Exoplanets
Introduction and classification

Planets and Astrobiology (2022-2023)

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What is an exoplanet?

As per the International Astronomical Union (IAU), an exoplanet must:

1. orbit a star other than the Sun, a brown dwarf or a stellar remnant (neutron star, white dwarf…) → location condition

1. have a mass below the limit for thermonuclear fusion of deuterium (D)
→ upper mass limit

1. be sufficiently massive to be considered a planet if were in our Solar System
→ lower mass limit

1. have a mass ratio with the central object of the system that allows for the existence of L4/L5 Lagrangian points → relation with the central body

https://www.iau.org/science/scientific_bodies/commissions/F2/info/documents/

Upper mass limit

Higher mass objects have more favorable conditions for nuclear reactions:

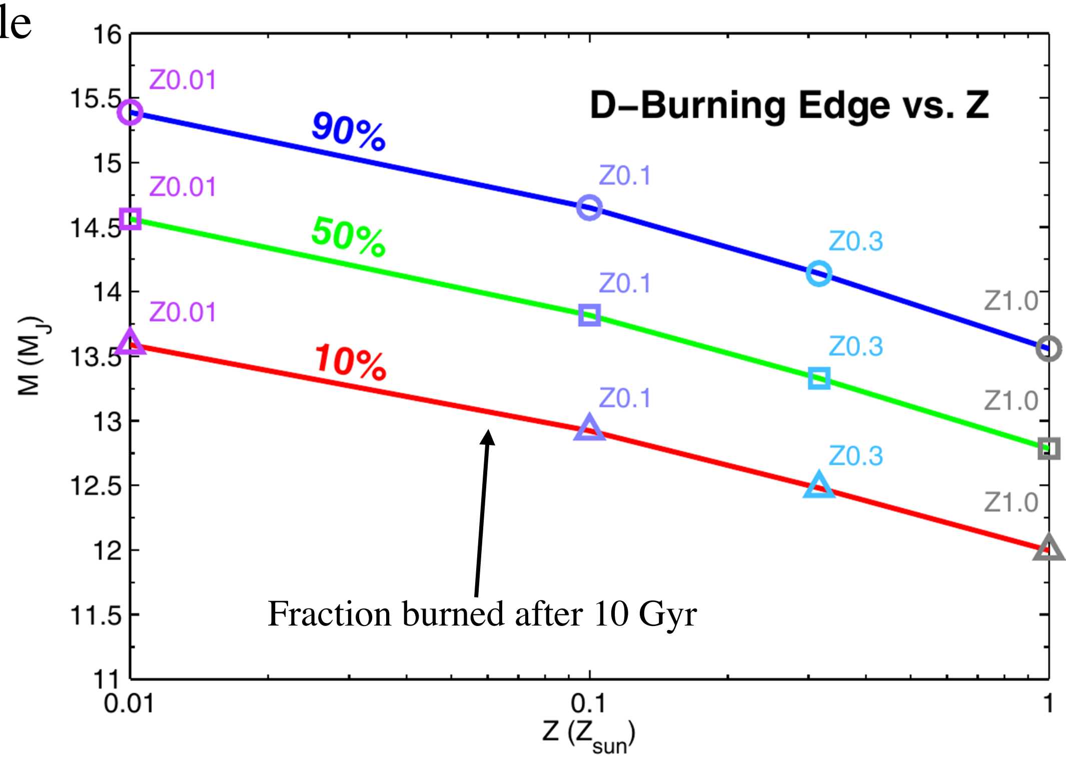
1. diffuse (i.e. non-rocky) cores
1. higher densities and formation temperatures

⇒ burned D fraction is a continuous function of the planet's mass

It also depends on the planet metallicity (higher metallicity ⇒ higher burned fraction at equal mass)

50% burned D @ solar metallicity: 13 M_J or 4200 M_E (widest used reference value)

1 M_J = 317 M_E



Spiegel+ 2011ApJ..727..57

Lower mass limit (I)

First condition to be a Solar System planet: self-gravity must be able to overcome internal rigid forces ⇒ hydrostatic equilibrium (i.e. the object must have a round shape)

Lower limit from known objects: ~10-4 M_E (Ceres)

Second condition to be a Solar System planet: must have cleared its orbital region from minor bodies (asteroids…)

Not straightforward! What means “cleared”? What is the width of the “orbital region”?

Possible definition based on diffusion time of the minor bodies orbital energies (Tremaine 1993..ASPCS..36..335)

Diffusion coefficient: root mean square change of energy per orbit

Diffusion time: time required to change the energy of an amount equal to itself

Lower mass limit (II)

Hill Sphere: region in which the planet gravity is higher than the star gravity

$$R_{\mathrm{H}} = \left(\frac{M_{\mathrm{p}}}{3M_{\star}}\right)^{1/3} a_{\mathrm{p}}$$

Feeding Zone: region from which the planet accretes material during formation in Hill radii ($C=2\sqrt{3}\,R_H$)

Time to clear the Feeding Zone:

$$t_{\mathrm{clear}} = C^2 1.1 \times 10^5 \text{ years} \left(\frac{M_{\star}}{M_{\odot}}\right)^{5/6} \left(\frac{M_{\mathrm{p}}}{M_{\oplus}}\right)^{-4/3} \left(\frac{a_{\mathrm{p}}}{1 \text{ au}}\right)^{3/2}$$

Mass to clear the Feeding Zone in a stellar lifetime:

$$t_{\mathrm{MS}}/t_{\odot} \propto (M_{\star}/M_{\odot})^{-2.5}$$

$$\frac{M_{\mathrm{p}}}{M_{\oplus}} \gtrsim 1.9 \times 10^{-4} C^{3/2} \left(\frac{M_{\star}}{M_{\odot}}\right)^{5/2} \left(\frac{a_{\mathrm{p}}}{1 \text{ au}}\right)^{9/8}$$

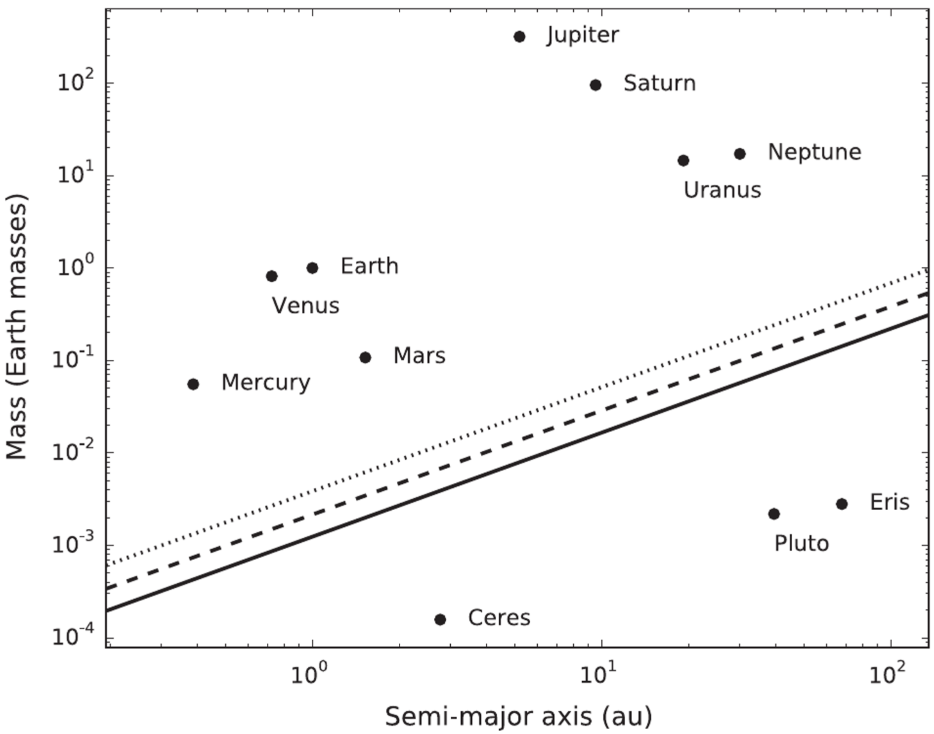
$M_{\star}$= star mass; M_p= planet mass; a_p= planet semi-major axis;
t_{MS}= time in Main Sequence

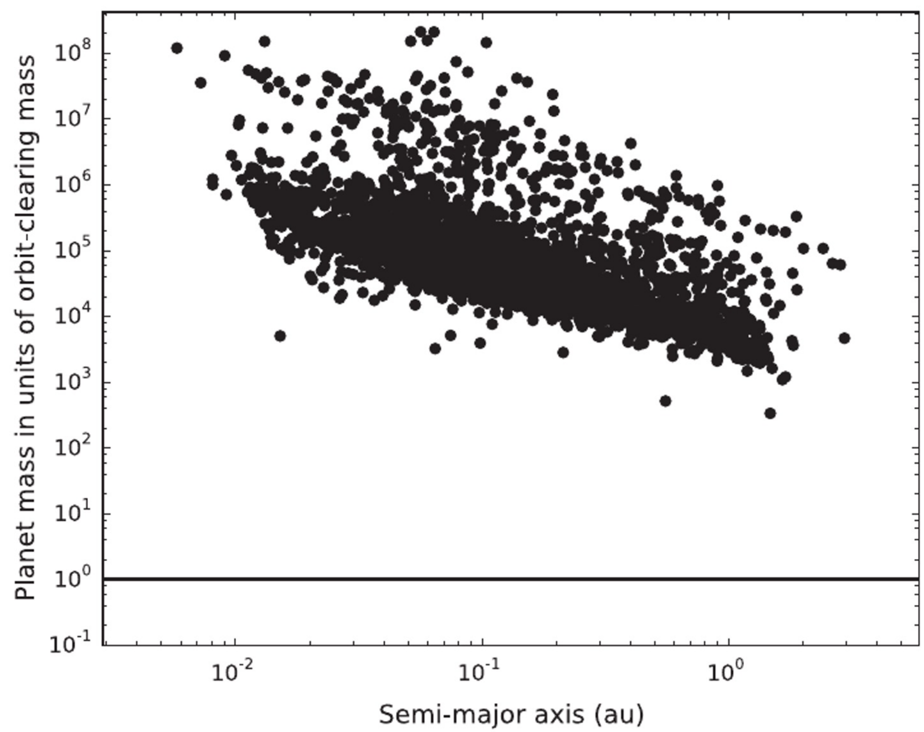
Lower mass limit (III)

Left: minimum mass criterion applied to the Solar System

Right: minimum mass criterion applied to the Kepler exoplanets population

Rule-of-thumb: 0.1 ME





dotted: C=5, t_clear=4.6 Gyr **solid:** C=2√3, t_clear=10 Gyr
dashed: C=5, t_clear=10 Gyr

Margot 2015AJ..150..185

L4/L5 Lagrange Points

L4/L5 at the vertices of equilateral triangles built on the m_1m_2 segment

An object in that position is in orbit around the m_1m_2 system barycentre

Condition of stability:

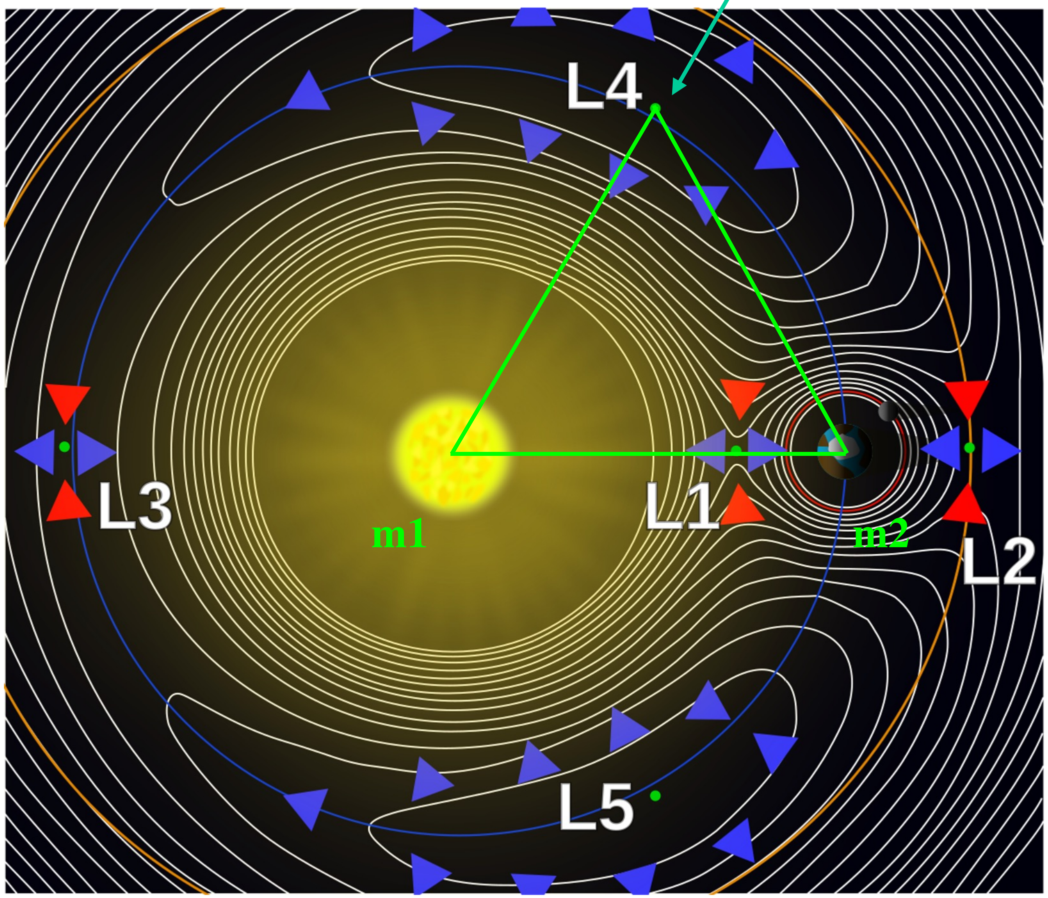
$27(m_1m_2 + m_2m_3 + m_1m_3) < (m_1 + m_2 + m_3)^2$

If $m3 \rightarrow 0$:

$m_1^2 - 25m_1m_2 + m_2^2 > 0$

$m_1/m_2 > (25+\sqrt{621})/2 \sim 24.96$

Object with mass m3 here



Least massive stars: ~80 MJ ⇒ mass limit to be a planet there: ~3 MJ

Other definitions of (exo)planet

The IAU definition notably excludes exoplanets which are not gravitationally bound to a star or stellar remnant (generally called rogue planets)

1. Formation pathway: Sahlmann+ 2011 (IAU Symposium) identified a change in the shape of the Initial Mass Function of substellar bodies at around 20-40 M_J ⇒ different formation pathways for stars /high mass brown dwarfs and planets ?

1. Internal structure: above ~1 M_J the body interiors is supported mainly by electron degeneracy instead of Coulombian repulsion, below ~10^{-4} M_E the body is not well-differentiated

1. Formation location: a planet is something that formed from a protoplanetary disk (regardless of its mass and *current* location)

for a discussion see e.g. Basri & Brown 2006..AREPS..34..193

Exoplanet classification

Exoplanets usually classified by mass and equilibrium temperature in analogy with Solar System planets (not formally defined but widespread in literature)

Classification by mass:

- Earths and Super-Earths: < 8 MT
- Mini-Neptunes and Neptunes: 8-40 MT
- Saturns: 40-120 MT
- Jupiters: > 120 MT (> 0.4 MJ)

Classification by temperature:

- Cold/Icy: < 180 K
- Cool/temperate: 180-350 K
- Warm: 350-1000 K
- Hot: 1000-2200 K
- Ultra-hot: 2200 K

From Super-Earths to Neptunes

Mass-radius relation for low-mass exoplanets:

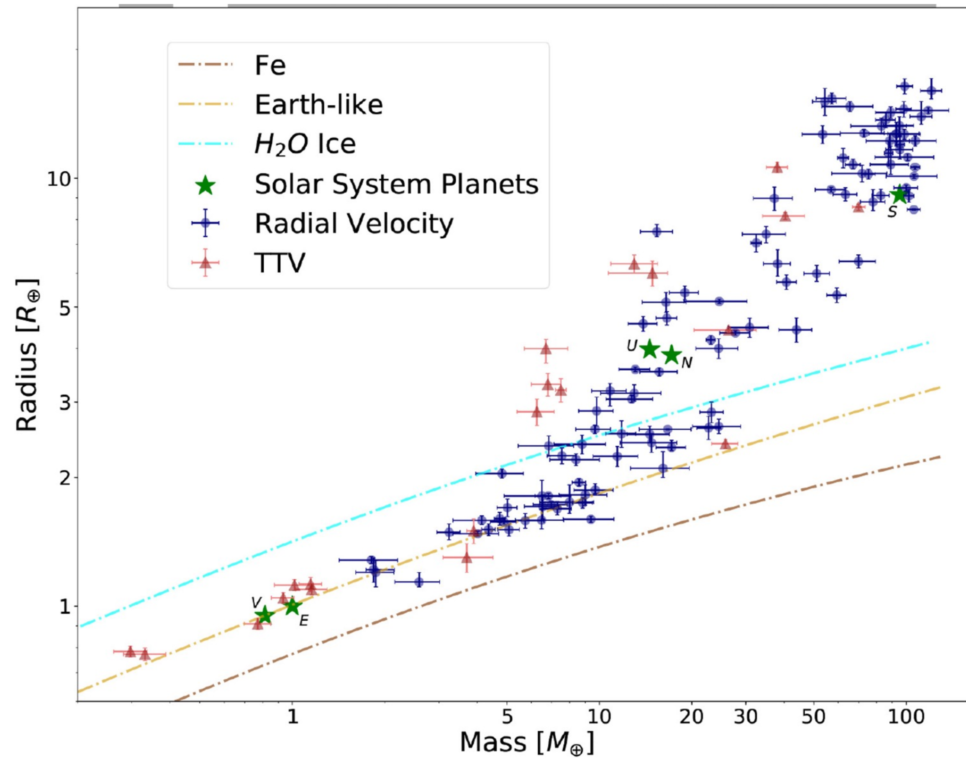
1. kink at ~8 ME
2. no “Earth-like” composition for M > 25 ME
3. stronger spread for M > 6 ME

⇒ compositional transition

Earths and Super-Earths: mainly rocky with no or small fluid envelopes (atmospheres, oceans…)

Neptunes: rocky cores surrounded by a fluid mantle

Explanation: below a critical mass, protoplanetary cores are unable to accrete/retain large fluid envelopes

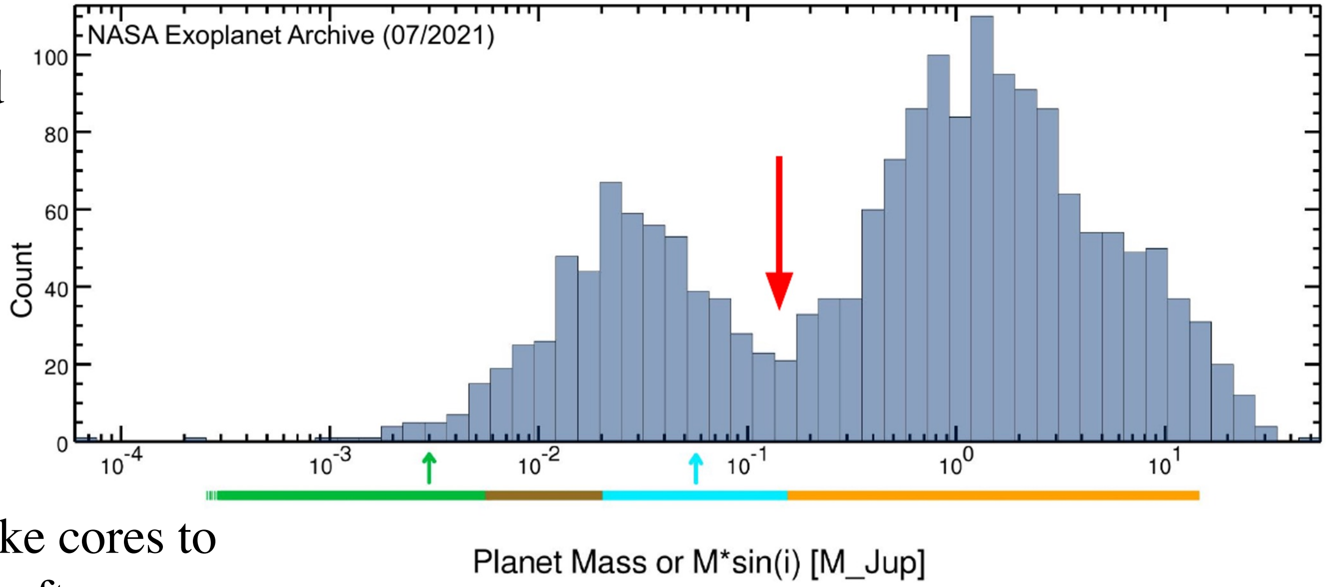


Otegi+ 2020..A&A..634..43

From Neptunes to Saturns

Counts distribution:

1. valley at ~40 MT
2. not caused by observational biases (most probably…)
3. caused by the absence of Hot Neptunes



Neptunes: metal-dominated (C, N, O…) by mass

Saturns and Jupiters: H/He dominated (just like stars)

Explanations:

1. inability of Neptune-like cores to retain H/He (during or after formation)
2. different formation pathways

From Saturns to Jupiters

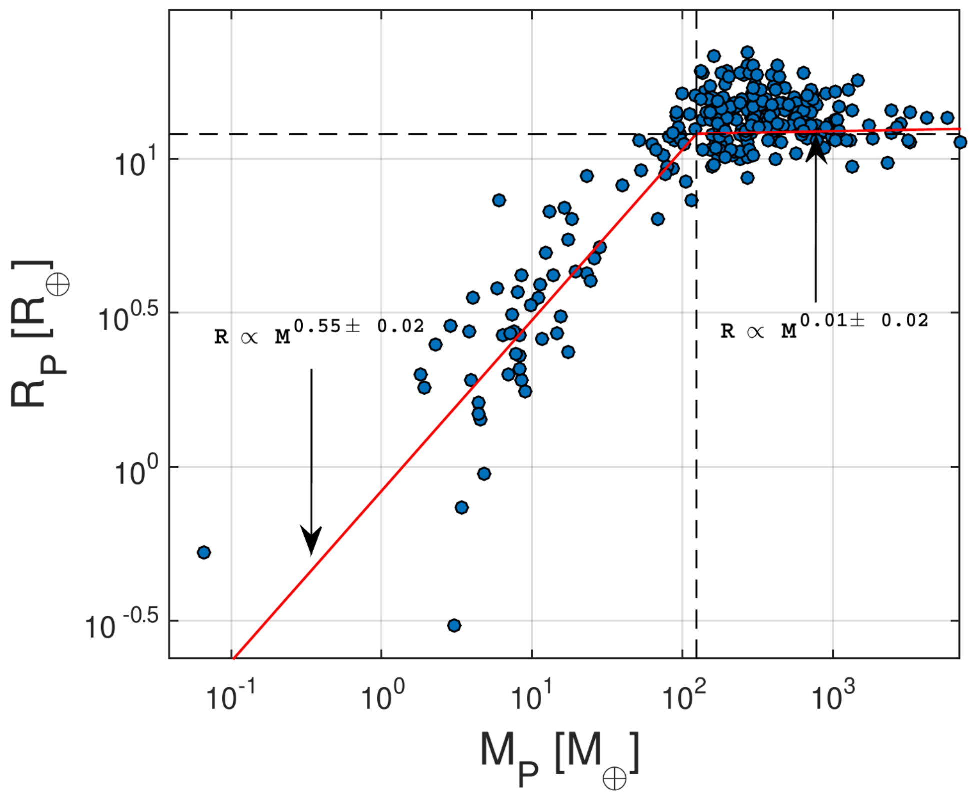
Mass-radius relation for high-mass exoplanets:

1. flat mass-radius distribution above ~120 MT (~0.4 MJ)
2. for M > 1 MJ, slightly negative slope

⇒ structural change

Saturns: mostly/entirely supported by Coulombian repulsion

Jupiters: increasingly dominated by electron degeneracy pressure (which means that, for a given T profile, adding mass shrinks the planet)



Bashi+ 2017..A&A..604..83

Equilibrium temperature

Incoming stellar radiation:

$$\tilde{\mathcal{I}} = L_\star(1-\alpha)f_{\mathrm{geom}} = 4\pi R_\star^2 \sigma_{\mathrm{SB}} T_\star^4 (1-\alpha)\left(\frac{R_p^2}{4a_p^2}\right)$$

Outgoing planetary radiation:

$$\mathcal{O} = 4\pi R_p^2 \sigma_{\mathrm{SB}} T_p^4$$

Equilibrium temperature (i.e. when O = I):

$$T_p = \left(\frac{R_\star^2 T_\star^4 (1-\alpha)}{4a_p^2}\right)^{1/4}$$

Important for the chemistry of the atmosphere and the astrobiological implications

However, the equilibrium temperature can be radically different from the surface (for rocky planets) or deep atmosphere (for gaseous planets) temperature

$R_\star$= star radius, R_p= planet radius, σ_{SB}= Stefan-Boltzmann constant, $T_\star$= star temperature, α= planetary albedo

Temperature classification

Cold/icy planets (< 180 K): those that lie beyond the ice line

Cool/temperate planets (180-350 K): those that lie inside or near the Circumstellar Habitable Zone

Warm planets (350-1000 K): those consistently hotter than Earth but that receive a stellar flux comparable or somewhat higher to that of Mercury

Hot planets (1000-2200 K): those that receive stellar fluxes > 30 times higher than Mercury, allowing for exotic conditions (e.g. magma oceans on rocky planets)

Ultra-hot planets (> 2200 K): as hot as M and K-dwarf stars, with mostly atomic (rather than molecular) atmospheres

Important: while stellar radiation usually dominates the planetary energy balance, in some cases (e.g. newly formed planets) is not the only contributor

Historical context

XV-XVI centuries: hypothesized in the wake of the Copernican Revolution (by e.g. Giordano Bruno)

XIX-XX centuries: first tentative detections as explanations for supposed astrometrical anomalies (Jacob 1855, See 1896, Strand 1957, van de Kamp 1963…)

1988: first non-rejected detection (Tadmor/γ Cep b) by Campbell et al., later confirmed to be correct

1991: first robust detection of an exoplanet orbiting a pulsar (Lich/PSR1257+12) by Wolszcan and Frail

1995: first robust detection of an exoplanet around a Main Sequence Star (Helvetios/51 Peg) by Mayor & Queloz

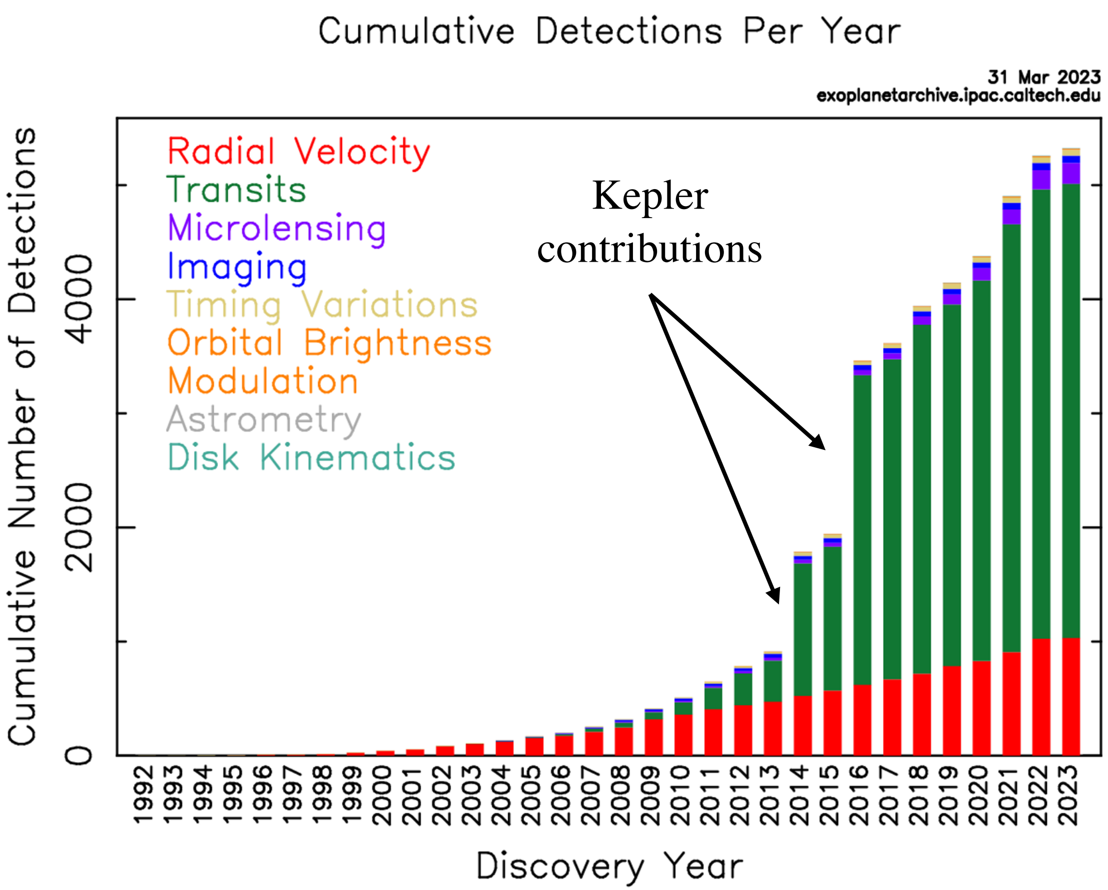
2002: first exoplanetary atmosphere detection (of HD 209458b) by Charbonneau et al.

2013: first detected Earth-like exoplanet (Kepler-186f) by Quintana et al.

Current situation

5322 confirmed exoplanets + 6237 candidates

170+ low resolution atmospheric spectra



Exoplanet catalogs

Main exoplanets catalogs:

1. NASA Exoplanet Archive (https://exoplanetarchive.ipac.caltech.edu/)
   Reference point for the exoplanetary community

1. The Extrasolar Planet Encyclopedia (http://exoplanet.eu/)
   Include more objects (due to a relaxed inclusion policy)

Naming:

1. Planets around star X are denoted as X b, c, … in alphabetic order *according to the discovery sequence* (not according to the semi-major axis, which would demand constant revision as additional planets are discovered around the same star)

1. A small number of exoplanets have been given a *proper names* via the IAU public outreach campaign NamingExoWorlds

Importance of studying the exoplanets

- Main scientific motivations
  - Setting our understanding of planetary physics in a global context

    Planetary physics so far only based on the Solar System

    Testing models of formation and evolution of planetary systems

  - Understanding how general are the Solar System properties

    Architecture: dichotomy between rocky and giant planets

    Dynamical properties: nearly circular and aligned orbits

  - Setting terrestrial life in a universal context

    Quantifying the frequency of planets that have suitable conditions for hosting life ("habitable planets")

Importance of studying the exoplanets

- Technological and scientific spin-offs
  - Exoplanet observations are driving huge technological improvements to classical astronomical instrumentation

    Imaging, coronagraphy, high resolution spectroscopy, photometry, interferometry, etc.

  - Stellar physics strongly benefits from exoplanet observations

    A huge amount of high quality stellar measurements is becoming available

    Studies of asteroseismology, microvariability, …

    Exoplanet science is providing fresh motivation to improve our understanding of stellar physics and stellar chemical abundances

Detection methods of exoplanets

- Direct methods
  - direct imaging

- Indirect methods
  - radial velocimetry
  - transit photometry
  - timing (transit time, eclipse time, pulsar time)
  - gravitational microlensing
  - astrometry
  - disk kinematics

Geometric configuration of detection

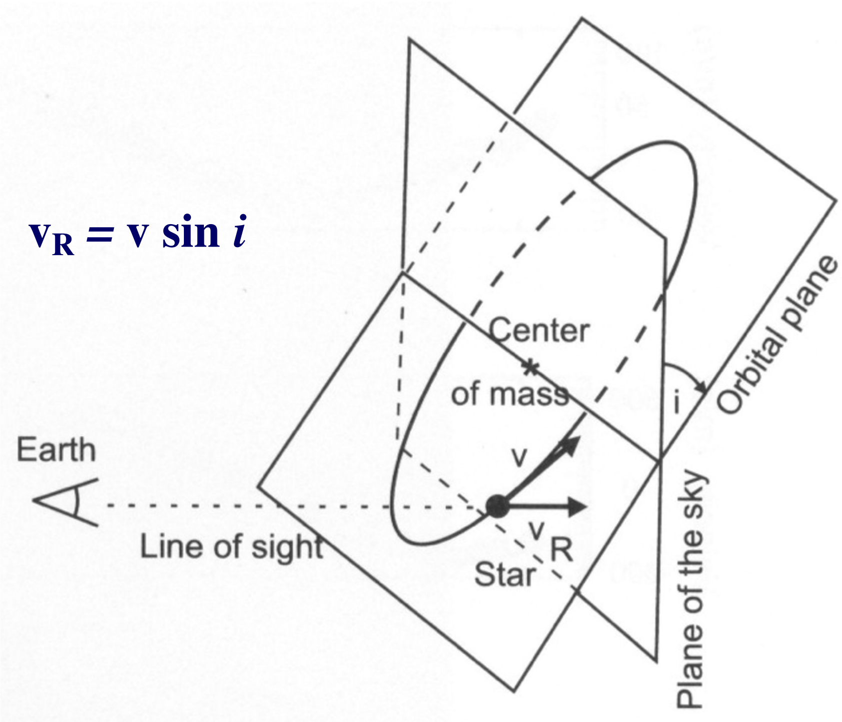
We call ***i*** the angle between the orbital spin and the line of sight (i.e., the angle between the orbital plane and the plane of the sky)

$i = 0^{o} \rightarrow$ face on

$i = 90^{o} \rightarrow$ edge on

With this convention, the velocity vector of the motion of the central star in the orbital plane is projected along the line of sight with a factor **sin *i***

$v_R = v \sin i$



Derivation of orbital period and semi-major axis

- We use the third Kepler's law

$$P^2 = \frac{4\pi^2 a^3}{G(M_\star + m_p)}$$

- We assume that the planet mass is negligible compared to the mass of the central star: $m_p << M_*$
- We estimate the mass of the central star, M_*, from a spectroscopic study of the star and models of stellar evolution
- In most cases we obtain a measurement of the orbital period, P using indirect methods. We then use the third Kepler's law to estimate the semimajor axis, a
- If the detection method provides a direct measurement of the semimajor axis, a, we use the third Kepler's law to estimate the orbital period, P

Temporal baseline for (indirect) detection

– The orbital period P is measured from the time variability of a stellar signal that bears signatures of the presence of a planet

Different types of signal can be employed:

stellar pulses, spectroscopy, photometry or angular position of the star

– In order to measure P (and to derive a from the third Kepler's law), the star should be observed over a temporal baseline covering at least a few orbital periods

– This leads to an observational selection bias: *planets with long orbital periods will require a long temporal baseline of observations*

Temporal baseline for (indirect) detection

– The orbital periods of the Solar System planets show that a temporal baseline in the order of tens of years would be required to prove the existence of periodicity for planets with $a \gtrsim 5$ AU

- This observational bias affects all indirect methods of exoplanet detection and favours the discovery of planets with short orbital periods, very close to the host star
  - This is (one of the reasons) why most detected exoplanets have orbital period of a few days and $a \lesssim 0.1$ AU

Planet	a [AU]	P [years]
Mercury	0.387	0.24
Venus	0.723	0.62
Earth	1.000	1.00
Mars	1.523	1.88
Jupiter	5.203	11.86
Saturn	9.537	29.42
Uranus	19.191	83.75
Neptun	30.069	163.72