosphere interaction

If the second mechanism dominates, then it is possible to infer the planetary magnetic moment (in this case, ~1/10 that of Jupiter)

HD209458b



Kislyakova et al. (2014)

Energetic Neutral Atoms (mainly H)

Interaction between planet and star

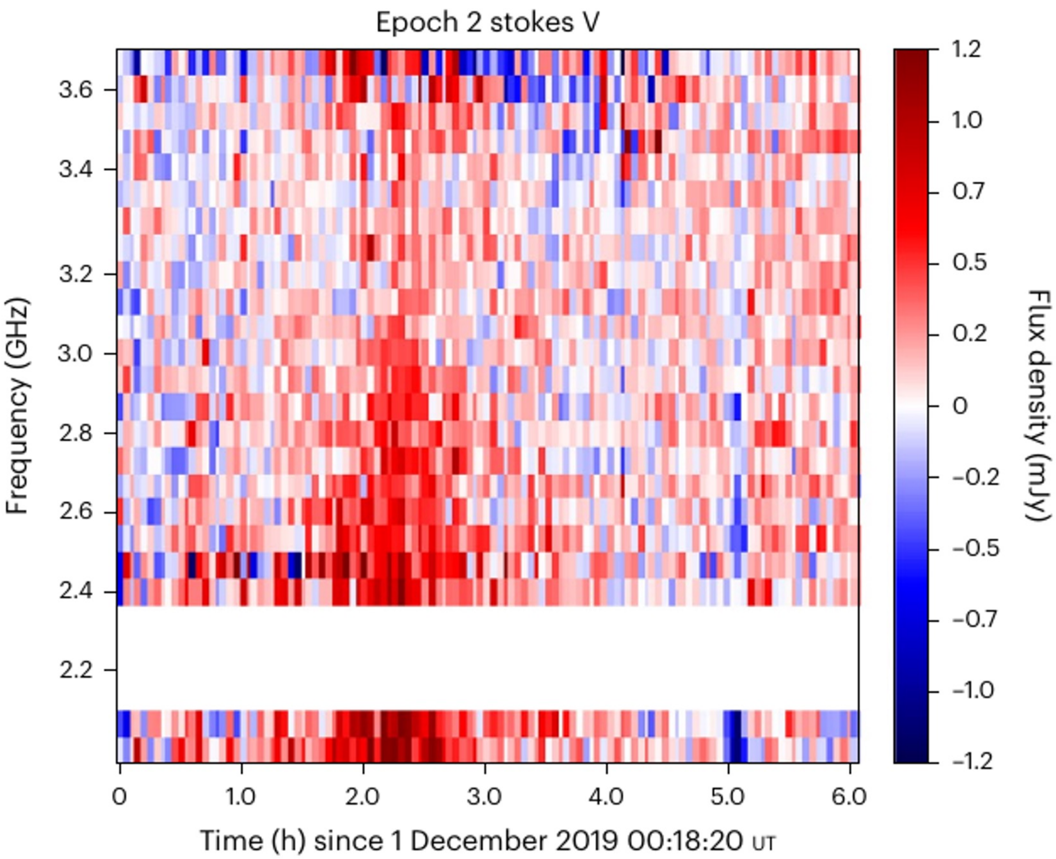
Possible explanations:

- non-planetary: the burst has been produced by the star (which is an M-dwarf, albeit slowly rotating)
- planetary: produced by the impact of plasma on the planetary magnetosphere

The planet origin is suggested by the recurrence of the event at similar (but not equal) orbital phase

If confirmed, it will be possible to estimate the planetary magnetic field from the event luminosity

Polarized and coherent radio burst from YZ Ceti b



Pineda et al. (2023)