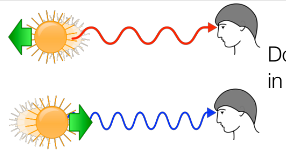
Lecture 8: Exoplanets and life in the Universe

Ch. 27 of “Astronomy: a Physical Perspective” (M. Kutner)

Prof Aline Vidotto

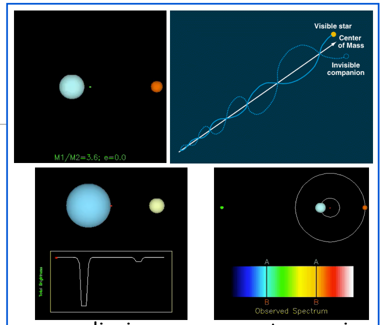
Quick recap of last lecture



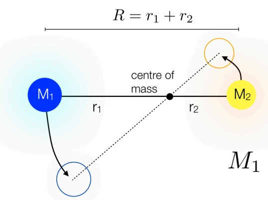
Doppler effect in Astronomy

Doppler shift caused by star in circular orbit

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v_r}{c} = \frac{v\cos(2\pi t/P)\sin(i)}{c}$$



eclipsing spectroscopic

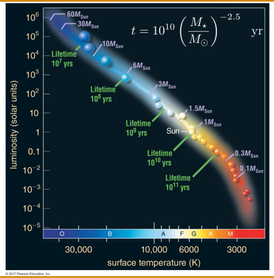


Deriving the stellar mass

$$M_1 + M_2 = \frac{4\pi^2}{G}\frac{R^3}{P^2}$$

or

$$M_1 + M_2 = \frac{P}{2\pi G}(v_1 + v_2)^3$$



The main sequence is a mass sequence

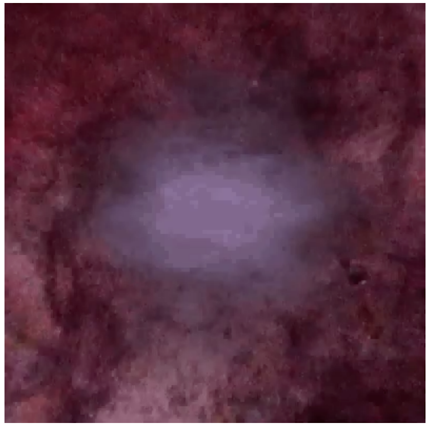
What we will cover today...

Goal: look at the steps that led up to life on Earth and put our Solar System into context of other planetary systems

Outline:

1. Planet formation
2. Detecting planets outside our solar system
3. Exoplanet demographics
4. Can any of these planets host (some sort of) life?

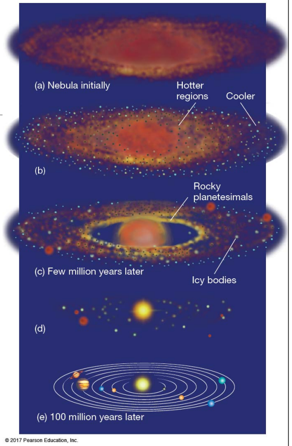
1. Planet formation

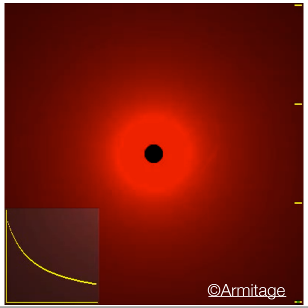


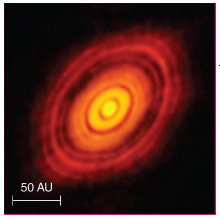
Example: animation shows the effects of rotation on the formation of the **solar system**

The birth of our solar system: the nebular theory

- Solar system formed from the gravitational collapse of a giant interstellar gas cloud: the solar nebula.
- Cloud rotation is key: a rotating cloud gives rise to a disc, within which planets form
- Condensation occurs when gas cools and changes its state to become tiny solid particles: building blocks of planets.



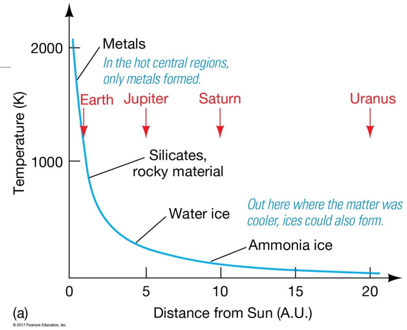


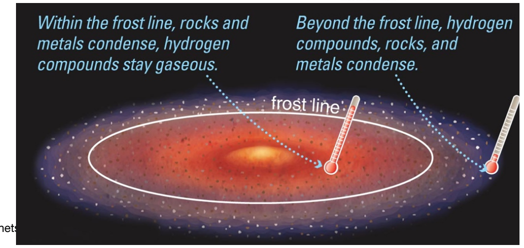


The gaps in this protoplanetary disc, as imaged by ALMA, are likely due to forming planets (TW Hya)

The birth of our solar system: the nebular theory

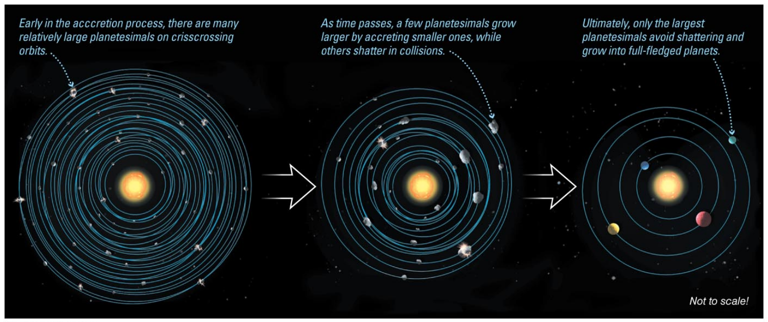
- Temperature in the cloud determines where various materials condense out; this determines where rocky planets and gas giants form.
- Theory of giant planet formation indicates that gas giants have to form outside the 'frost line'





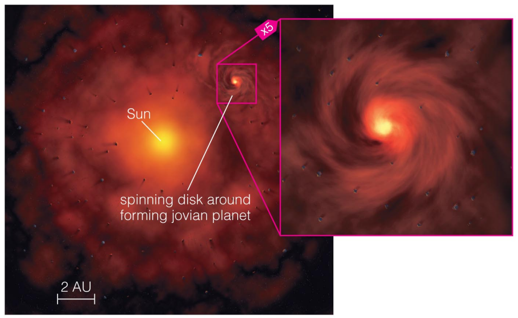
How did the terrestrial planets form?

- Small particles of rock and metal were present inside the frost line.
- Planetesimals of rock and metal built up as these particles collided.
- Gravity eventually assembled these planetesimals into terrestrial planets.
  - This process is called accretion.



How did the jovian (gas giant) planets form?

- Ice could also form small particles outside the frost line.
- Larger planetesimals and planets were able to form.
- Gravity of these larger planets was able to draw in surrounding H and He gases. This is why these planets became gas giants.

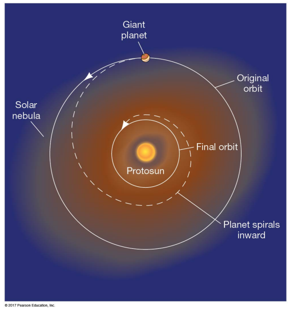


Note: A combination of photons and the solar wind - outflowing matter from the Sun - blew away the leftover gases.

How about planet formation in extrasolar planetary systems?

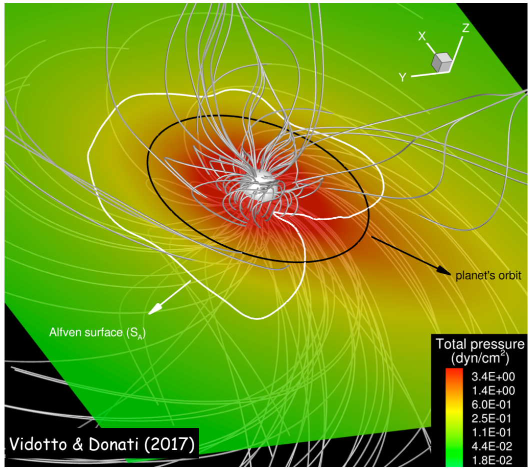
- The nebular theory explains what we see in the solar system: it was developed when the solar system was the only known planetary system
- Many known planetary systems are NOT like ours: many gas giant exoplanets orbit within the “frost line” → we need a new theory to explain how these exoplanets got so close to their host stars
- One idea is that planets form beyond the frost line and later migrate inwards (interactions between planet and gaseous disc causes ‘friction’ and remove orbital angular momentum)

> - It is difficult to detect very young planets, as they are still enshrouded in the disc
> - The youngest exoplanet detected so far is V830Tau b



V830Tau b: a newborn planet

Simulation of stellar wind interacting with the exoplanet V830 Tau b



Why so special?

- The youngest detected exoplanet (Donati et al 2015, 2016)
  - Star is a protostar: only 2 Myr-old
  - This indicates that planet formation occurred within 2 Myr
  - Strong interactions between planet and host-star wind

Check all the research themes of the Astro TCD group in this link.

Conceptual question

Why do we think the inner (terrestrial) planets became denser than the outer planets?

(a) As the solar nebula collapsed, denser materials sank toward the centre.

(b) The Sun's gravity pulled denser materials toward the centre.

(c) The inner part of the solar nebula was so hot that only dense metals and rocks were able to accrete there.

(d) The rotating disk in which the planets formed flung lighter elements outward by centrifugal force.

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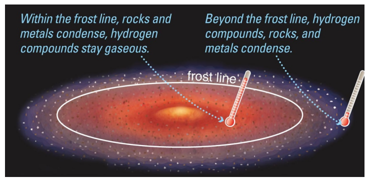


2. Detecting planets outside our solar system

Main techniques

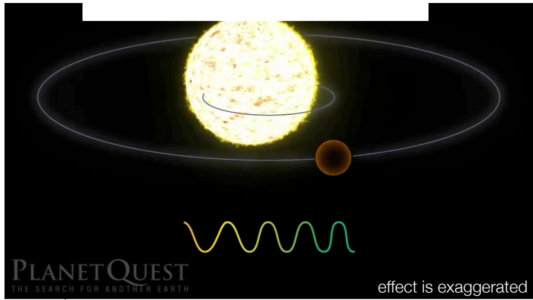
(i) Radial velocity technique
(ii) Transit method
(iii) Direct imaging
(iv) Gravitational μlensing

The two most successful techniques

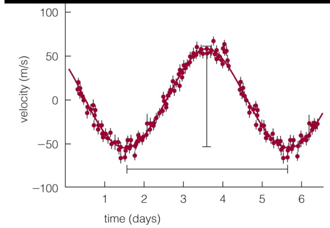
- All techniques are important, because each one preferentially detects planets orbiting at different distances from their host star.
- Diversity of techniques allow us to survey different architecture of planetary systems.

Radial velocity technique

https://exoplanets.nasa.gov/interactable/11/

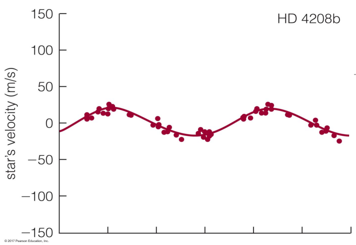


- The planet's gravity causes the star to 'wobble' around a little bit. Planet and star orbit around the common centre of mass.
- The star therefore wobbles around that centre of mass with same period as the planet.

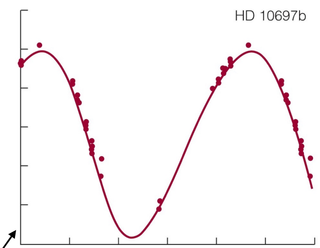


Radial velocity curve: By measuring the Doppler shift, we derive the radial velocity (as in spectroscopic binaries).
→ A periodic Doppler shift in the spectrum of the star 51 Peg shows the presence of a large planet with an orbital period of ~4 days

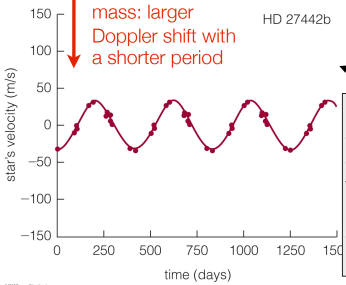
Examples of radial velocity curves



Planet in same orbital distance & more massive: larger Doppler shift → larger radial velocity amplitude

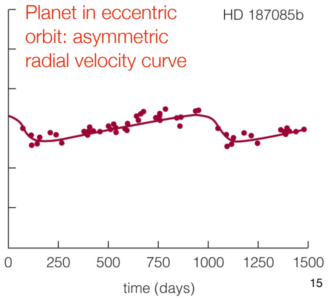


Planet in closer orbit & same mass: larger Doppler shift with a shorter period



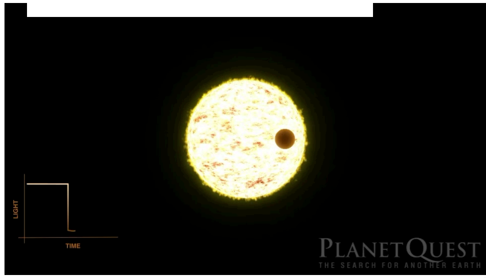
Massive planets and/or in closer orbits are easier to detect because they cause larger Doppler shifts

Planet in eccentric orbit: asymmetric radial velocity curve



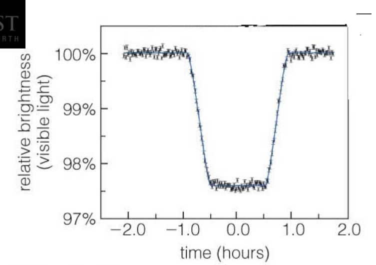
Transit method

https://exoplanets.nasa.gov/interactable/11/



- When a planet passes directly between an observer and the star it orbits, it blocks some of that star's light. For a brief period of time, that star actually gets dimmer.

Transit lightcurve: In this example, the planet blocks 2.5% of the star's light during transit (transit depth=0.025).

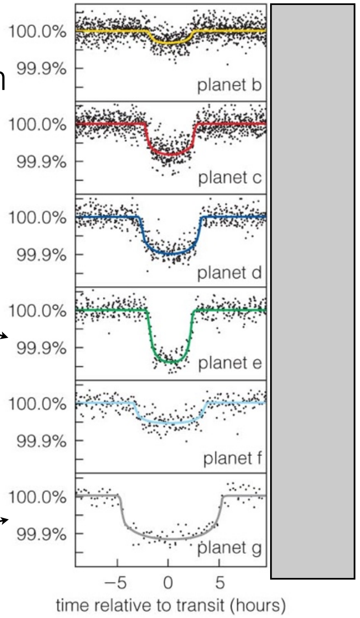


Examples of transit lightcurves: Kepler-11 system

- Transit depth ΔF is related to planet's radius R_p and stellar radius R_{star} as

$$\frac{R_p}{R_\star} = \sqrt{\Delta F}$$

  - Larger planet → deeper transit
- The farther away a planet is, the longer it takes to orbit and pass in front of its star (Kepler's law). So the longer a transit event lasts, the farther away that planet is from its star.
  - Planet "g" is the farthest among the ones shown on the right ("widest" transit)



The Kepler Mission: a revolution in the number of planets detected using the transit technique

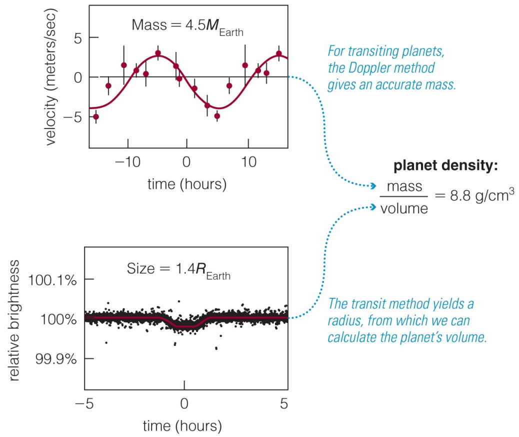
Was in operation for nearly 10 years.

Kepler retired on December 2018.

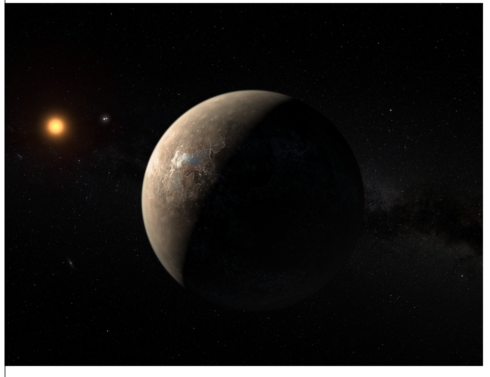
The new exoplanet hunter: TESS

Calculating density of exoplanets

- Using mass, determined using the radial velocity technique, and size, determined using the transit technique, density can be calculated.



Aside: how we name exoplanets



- Definition: planet is named after its host-star, by adding a letter after the star's name starting with "b" and in order of discovery
- Example:
  - HD189733 b
  - 55 Cnc b (1st discovered)
  - 55 Cnc c (2nd discovered)
  - 55 Cnc d (3rd discovered)
- Note: Capital letters are reserved for binary star systems
  - α Cen A and α Cen B are stars in a binary system

Conceptual question

Suppose you found a star similar to the Sun moving back and forth with a period of 2 years. What could you conclude?

(a) It has a planet orbiting at less than 1 AU.
(b) It has a planet orbiting at greater than 1 AU.
(c) It has a planet orbiting at exactly 1 AU.
(d) It has a planet, but we don't know its mass so we can't know its orbital distance for sure.

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3. Exoplanet demographics

Important: The number of detected planets (~4000) is just a subset of the planets out there!

Confirmed Exoplanet Statistics

Discovery Method	Number of Planets
Astrometry	1
Imaging	44
Radial Velocity	727
Transit	3030
Transit timing variations	15
Eclipse timing variations	9
Microlensing	72
Pulsar timing variations	6
Pulsation timing variations	2
Orbital brightness modulations	6

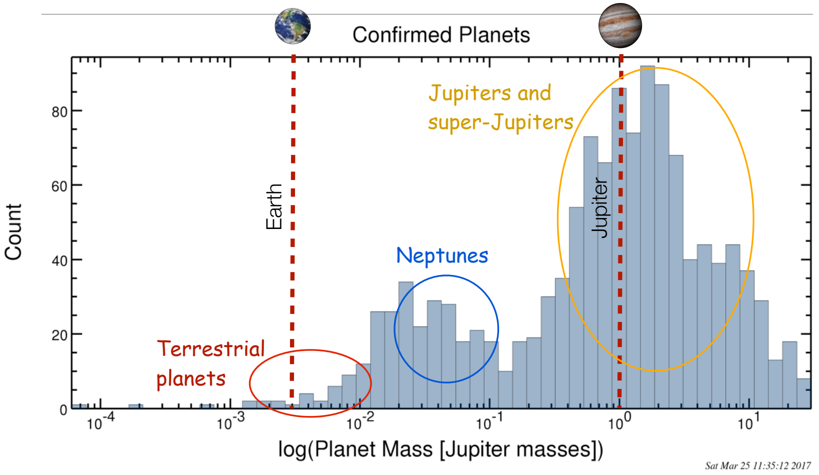
Transiting Exoplanets	**3054**
All Exoplanets	**3912**

Many websites keeping up with searches (go & explore them): www.exoplanets.org ; www.exoplanets.eu ; exoplanetarchive.ipac.caltech.edu ; www.hzgallery.org ;

as of 13 Feb 2019

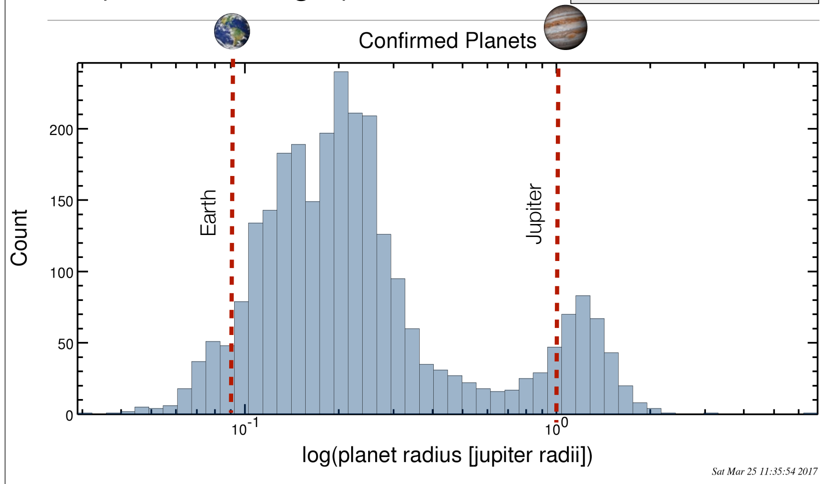
Exoplanet demographics: mass

We can only measure mass if planet is detected with the radial velocity technique



Exoplanet demographics: radius

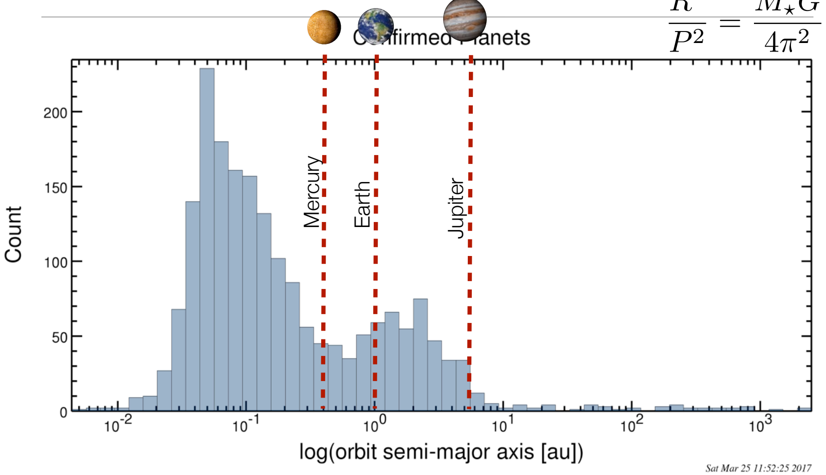
We can only measure radius in transiting planets

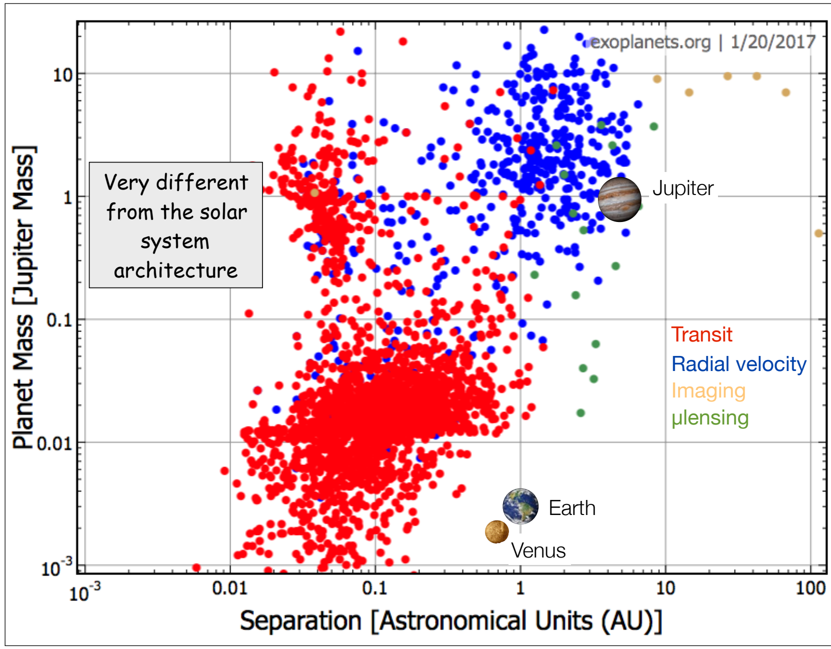


Exoplanet demographics: semi-major axis

Knowing the mass of the host star and the orbital period, we can derive the semi-major axis with Kepler's law.

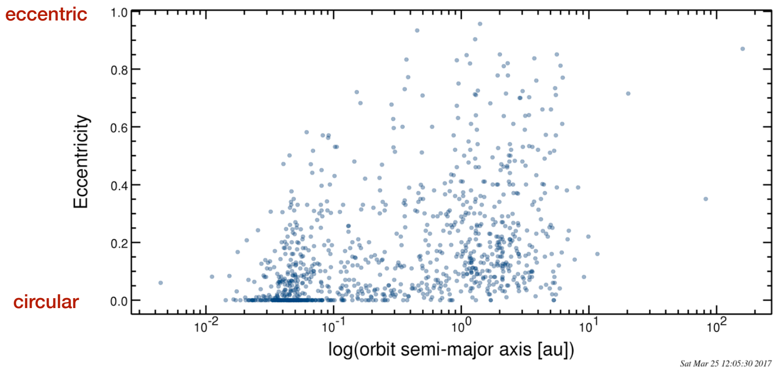
$$\frac{R^3}{P^2} = \frac{M_\star G}{4\pi^2}$$





Exoplanet demographics: eccentricity

- Orbits of some extrasolar planets are much more elongated (have a greater eccentricity) than those in our solar system: Mercury (e=0.2), all the other solar system planets (e<0.1)



Unanticipated characteristics of exoplanets

- Surprise: most of these exoplanetary system have very different architecture than our solar system.
  - The majority of them are located very close to the star ("hot planets")
  - Many are larger than solar system planets
  - Many of them are more massive than Jupiter ("super Jupiters")
  - Many have high orbital eccentricities
- Much of this is a selection effect
  - Radial velocity and transit methods more sensitive to planets close to parent stars
- Nevertheless, there are many more *close-in* exoplanets than were expected
- It is a big challenge to explain this using theories of solar system formation (need to take into account planet migration)

Conceptual question

Extrasolar planets the size of Earth have NOT yet been seen with current techniques because

(a) small planets probably don't exist.
(b) the large planets nearby have swept them up.
(c) Earth-like planets take time to form.
(d) large planets orbiting near their stars are more easily detected.
(e) small planets can only be seen if they cross in front of their star.

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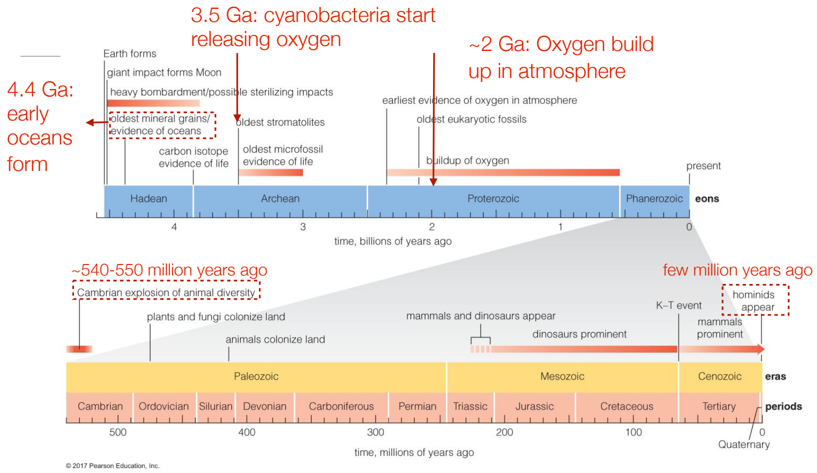
4. Can any of these planets host (some sort of) life?

Too close to the Sun: too warm, water becomes vapour

© city of physics

Too far from the Sun: too cold, water becomes ice

Brief history of life on Earth

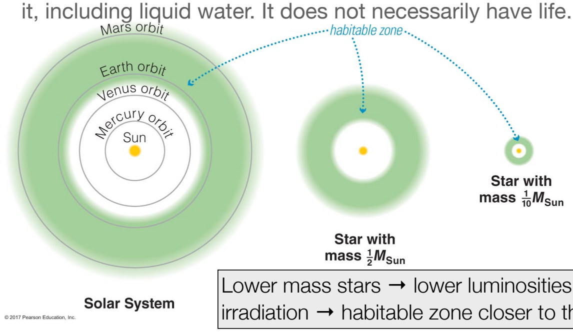


Requirements for life

1. A nutrient source
2. Energy (sunlight, chemical reactions, internal heat)
3. Liquid water

→ Hardest to find on exoplanets

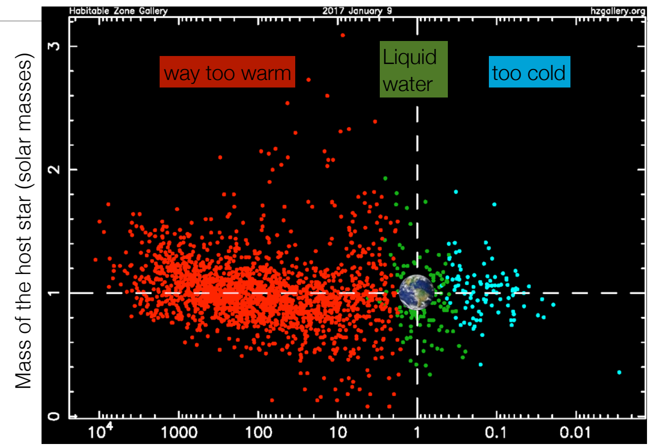
- Habitable-zone planet contains the basic necessities for life as we know it, including liquid water. It does not necessarily have life.



Habitable zone: region around star where stellar irradiation is enough to allow temperatures required for liquid water (between 0°C and 100°C).

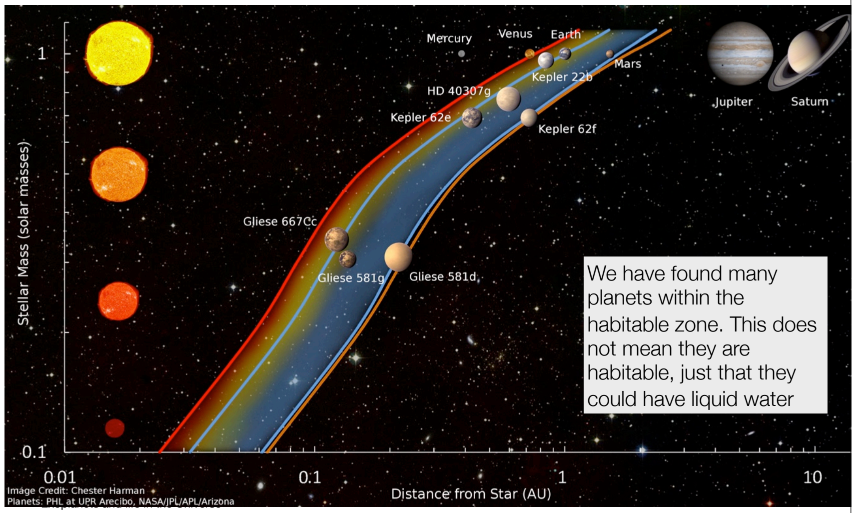
Lower mass stars → lower luminosities → lower irradiation → habitable zone closer to the star.

The surface liquid water habitable zone



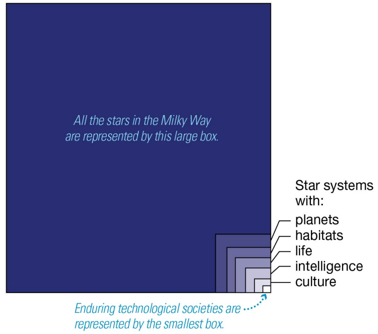
Stellar irradiation received by the planet (compared to Earth)

The surface liquid water habitable zone



How many civilisations are there in the Galaxy? The Drake equation (for fun only...)

number of technological, intelligent civilizations now present in the Galaxy = rate of star formation, averaged over the lifetime of the Galaxy × fraction of stars having planetary systems × average number of habitable planets within those planetary systems × fraction of those habitable planets on which life arises × fraction of those life-bearing planets on which intelligence evolves × fraction of those intelligent-life planets that develop technological society × average lifetime of a technologically competent civilization.



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- The rate of star formation: 10 stars per year (dividing population of Milky Way by its present age)
- Fraction of stars having planetary systems: Most planetary systems like our own have not been detected yet, but we would expect to be able to detect them using current methods.
  - We expect most (all?) star systems to have formed planets as well, and assign this factor a value near 1.
- Number of habitable planets per planetary system: Probably only significant around F-, G-, and K-type stars. Smaller stars are too magnetically-“active”, and larger stars have a too-short lifetime.
  - Give this factor a value of 1/10: one habitable planet in every 10 planetary systems.

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- Fraction of habitable planets on which life actually arises: very hard to say! Let’s give this factor a value of 0.1 (i.e., one in each 10 stars).
- Fraction of life-bearing planets where intelligence arises: Here we have essentially no facts, just speculation and opinion. Let’s assign this factor a value of 0.01 (i.e., 1 in each 100 stars).
- Fraction of planets where intelligent life develops and uses technology: Again, we have no facts. Let’s say, 50% of the civilisations would chose to communicate.
- For the average lifetime of a technological civilisation, we can’t even use ourselves as an example: Our civilisation has been technological for about 100 years, but who knows how long it will last? Let’s try an average lifetime of 10^5yr.

How many civilisations are there in the Galaxy? The Drake equation (for fun only...)

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	=	10/yr	x	1	x	1/10	x	0.1	x	0.01	x	0.5	x	10^5 yr

≈50 civilisations in our Galaxy would be able to contact each other

- Remember: there are several very uncertain factors; even if only one of them is low, the number of expected civilisations drops quickly.
- If N=50 civilisations are uniformly spread over the disc of the Galaxy, then the surface density of civilisations is σ=N/area = 50/(π [15 kpc]^2) ~0.07 civilisation/kpc^2.
- mean separation of between civilisations is $\sigma^{-1/2}$ ≈ 3kpc ≈10,000 light-years
- **Even if** possible for spacecraft to travel at 0.1c, it would take 10^5yr to reach a civilisation
  - even if life is abundant in the Galaxy, it is unlikely we are being visited by alien spacecraft!

Conceptual question

What is meant by the “habitable zone”?

(a) the zone in which water can be a liquid around the centre of the Galaxy

(b) the region around each star in which terrestrial planets could have liquid water on their surfaces

(c) the zone in which terrestrial-sized planets could form around each star

(d) the region in dense atmospheres like Jupiter’s in which water droplets could form

(e) the regions near the poles of mercury in which liquid water might exist

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