



Lecture 14: Synthesis Solar System in Context, Astrobiology

Planetary Systems

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2026



Learning Objectives

By the end of this lecture, you will be able to:

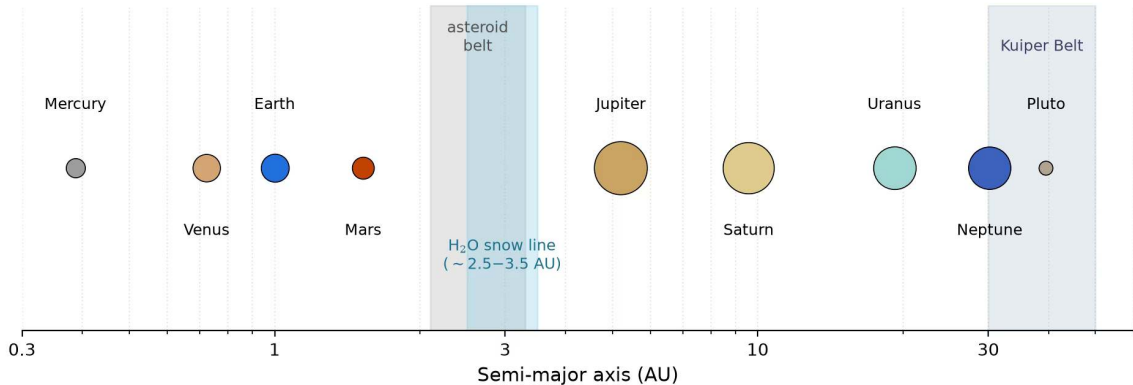
- Place our solar system within the observed exoplanet population
- Evaluate habitability as a coupled *systems* property and derive the classical habitable-zone boundaries
- Identify the most promising life-detection targets for the next decade

Habitability is a trajectory, not a snapshot.

The Thread of the Course

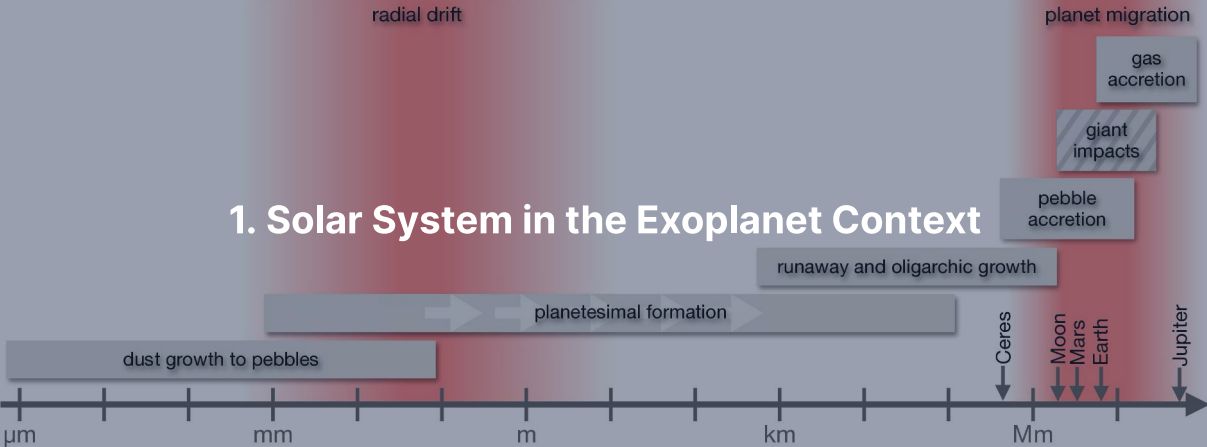
- L1–L8: accretion, differentiation, internal heat engines, and atmosphere-surface coupling
- L9–L12: terrestrial and giant planet evolution traced body by body
- L13: over 6000 exoplanets revealing architectural diversity

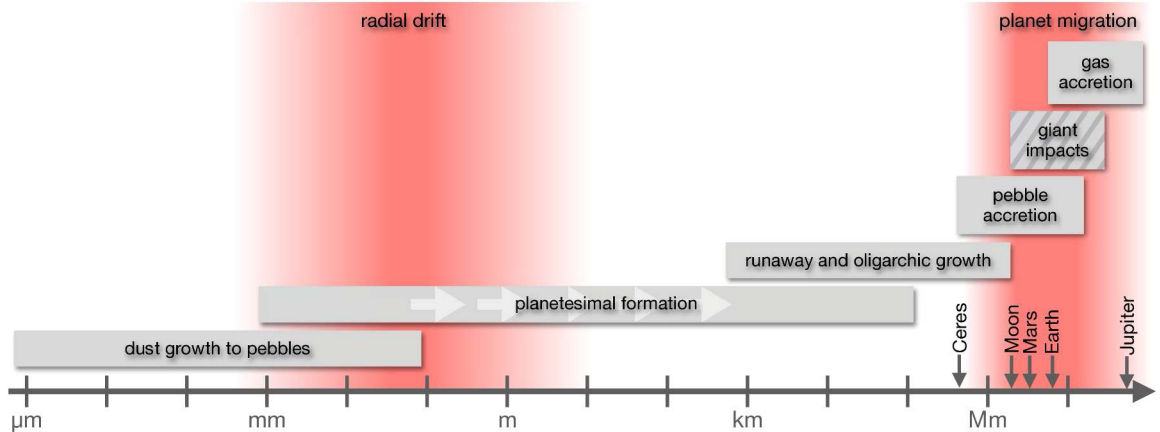
Today: Step back to evaluate the solar system in context and test astrobiological habitability.



Architecture of the solar system on a logarithmic semi-major axis scale with symbol area scaled to radius; shaded spans mark the asteroid belt, the Kuiper belt and the water snow line region. Credit: Course-original figure; NASA NSSDC.

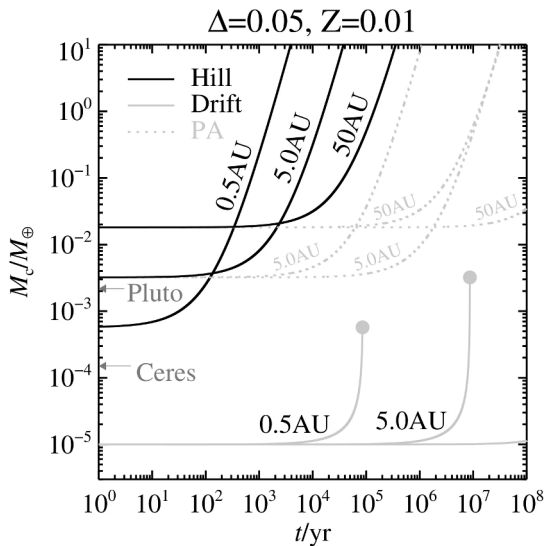
1. Solar System in the Exoplanet Context





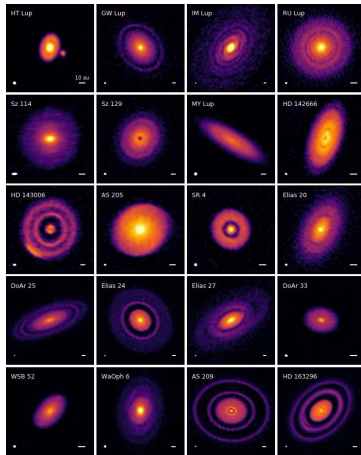
Growth processes from dust to planets. Drążkowska et al. (2023).

Dust grows to pebbles, planetesimals and embryos by streaming instability, pebble accretion and runaway envelope accretion; the disk lifetime of 3–5 Myr is the deadline, and ALMA disk substructure is direct observational input.



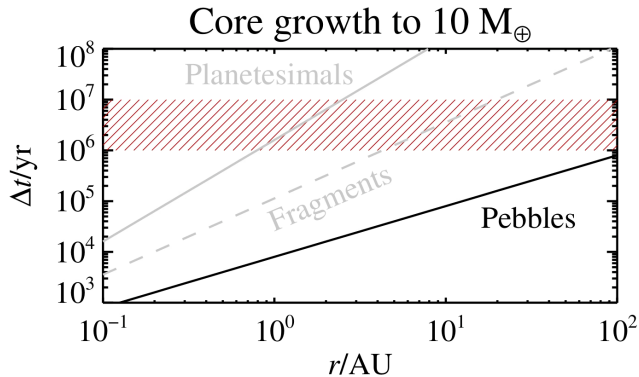
Core mass against time at 0.5, 5 and 50 AU: pebble accretion (solid) against classical planetesimal accretion (grey dotted), with Ceres and Pluto marked. Lambrechts & Johansen (2012).

From the transition mass, pebble accretion builds 10 Earth masses in less than a million years; 3D planetesimal accretion at 5 AU needs more than 10^7 years.



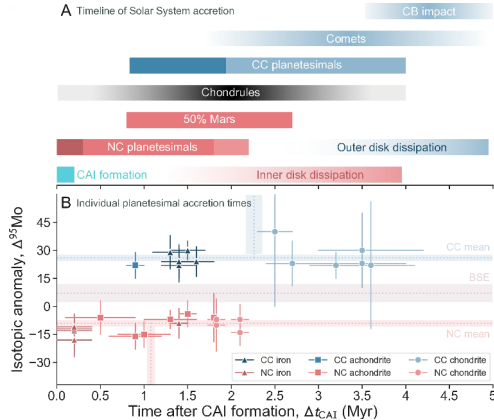
ALMA DSHARP 240 GHz continuum images of 20 nearby disks. Andrews et al. (2018).

Concentric rings, gaps and asymmetries are nearly ubiquitous, and most are interpreted as signatures of planet growth in progress.



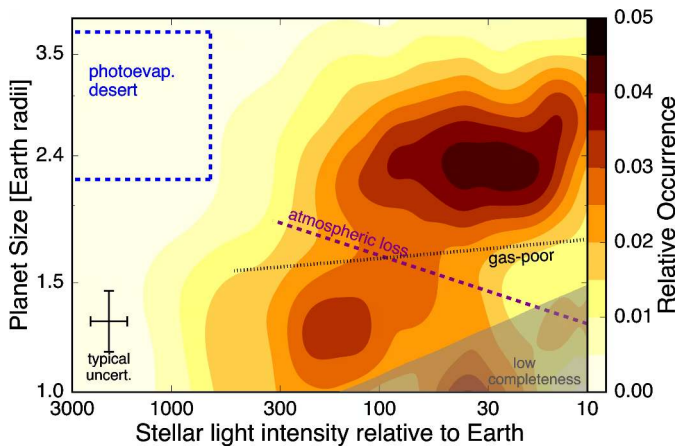
Time to grow a 10 Earth-mass core against distance from the star, by pebble (black), planetesimal (grey) and fragment (dashed) accretion; hatched: gas dispersal at 1 to 10 Myr. Lambrechts & Johansen (2012).

A core that is to capture an envelope must reach 10 Earth masses before the gas goes: the pebble line stays below the band at every radius, the planetesimal line rises through it within a few AU.



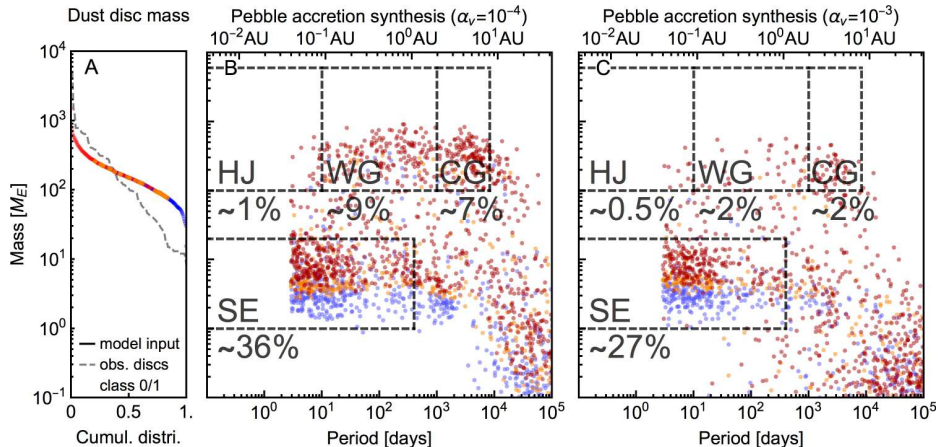
Timeline of solar system formation from isotopic dating of meteorites: the non-carbonaceous (NC, red) and carbonaceous (CC, blue) reservoirs. Lichtenberg et al. (2023).

The two reservoirs keep distinct isotopic signatures from CAI formation onward, so they accreted in physically separated regions of the disk for at least the first 2 to 3 Myr.



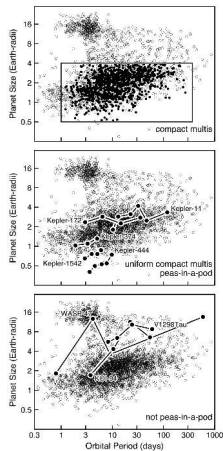
The Fulton gap: planet size against incident flux, with the deficit near $1.8 R_{\oplus}$; dashed: atmospheric-loss model, dotted: gas-poor model. Fulton et al. (2017).

Photoevaporation models reproduce both the location and the slope of the valley with irradiation.



Population synthesis: planet mass against period under pebble accretion at low (B) and moderate (C) turbulence. Drążkowska et al. (2023).

At either turbulence level, pebble accretion readily forms the super-Earths and close-in giants that the solar system lacks.

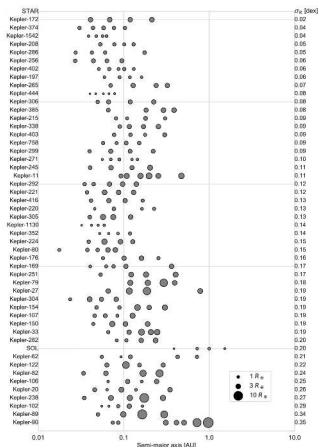


Transiting census with compact multi-planet systems boxed: five uniform ones (middle), three non-uniform ones (bottom). Weiss et al. (2023, PPVII).

Many compact multi-planet systems show striking size uniformity (middle), while others do not (bottom).

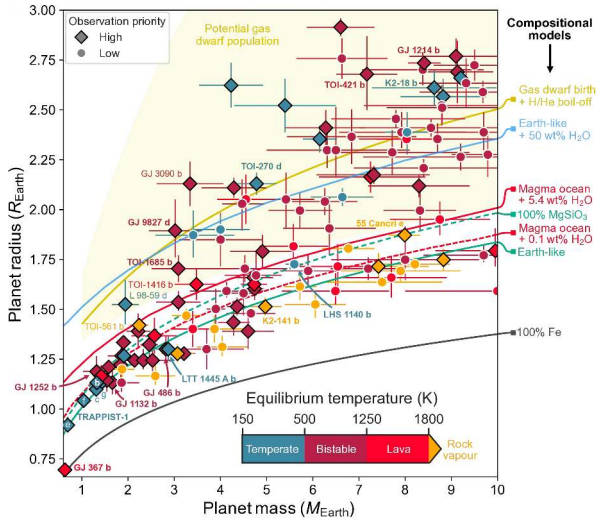
Where the Solar System is Atypical

- No super-Earths or sub-Neptunes: the most common exoplanet size class is absent
- No close-in giant planets: hot Jupiters orbit $\sim 0.5\text{--}1\%$ of Sun-like stars, hot Neptunes are rarer still
- Outer giants on wide, circular orbits, while the inner terrestrials lack compact uniformity



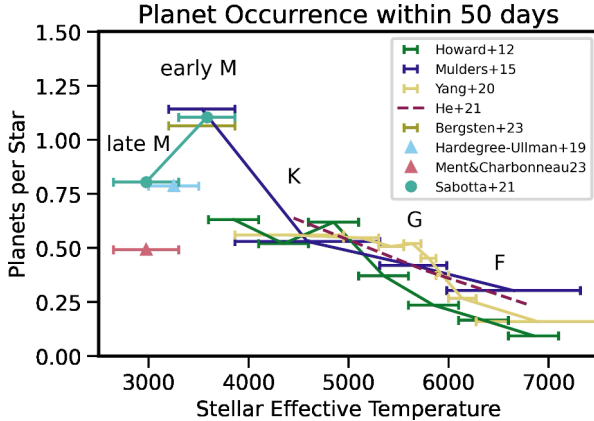
Compact multi-systems with at least four transiting planets within 1.52 AU, ranked by the uniformity of their planet sizes. Weiss et al. (2023).

The solar system falls in the bottom quintile of size uniformity: the inner solar system did not produce the typical compact-multi architecture.



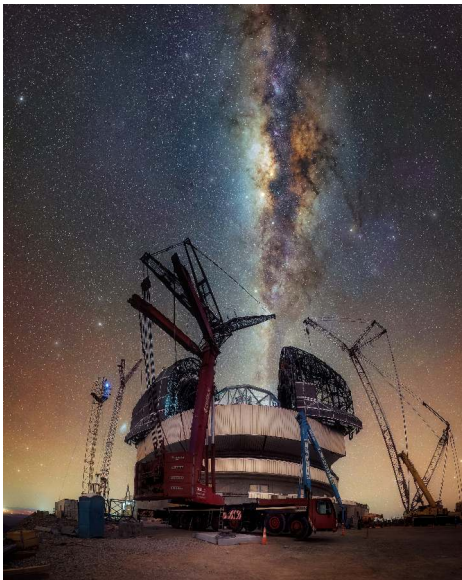
Mass-radius diagram with composition tracks: pure Fe, Earth-like, MgSiO_3 , water-rich, magma plus H_2O , and gas dwarf. Lichtenberg et al. (2025).

The close-in super-Earths sit on the Earth-like curve as stripped cores that lost their gas envelopes; larger planets carry volatile envelopes that swell their radii.



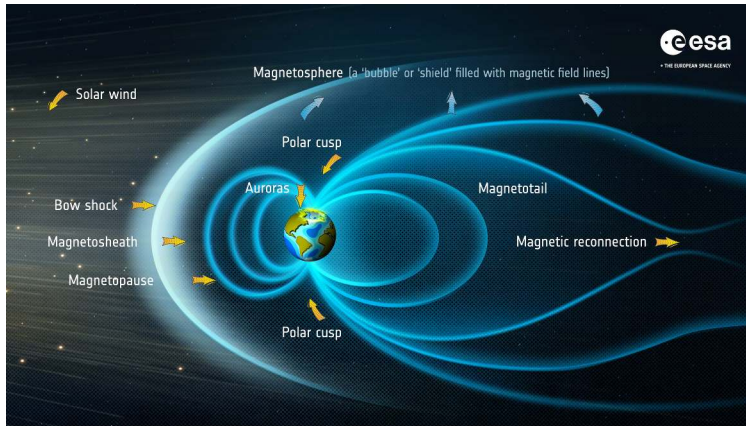
Occurrence of small planets ($1-4 R_{\oplus}$, $P < 50$ d) per star against stellar effective temperature. Mulders (2024).

Occurrence is two to four times higher around early M dwarfs than around FGK stars and drops again for the late M dwarfs, where the surveys cover only periods below 10 d: small planets are most common around low-mass stars.



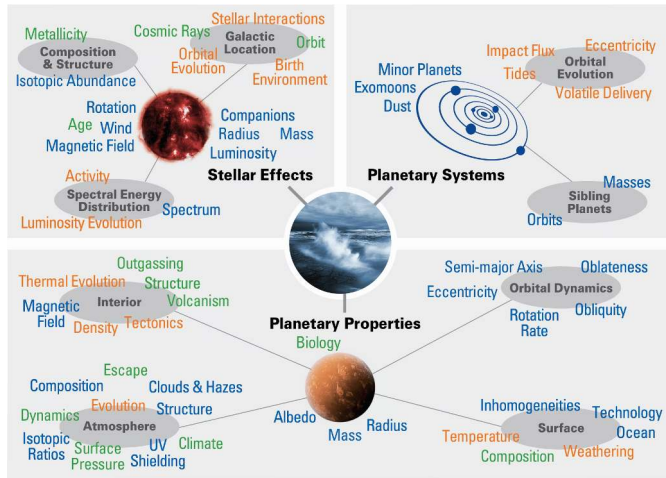
The Milky Way over the ELT site.
Credit: C. Letelier/ESO.

Whether our architecture is rare stays open until Gaia DR4 and DR5 complete the census of Jupiter analogues and PLATO (2027) reaches Earth analogues at 1 AU; the 39 m ELT will then image temperate rocky planets around nearby M dwarfs directly.



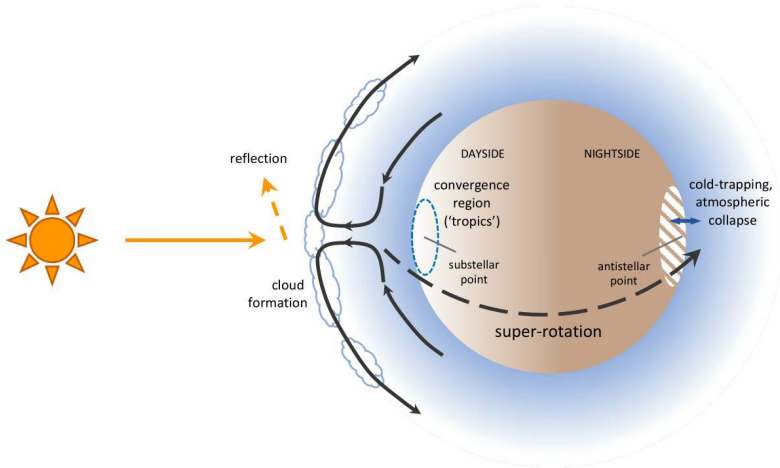
Anatomy of Earth's magnetosphere. Credit: ESA, CC BY-SA 3.0 IGO.

Habitability is a coupled stack, not a checklist: a stable, benign star and orbit; a geophysical engine that drives a dynamo and recycles volatiles; an atmosphere that keeps surface water liquid; a biosphere that feeds back on weathering and redox.



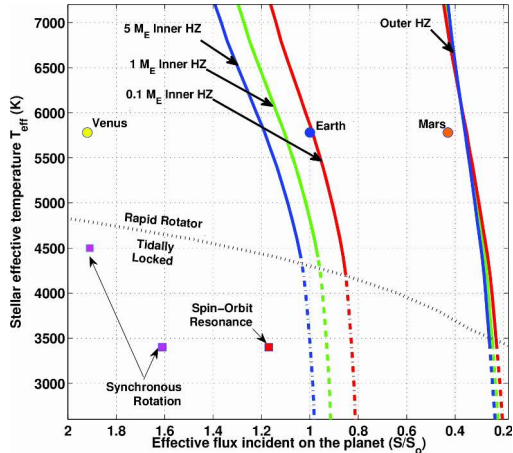
Stellar, planetary and orbital factors that shape habitability, coloured by evidence type: blue observable, green model-interpreted, orange theoretical. Meadows & Barnes (2018).

Breaking any one of these couplings can end surface water stability.



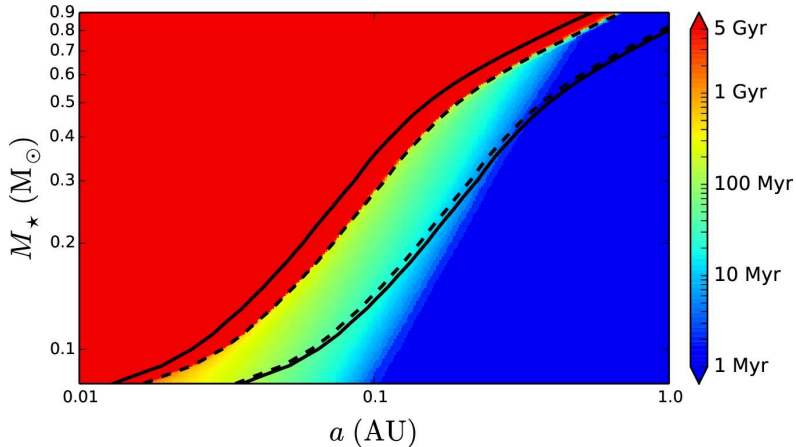
Atmospheric circulation on a tidally locked rocky planet: substellar convection and equatorial super-rotation transport heat. Wordsworth & Kreidberg (2022).

Nightside cold traps risk atmospheric collapse.



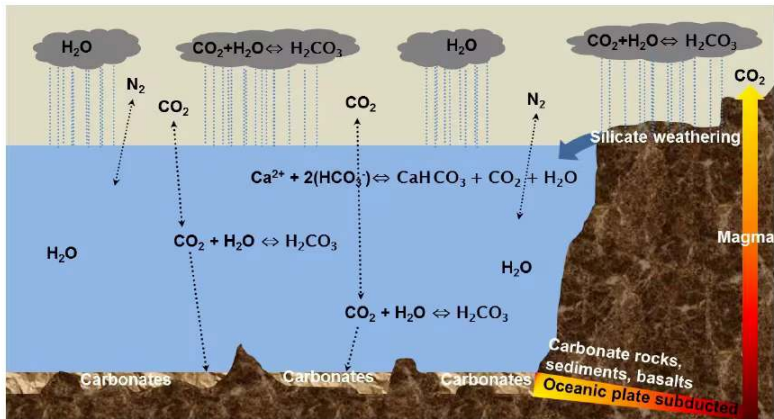
Habitable zone limits against stellar effective temperature. Kopparapu et al. (2014).

Inner edge: the runaway greenhouse limit; outer edge: the maximum CO_2 greenhouse; stars brighten over their main-sequence lifetime, so orbiting in the zone today does not guarantee a habitable history.



Runaway greenhouse duration of a water-bearing planet against stellar mass.
Luger & Barnes (2015).

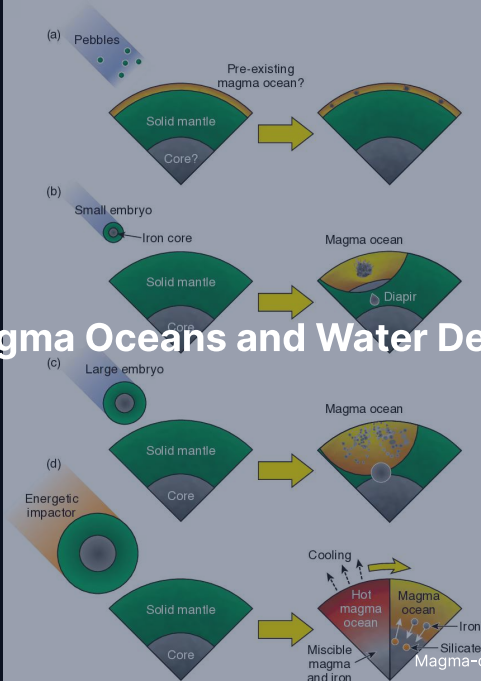
Planets around late M dwarfs spend up to a Gyr *inside* the runaway zone during the star's bright pre-main sequence, and lose their initial water inventory.



The carbonate-silicate cycle. Lammer et al. (2018).

Volcanic CO_2 outgassing is balanced by temperature-dependent silicate weathering and subduction, a negative feedback that needs surface liquid water, active volcanism and tectonic recycling; its failure produces the Venus-like 92 bar.

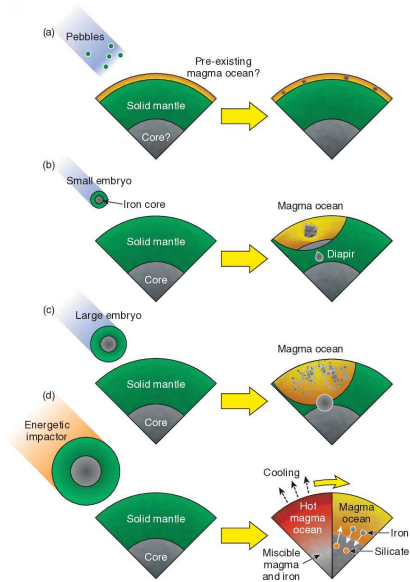
3. Magma Oceans and Water Delivery



Why "Delivery" Isn't the Right Frame

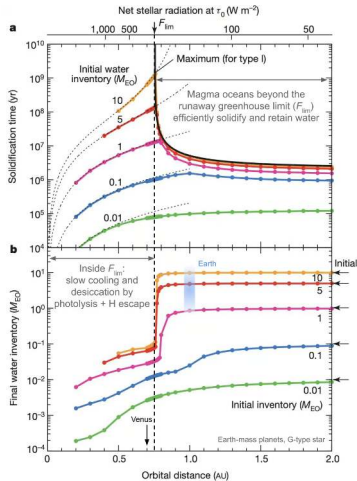
- Earth, Venus, and Mars received similar initial accreted volatile budgets
- Magma ocean partitioning sets the core, mantle, and steam atmosphere reservoirs
- Evolutionary controls: early hydrodynamic escape, mantle outgassing, and stellar brightening

Terrestrial volatile inventories diverge because differentiation and evolution matter far more than initial delivery.



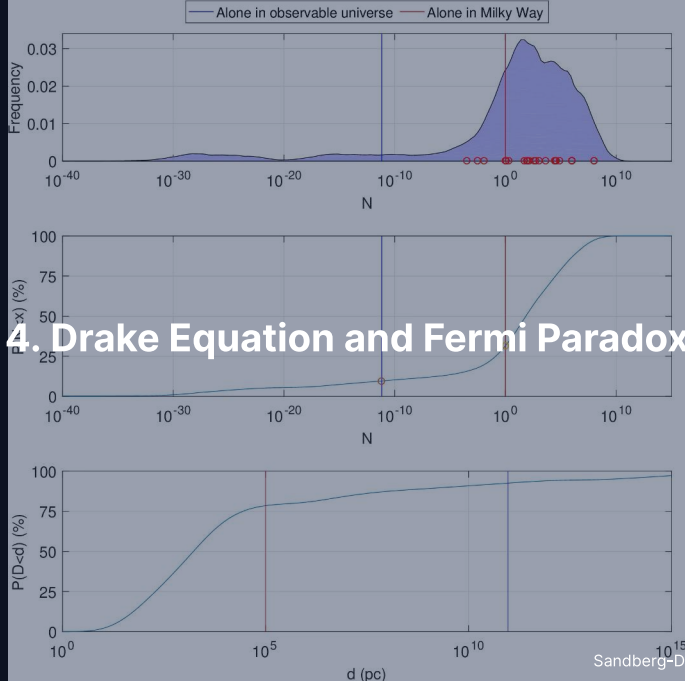
Metal-silicate differentiation by pebbles, small and large embryos, and an energetic impact. Lichtenberg et al. (2023).

The accretion mode sets how much of the mantle melts. Volatiles partition between liquid silicate and the steam atmosphere; the sequestered fraction depends on mantle redox, solidification time and depth, so identical initial budgets yield radically different atmospheric masses.



Two types of terrestrial planet from magma ocean evolution. Hamano et al. (2013).

Inside the critical flux, Type II planets lose their water to hydrodynamic escape before solidifying; Type I planets further out solidify quickly and retain oceans.



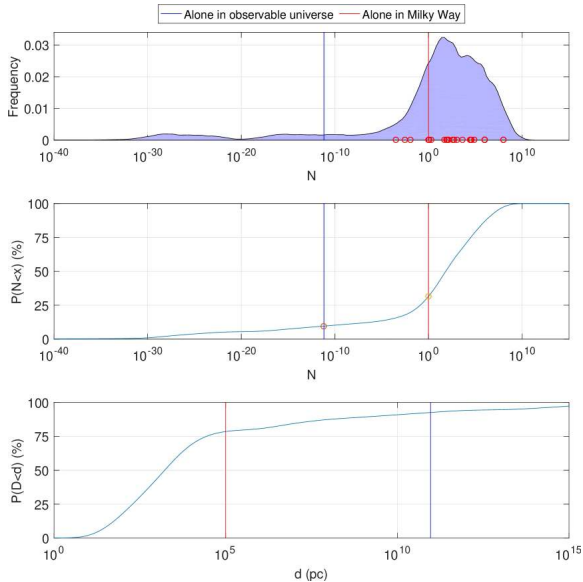
The Drake Equation: A Framing Tool

$$N = R_{\star} \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$

$R_{\star}$ star-formation rate, f_p fraction with planets, n_e habitable planets per system, f_l life, f_i intelligence, f_c communication, L lifetime of a signalling civilisation.

- Astrophysical factors are now measured: $R_{\star}, f_p \sim 1, n_e \approx 0.4$ to 0.9 (Bryson+ 2021)
- Biological and social terms (f_l, f_i, f_c, L) span 4–10 orders of magnitude
- Factors co-evolve rather than acting as independent pipeline stages

The Drake equation is a tool for framing ignorance, not a numerical estimator.



Monte Carlo posterior for the number N of communicating civilisations, sampled over the full published parameter ranges. Sandberg, Drexler & Ord (2018).

The distribution is broad and heavy-tailed, with about a third of the probability below $N = 1$ in the Milky Way: the apparent cosmic silence is unsurprising once the priors are honest.

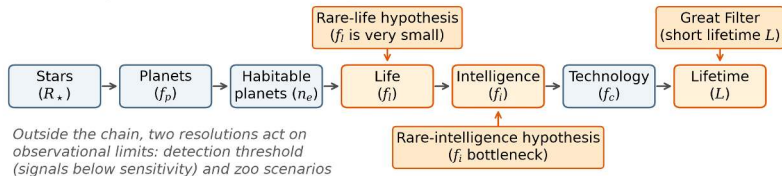
Why So Broad? Log-Sum of Broad Priors

Taking the logarithm turns the Drake product into a sum of broad priors:

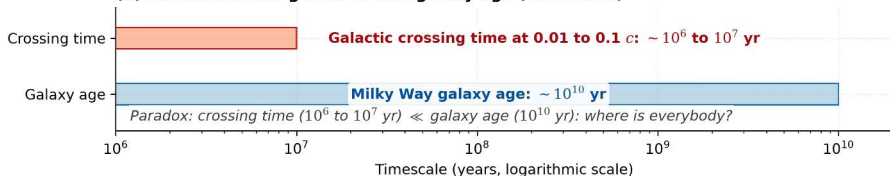
$$\log_{10} N = \log_{10}(R_{\star} f_p n_e) + \log_{10} f_l + \log_{10} f_i + \log_{10} f_c + \log_{10} L$$

- Unconstrained factors have log-uniform priors spanning many decades
- The log-sum of broad, skewed priors spreads $\log N$ over tens of decades; the long low tail of f_l puts a third of the mass below $N = 1$
- The posterior spans ~ 30 decades, placing high probability on $N < 1$

(a) Drake-equation filter chain and proposed resolutions (schematic)



(b) Galactic crossing time versus galaxy age (schematic)



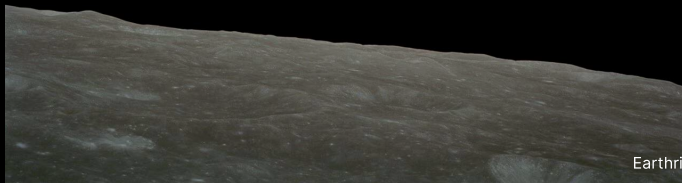
The Fermi paradox as a chain of filters, with a galactic crossing of 10^6 to 10^7 yr against a 10^{10} yr galaxy age. Course figure.

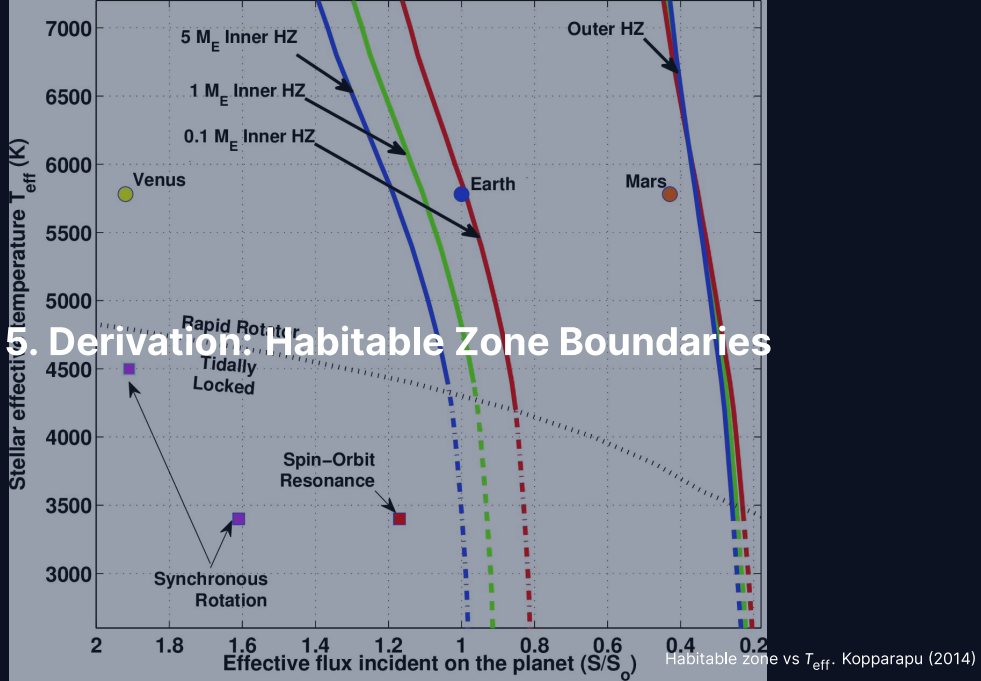
The silence is an intuition check on subjective priors, not physical evidence: rare abiogenesis or intelligence, a Great Filter that keeps L short, or transmissions below current detection limits.

Break

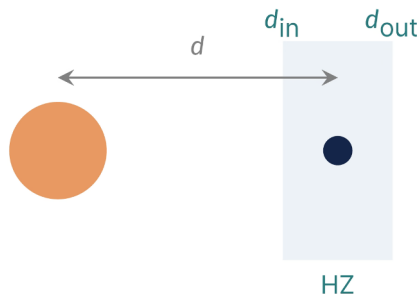


End of Part 1: Solar System Context and Habitability
Part 2: Habitable Zone Derivation, Astrobiology, Life Detection





Goal and strategy



Goal: locate the inner and outer edges of the habitable zone from one energy balance.

- Step 1: energy balance gives $T_{eq}(d)$
- Step 2: a boundary as an effective flux S_{eff} , then a distance
- Step 3: inner edge from the runaway limit (Lecture 9); then the outer edge
- Step 4: G, K and M dwarfs, limits that depend on the star, lifetimes

The zone is the strip between d_{in} and d_{out} .

Setup: Energy In, Energy Out

Star of bolometric luminosity L_* ; planet of radius R_p at distance d , Bond albedo A_B , emissivity ϵ , rotating fast enough for one uniform temperature.

Flux at the planet's orbit (inverse-square law):

$$F_*(d) = \frac{L_*}{4\pi d^2}$$

In: the planet intercepts on its cross-section πR_p^2 and keeps the fraction $1 - A_B$:

$$P_{\text{in}} = (1 - A_B) F_* \pi R_p^2$$

Out: the planet radiates from its whole surface $4\pi R_p^2$ (Stefan-Boltzmann):

$$P_{\text{out}} = 4\pi R_p^2 \epsilon \sigma T_{\text{eq}}^4$$

The ratio of the two areas, $1/4$, is geometry, not albedo.

Step 1: Equilibrium Temperature

Set $P_{\text{in}} = P_{\text{out}}$; the planet's area cancels:

$$(1 - A_B) F_{\star} \cancel{\pi R_p^2} = 4 \cancel{\pi R_p^2} \epsilon \sigma T_{\text{eq}}^4$$

Solve for T_{eq}^4 and insert $F_{\star} = L_{\star} / (4\pi d^2)$:

$$T_{\text{eq}}^4 = \frac{(1 - A_B) F_{\star}}{4\epsilon\sigma} = \frac{(1 - A_B) L_{\star}}{4\epsilon\sigma \cdot 4\pi d^2}$$

Take the fourth root:

$$T_{\text{eq}}(d) = \left[\frac{L_{\star}(1 - A_B)}{16\pi\sigma\epsilon d^2} \right]^{1/4}$$

The planet's size drops out: T_{eq} depends only on $L_{\star}$, d , A_B and ϵ .

Step 1: Earth's Equilibrium Temperature

Earth: $A_B = 0.3$, $\epsilon = 1$, $L_\odot = 3.828 \times 10^{26} \text{ W}$, $d = 1 \text{ AU} = 1.496 \times 10^{11} \text{ m}$,
 $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

$$(1 - A_B) L_\odot = 0.7 \times 3.828 \times 10^{26} \text{ W} = 2.680 \times 10^{26} \text{ W}$$

$$d^2 = (1.496 \times 10^{11} \text{ m})^2 = 2.238 \times 10^{22} \text{ m}^2$$

$$16\pi\sigma d^2 = 16 \times 3.142 \times 5.67 \times 10^{-8} \times 2.238 \times 10^{22} = 6.379 \times 10^{16} \text{ W K}^{-4}$$

$$T_{\text{eq}}^4 = \frac{2.680 \times 10^{26}}{6.379 \times 10^{16}} \text{ K}^4 = 4.201 \times 10^9 \text{ K}^4$$

$$T_{\text{eq}} = \sqrt{\sqrt{4.201 \times 10^9}} \text{ K} = \sqrt{6.48 \times 10^4} \text{ K} = 255 \text{ K}$$

Two square roots make the fourth root. The surface is at 288 K: the greenhouse effect adds $\sim 33 \text{ K}$.

T_{eq} is the yardstick; 1D climate models (Kopparapu et al. 2013) give the real boundaries as fluxes, which we convert to distances next.

Step 2: Effective Stellar Flux and the Distance

Earth's present top-of-atmosphere flux:

$$S_{\oplus} = \frac{L_{\odot}}{4\pi(1 \text{ AU})^2} = \frac{3.828 \times 10^{26} \text{ W}}{2.812 \times 10^{23} \text{ m}^2} = 1361 \text{ W m}^{-2}$$

Define the effective flux as the flux at the planet over $S_{\oplus}$; the 4π cancels:

$$S_{\text{eff}} = \frac{F_{\star}(d)}{S_{\oplus}} = \frac{L_{\star}/(4\pi d^2)}{L_{\odot}/(4\pi (1 \text{ AU})^2)} = \frac{L_{\star}}{L_{\odot}} \left(\frac{1 \text{ AU}}{d} \right)^2$$

Solve for d :

$$d^2 = (1 \text{ AU})^2 \frac{L_{\star}/L_{\odot}}{S_{\text{eff}}} \Rightarrow \boxed{d = 1 \text{ AU} \sqrt{\frac{L_{\star}/L_{\odot}}{S_{\text{eff}}}}}$$

A boundary is a flux, not a temperature. Flux falls as d^{-2} , so d goes as a square root.

Step 3: Inner Edge, the Runaway Greenhouse

- Lecture 9: saturation clamps the photosphere temperature, so a moist atmosphere emits at most $F_{\text{OLR}}^{\text{max}} \approx 280 \text{ W m}^{-2}$ (grey 253, line by line 280 to 310)
- Absorbed flux above it: the oceans go into the atmosphere

Step 1 balance divided by $4\pi R_p^2$, with $F_{\text{OLR}}^{\text{max}}$ for $\epsilon\sigma T_{\text{eq}}^4$ and $F_{\star} = S_{\text{eff}} S_{\oplus}$:

$$\frac{(1 - A_B) S_{\text{in,eff}} S_{\oplus}}{4} = F_{\text{OLR}}^{\text{max}} \Rightarrow \boxed{S_{\text{in,eff}} = \frac{4 F_{\text{OLR}}^{\text{max}}}{(1 - A_B) S_{\oplus}}}$$

Kopparapu et al. (2013), cloud-free steam atmosphere: $F_{\text{OLR}}^{\text{max}} = 291 \text{ W m}^{-2}$, $A_B = 0.19$:

$$S_{\text{in,eff}} = \frac{4 \times 291}{0.81 \times 1361} = \frac{1164}{1102} = 1.06$$

Water vapour absorbs near-infrared sunlight: the hot steam atmosphere reflects 0.19, against ~ 0.3 for the same model at Earth-like temperatures.

Step 3: Inner Edge, the Distance

Insert $S_{\text{in,eff}} = 1.06$ into the boxed distance of Step 2, with $L_{\star} = L_{\odot}$:

$$d_{\text{in}} = \frac{1 \text{ AU}}{\sqrt{1.06}} = \frac{1 \text{ AU}}{1.030} = 0.97 \text{ AU}$$

Albedo check: with Earth's $A_B = 0.3$ instead of 0.19,

$$S_{\text{in,eff}} = \frac{4 \times 291}{0.7 \times 1361} = \frac{1164}{953} = 1.22, \quad d_{\text{in}} = \frac{1 \text{ AU}}{\sqrt{1.22}} = 0.90 \text{ AU}$$

An albedo higher by 0.11 moves the edge 0.07 AU closer to the star.

Venus, at 0.72 AU:

$$S_{\text{eff}} = \left(\frac{1 \text{ AU}}{0.72 \text{ AU}} \right)^2 = \frac{1}{0.518} \approx 1.9 > 1.06$$

Venus receives about 1.8 times the runaway flux (1.9/1.06): it sits well inside the inner edge.

Outer Edge: the Maximum CO₂ Greenhouse

- More CO₂ warms a cold planet, but only up to a point: near 10 bar the atmosphere is optically thick at all infrared wavelengths, so the outgoing infrared flux stops falling
- Rayleigh scattering by CO₂ continues to raise the albedo: beyond this point more CO₂ cools the planet
- The maximum greenhouse sets a minimum stellar flux that keeps the surface above 273 K; Kopparapu et al. (2013), Sun-like star: $S_{\text{out,eff}} \approx 0.35$

$$d_{\text{out}} = \frac{1 \text{ AU}}{\sqrt{0.35}} = \frac{1 \text{ AU}}{0.592} = 1.69 \text{ AU} \quad \text{Mars, 1.52 AU: } S_{\text{eff}} = \left(\frac{1}{1.52}\right)^2 = \frac{1}{2.31} = 0.43 > 0.35$$

The Sun's habitable zone runs from 0.97 to 1.69 AU, a width of ~ 0.7 AU; Mars is just inside the outer edge.

Step 4: K and M Dwarfs, Every Root

The same two flux limits; only L_* changes, and the zone scales as $\sqrt{L_*}$.

K dwarf (ϵ Eri), $L_*/L_\odot = 0.3$:

$$d_{\text{in}} = \sqrt{0.3/1.06} \text{ AU} = \sqrt{0.283} \text{ AU} = 0.53 \text{ AU}$$

$$d_{\text{out}} = \sqrt{0.3/0.35} \text{ AU} = \sqrt{0.857} \text{ AU} = 0.93 \text{ AU}$$

M dwarf (TRAPPIST-1), $L_*/L_\odot = 5 \times 10^{-4}$:

$$d_{\text{in}} = \sqrt{5 \times 10^{-4}/1.06} \text{ AU} = \sqrt{4.72 \times 10^{-4}} \text{ AU} = 0.022 \text{ AU}$$

$$d_{\text{out}} = \sqrt{5 \times 10^{-4}/0.35} \text{ AU} = \sqrt{1.43 \times 10^{-3}} \text{ AU} = 0.038 \text{ AU}$$

Star	$L_*/L_\odot$	d_{in} [AU]	d_{out} [AU]
G (Sun)	1	0.97	1.69
K (ϵ Eri)	0.3	0.53	0.93
M (TRAPPIST-1)	5×10^{-4}	0.022	0.038

Step 4: HZ Across Stellar Types

- **G dwarf** ($L_{\odot}$): $d = 0.97\text{--}1.69$ AU, width ~ 0.7 AU; main-sequence lifetime ~ 10 Gyr; modest activity. The reference case.
- **K dwarf** ($0.3 L_{\odot}$): $d = 0.53\text{--}0.93$ AU; lifetime ~ 15 to 35 Gyr (~ 16 Gyr for ϵ Eri at $0.82 M_{\odot}$); modest flares; the zone is far enough out to avoid most tidal-locking and pre-main-sequence problems. Cuntz & Guinan (2016): perhaps the *most habitable* class of host star.
- **M dwarf** ($5 \times 10^{-4} L_{\odot}$): $d = 0.022\text{--}0.038$ AU with the solar limits (0.024 to 0.048 AU with the M-dwarf limits, next slide), inside Mercury's orbit; lifetime trillions of years, but every zone planet is tidally locked, and a late M dwarf such as TRAPPIST-1 spends a Gyr in a bright pre-main sequence that puts any zone planet into the runaway state (Luger & Barnes 2015). Early M dwarfs (M0 to M3): pre-main sequence of only ~ 50 to 150 Myr.

Step 4: The Flux Limits Depend on the Star

- Red light: weaker Rayleigh scattering ($\propto \lambda^{-4}$), more near-infrared absorption by H_2O and CO_2 , so lower A_B and lower limits
- Kopparapu et al. (2013) fit for 2600 to 7200 K: $S_{\text{eff}} = S_{\text{eff},\odot} + aT_* + bT_*^2 + cT_*^3 + dT_*^4$,
 $T_* = T_{\text{eff}} - 5780 \text{ K}$ (coefficients: their erratum, Table 3)
- TRAPPIST-1 (2560 K) is just below the range; at 2600 K and $L_*/L_\odot = 5 \times 10^{-4}$:

$$S_{\text{in,eff}} = 0.86 \quad \Rightarrow \quad d_{\text{in}} = \sqrt{5 \times 10^{-4} / 0.86} \text{ AU} = 0.024 \text{ AU}$$

$$S_{\text{out,eff}} = 0.22 \quad \Rightarrow \quad d_{\text{out}} = \sqrt{5 \times 10^{-4} / 0.22} \text{ AU} = 0.048 \text{ AU}$$

TRAPPIST-1 (Gillon et al. 2017)	e	f	g
S_{eff} received	0.66	0.38	0.26
Solar limits, 1.06 to 0.35	inside	inside	outside
Limits at 2600 K, 0.86 to 0.22	inside	inside	inside

The spectrum moves the edges outward: TRAPPIST-1's zone holds e, f and g.

Step 4: How Long the Zone Lasts

Fuel $\propto$ mass, burn rate = luminosity, $L_{\star} \propto M_{\star}^{3.5}$ (low- and intermediate-mass stars):

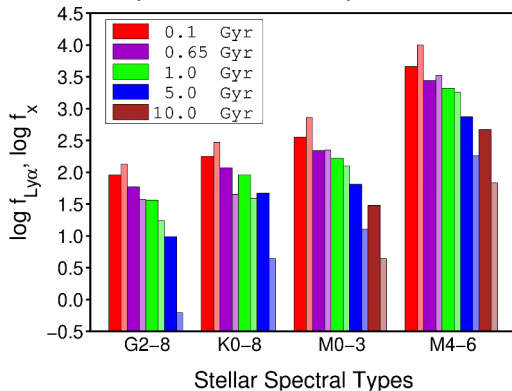
$$t_{\text{MS}} \sim \frac{E_{\text{nuc}}}{L_{\star}} \propto \frac{M_{\star}}{M_{\star}^{3.5}} = M_{\star}^{-2.5} \Rightarrow t_{\text{MS}} \approx 10 \text{ Gyr} \left(\frac{M_{\star}}{M_{\odot}} \right)^{-2.5}$$

Star	$M_{\star}/M_{\odot}$	$(M_{\star}/M_{\odot})^{-2.5}$	t_{MS}
ϵ Eri (K)	0.82	1.64	16 Gyr
K dwarf	0.7	2.44	24 Gyr
Early M dwarf	0.5	5.66	57 Gyr
Late M dwarf	0.1	316	$3 \times 10^3 \text{ Gyr} = 3 \times 10^{12} \text{ yr}$

$0.1 M_{\odot}$: far longer than the age of the universe; stellar models also give trillions of years (a fully convective star mixes all its hydrogen into the core).

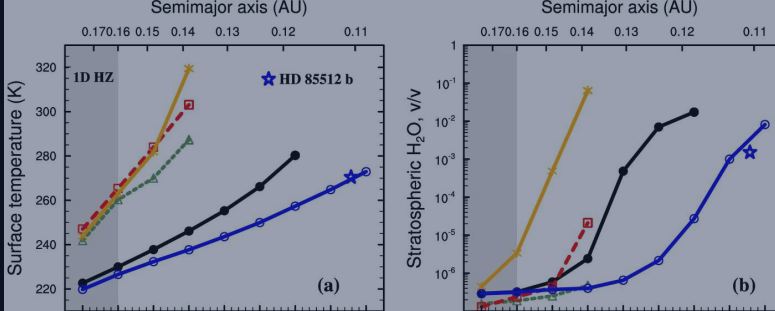
Cooler stars give biology more time, by a factor that grows steeply with decreasing stellar mass.

Lyman- α and X-ray Irradiance

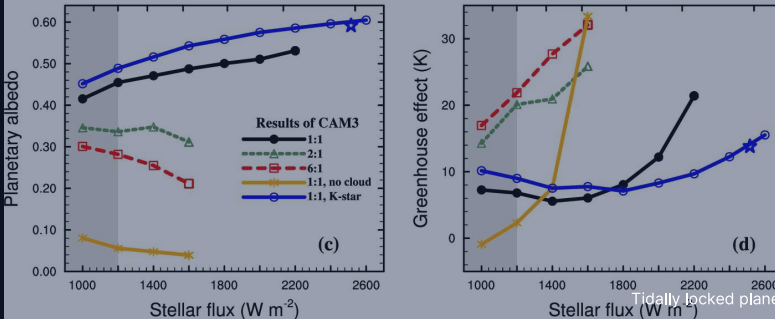


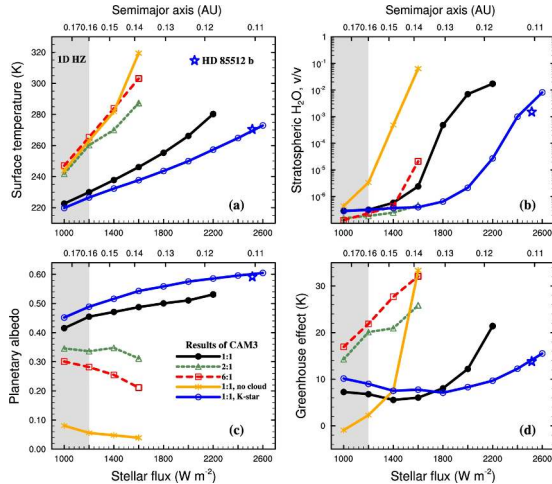
Lyman- α and X-ray flux at the Earth-equivalent distance against stellar type and age.
Cuntz & Guinan (2016).

M4-M6 dwarfs deliver about 50 to 300 times the G-dwarf flux; X-rays drop up to 200-fold over 5 Gyr but Lyman- α only 5 to 10-fold, so early K dwarfs offer long lifetimes without the M-dwarf XUV extremes.



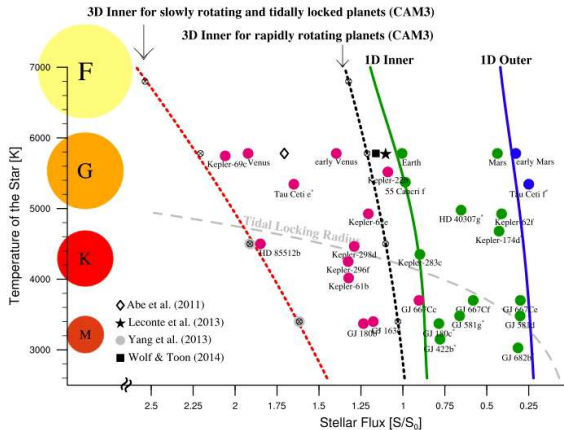
6. HZ Corrections: 3D Climate, Tidal Locking





3D global climate model of a tidally locked planet with clouds. Yang et al. (2013).

Substellar convection lifts thick water clouds, the albedo rises to ~ 0.5 (0.6 for a K dwarf), and the inner edge tolerates $\sim 2\times$ the 1D flux.



M-dwarf habitable-zone limits, flux increasing to the left: 1D Kopparapu boundaries (solid), 3D inner edge (red dotted) and the tidal-locking radius (grey dashed). Shields et al. (2016).

The 3D inner edge tolerates 1.7–2.2× the 1D flux, and the tidal-locking radius encloses almost all M-dwarf habitable-zone planets.

Tidal-Locking Timescale

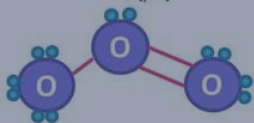
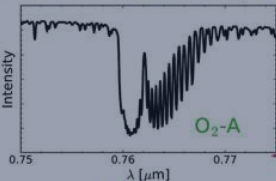
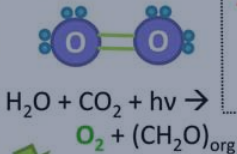
Tidal despinning scales steeply as a^6 , so close-in habitable planets around low-mass stars synchronise quickly:

$$\tau_{\text{lock}} \sim \frac{\omega_0 a^6 I_p Q_p}{3 G M_{\star}^2 k_{2,p} R_p^5}$$

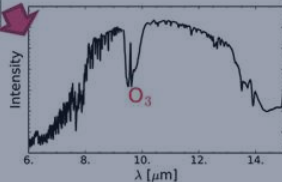
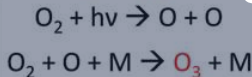
- Earth at 1 AU has $\tau_{\text{lock}} \sim 10^{11}$ yr, several times the age of the universe
- TRAPPIST-1 b ($a \approx 0.011$ AU) synchronises within decades to centuries, depending on Q_p
- With a system age of ~ 8 Gyr, essentially every known M-dwarf HZ world is locked

Gaseous

Ex: **Oxygenic Photosynthesis**



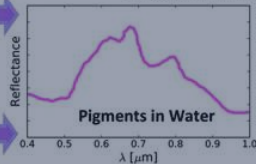
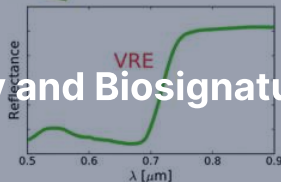
7. Astrobiology and Biosignatures



Surface



$$\text{NDVI} = \frac{\text{IR} - \text{VIS}}{\text{IR} + \text{VIS}}$$



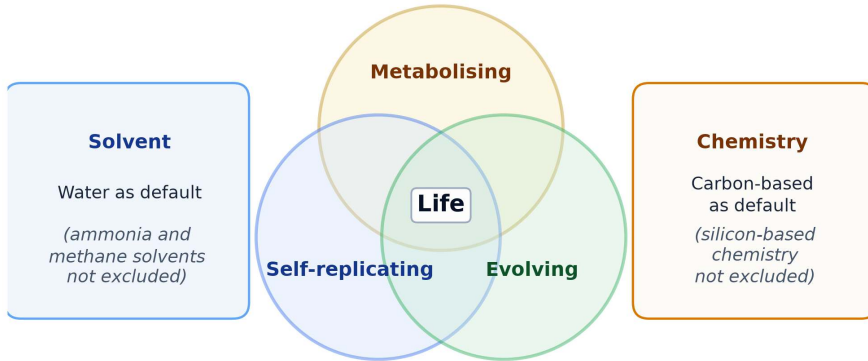
Temporal



Seasonal changes in Gases or Surface

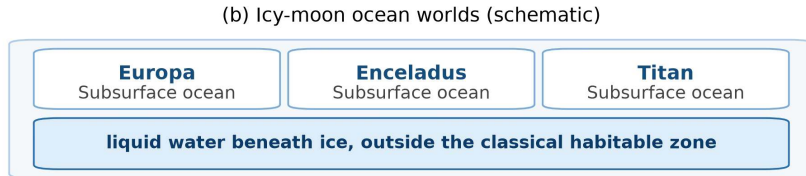
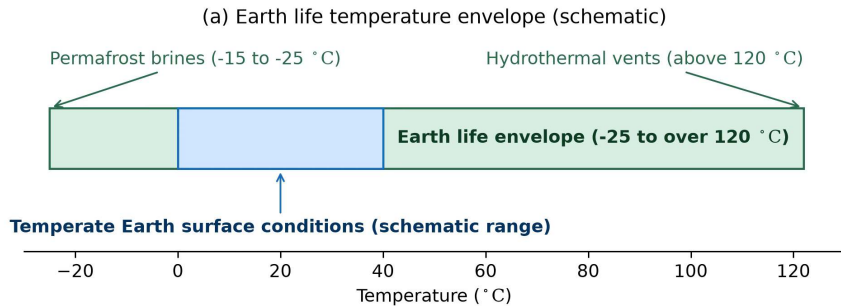


Working definition of life (schematic)



A working definition of life. Course figure.

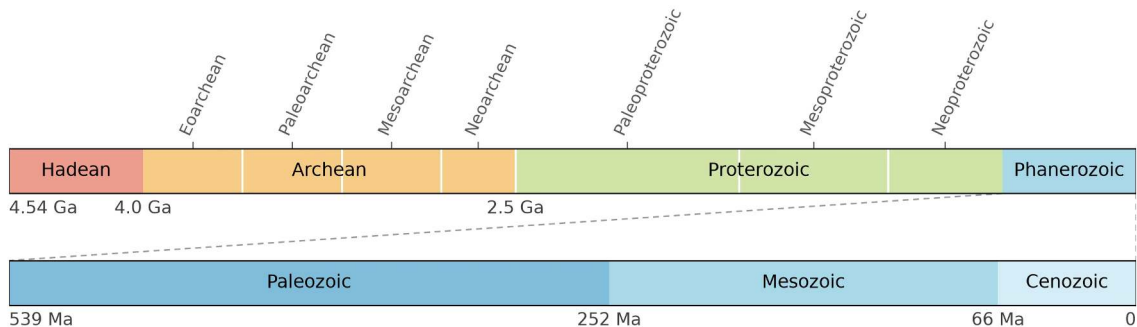
Life (Lederberg 1965): a self-replicating, metabolising, evolving chemical system.



Extremophiles widen the definition of habitable: Earth life spans -25 to over 120 °C, and the icy moons hold liquid water beneath ice outside the classical habitable zone, in contact with rock at Europa and Enceladus. Course figure.

Origin-of-Life Hypotheses

- **RNA world:** catalytic ribozymes carry the genetic code before proteins
- **Alkaline hydrothermal vents:** geochemical proton gradients drive early metabolism
- **Warm surface ponds,** where wet-dry cycles polymerise organic precursors, and **panspermia,** the transfer of viable organisms between bodies

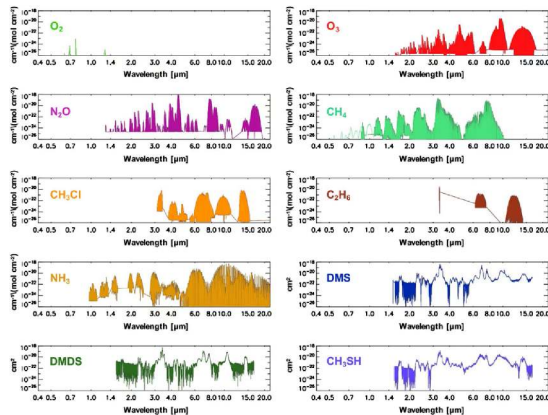


Geologic eons and eras of Earth across 4.54 Gyr: the Precambrian occupies almost 90% of the timeline, with life emerging early in the Archean.
Credit: Course-original figure; Gradstein et al. (2020).

Disequilibrium is the Diagnostic

- Individual gases in isolation almost always possess plausible abiotic origins
- Earth pair: O_2 (21%) and CH_4 (1.8 ppm) react on decade timescales
- Simultaneous persistence requires massive, continuous biological resupply fluxes

Chemically incompatible gases coexisting in an atmosphere are the most convincing remote signature of active biology.



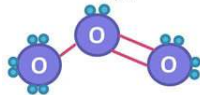
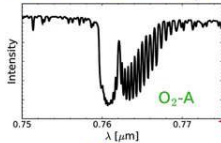
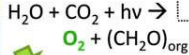
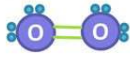
Absorption bands of ten candidate biosignature gases, 0.4 to 20 μm .

Schwieterman et al. (2018).

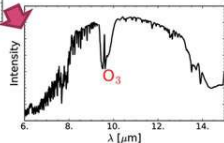
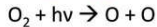
O_3 at 9.6 μm , CH_4 at 3.3 and 7.7 μm , N_2O and the DMS and DMDS window at 6–15 μm set the needs of the mid-IR interferometer LIFE; O_2 at 0.76 μm and the visible O_3 bands set those of the coronagraph HWO.

Gaseous

Ex: **Oxygenic Photosynthesis**



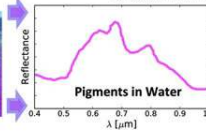
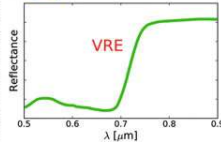
Photolytic Byproduct



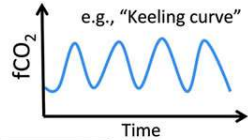
Surface



$$\text{NDVI} = \frac{\text{IR} - \text{VIS}}{\text{IR} + \text{VIS}}$$



Temporal



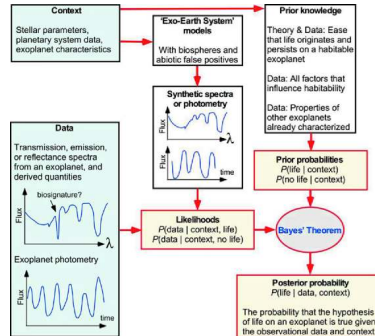
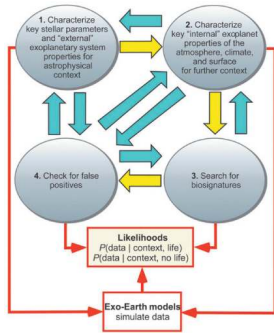
Seasonal Changes in Gases or Surface



Three classes of biosignature. Schwieterman et al. (2018).

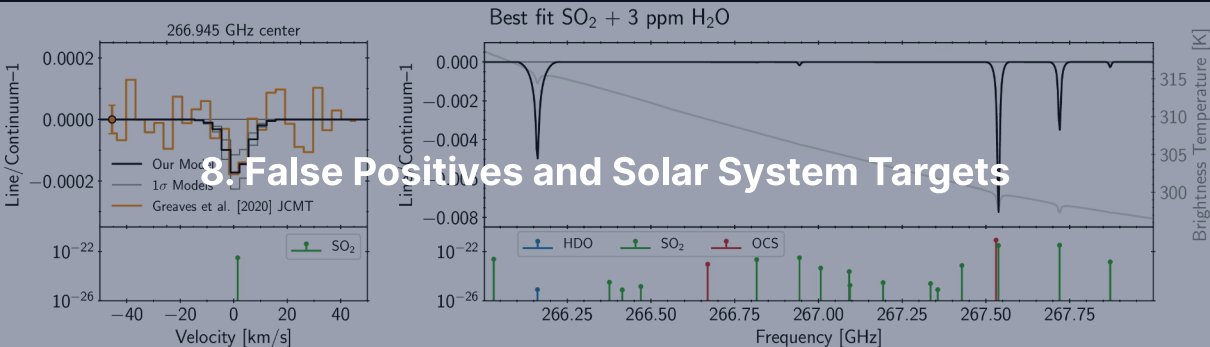
Gaseous (O_2 , O_3 , CH_4 , N_2O , organosulfur species), **surface** (the vegetation red edge near 700 nm) and **temporal** (seasonal cycles such as Earth's CO_2 Keeling oscillation): a credible detection needs several classes together.

Catling 2018: A Bayesian Framework



Detection is a Bayesian chain of inference over stellar context, planetary properties and abiotic mechanisms, not a single yes/no spectral peak.

Source: Catling et al. (2018)



False Positives: Every Gas Has an Abiotic Pathway

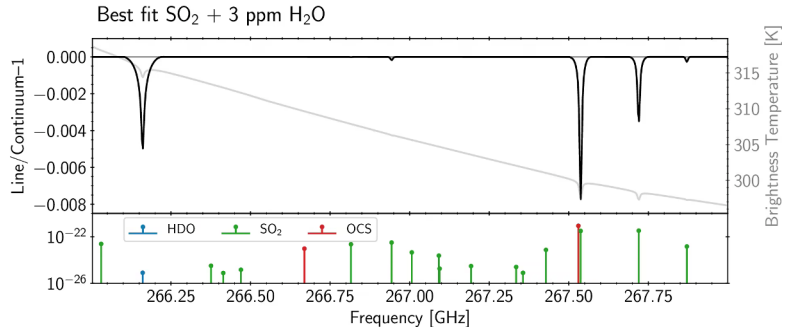
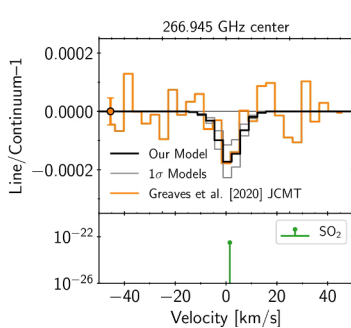
- Abiotic O_2 : H_2O photolysis followed by hydrogen escape, or CO_2 photolysis
- Abiotic CH_4 : hydrothermal serpentinisation or volcanic outgassing at low oxygen fugacity
- Abiotic N_2O from lightning and photochemistry; DMS has no significant abiotic Earth source, but one could exist elsewhere

Verification is an inverse problem: confirmation requires ruling out every plausible geochemical and photochemical false positive.

Solar System Targets for Life Detection

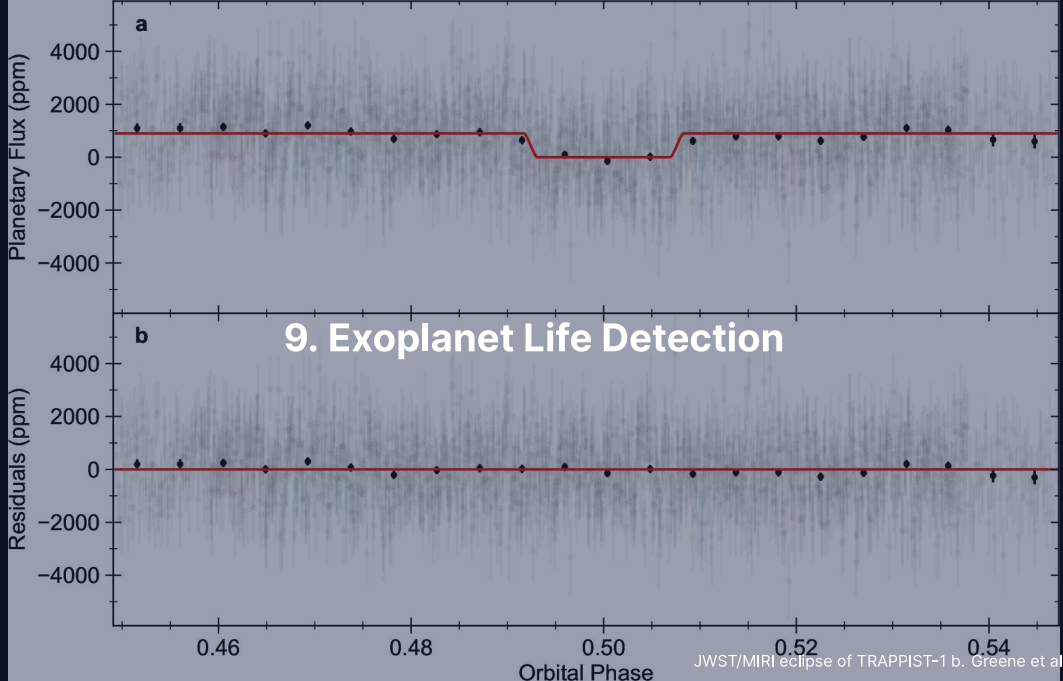
- Mars: ancient habitable lacustrine environments; returned samples are the most direct test, but Mars Sample Return has no funding since 2026
- Europa and Enceladus: confirmed subsurface oceans; Enceladus's plume carries H_2 , organics and phosphates from hydrothermal activity, hypothesised for Europa
- Titan and Venus: complex hydrocarbon hydrology and contested cloud chemistry

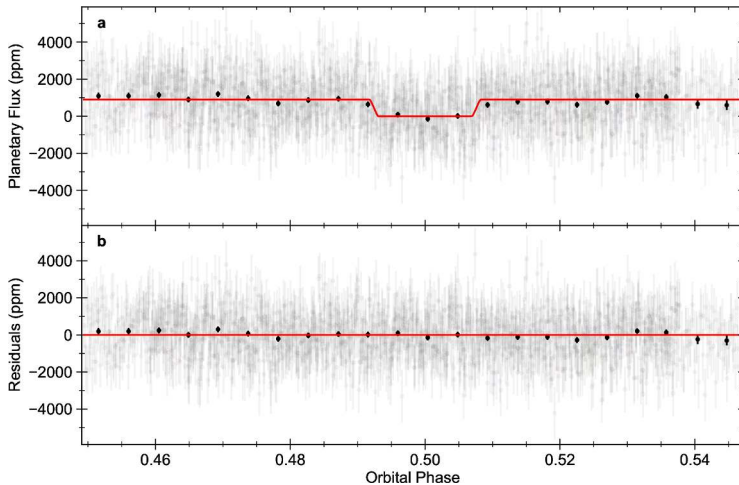
Five prime environments with liquid water reservoirs or rich organic chemistry.



The Venus phosphine controversy: the claimed PH₃ line against the mesospheric SO₂ fit.
Lincowski et al. (2021).

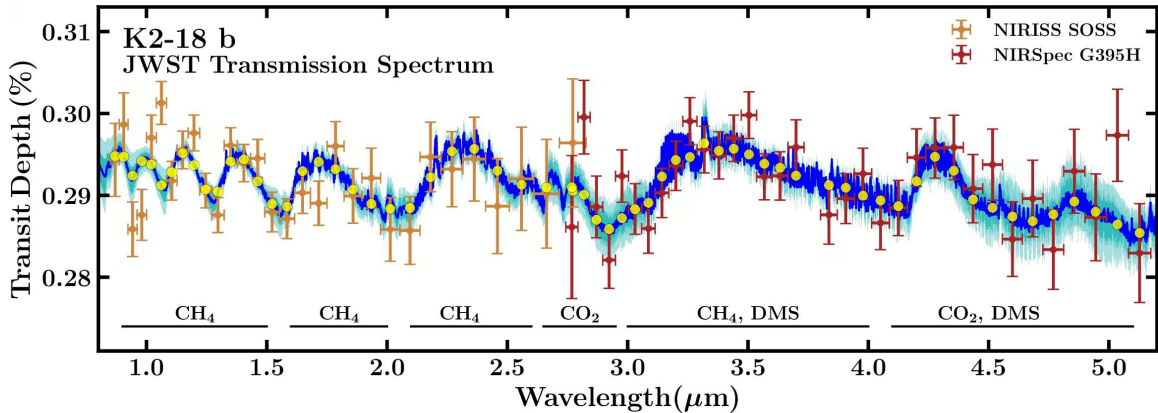
Greaves et al. (2021) claimed PH₃ in the Venus clouds, but the line is fit by mesospheric SO₂. DAVINCI tests Venus in situ, EnVision and VERITAS from orbit.





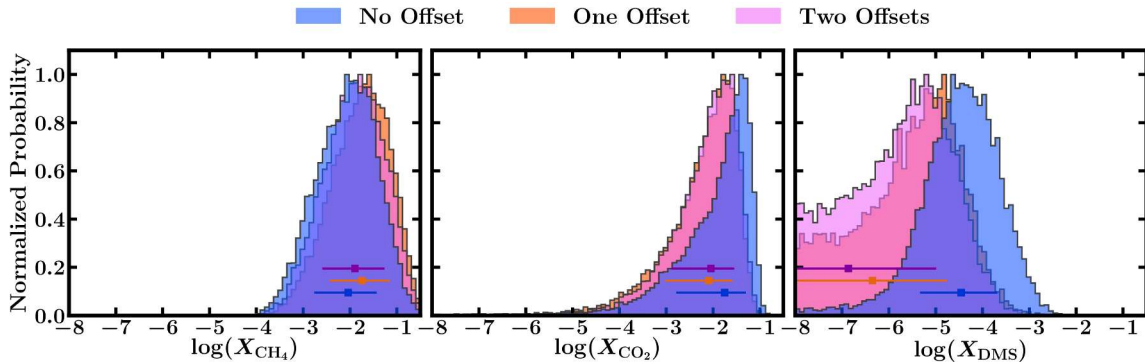
JWST MIRI 15 μm secondary eclipse of TRAPPIST-1 b. Greene et al. (2023).

The dayside brightness temperature of 503 K matches the 508 K bare-rock prediction and rules out a thick atmosphere.



JWST transmission spectrum of K2-18 b combining NIRISS and NIRSpec observations.
Madhusudhan et al. (2023).

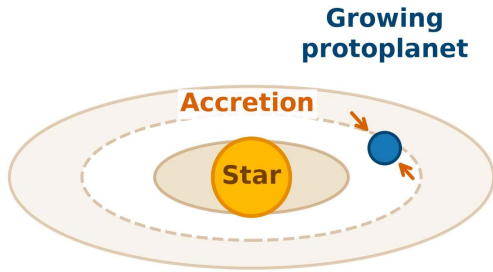
Absorption bands reveal atmospheric CH_4 and CO_2 alongside a tentative DMS feature near $3.4 \mu\text{m}$.



Retrieved mixing ratio posteriors for CH_4 , CO_2 and DMS in K2-18 b under zero, one and two floating instrument offsets. Madhusudhan et al. (2023).

CH_4 and CO_2 hold under every offset choice, while the DMS significance collapses from 2.4σ to below 1σ .

Planet formation



Protoplanetary disk

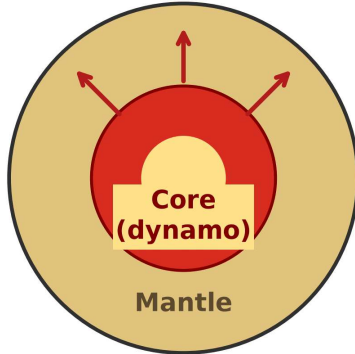
*Accretion and disk
(schematic)*

Lesson 1 of 5. Course figure.

Planet formation is a physical process governed by accretion, gravity and disk dynamics, producing a predictable diversity of outcomes.

Planetary interiors

Heat flux

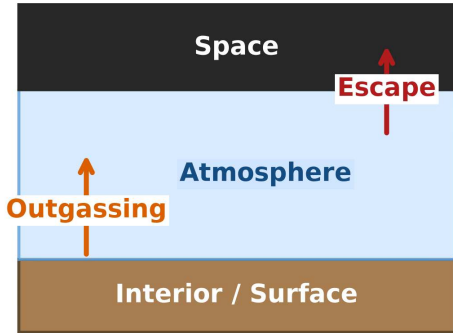


*Internal heat engine
(schematic)*

Lesson 2 of 5. Course figure.

Planetary interiors are heat engines whose evolution drives surface tectonics, volcanic outgassing, magnetic dynamos and long-term habitability on Gyr timescales.

Atmospheres

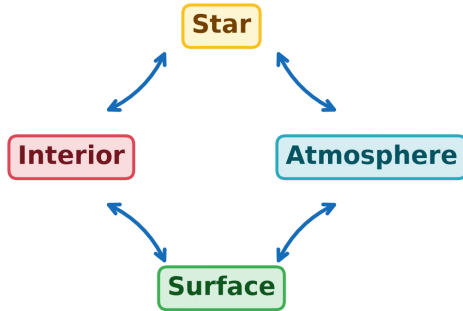


*Evolution and escape
(schematic)*

Lesson 3 of 5. Course figure.

Atmospheres are dynamic systems that form, evolve, escape and react with interiors and surfaces, so no default atmosphere exists.

Habitability

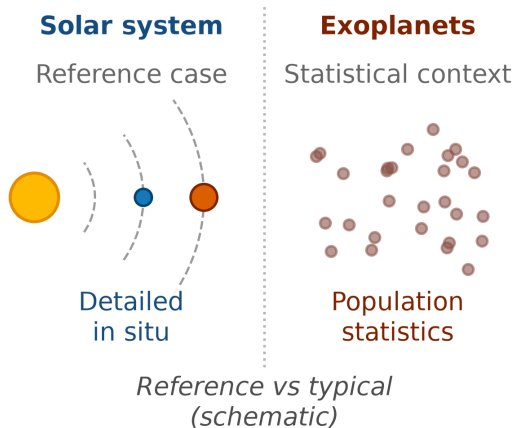


*Coupled habitability
(schematic)*

Lesson 4 of 5. Course figure.

Habitability is a coupled systems property linking stellar, orbital, planetary and biospheric factors across star, atmosphere, surface and interior.

The solar system



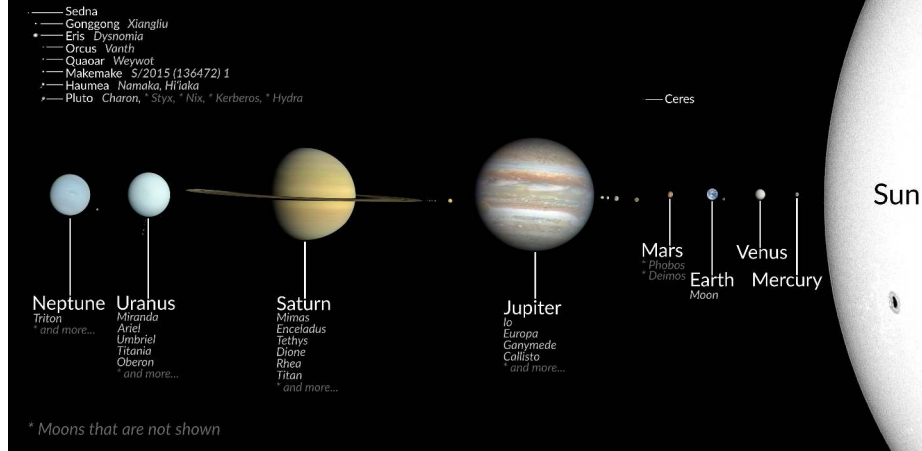
Lesson 5 of 5. Course figure.

The solar system is a detailed reference case, while the exoplanet population provides the statistical context for what is typical.

	Open question	What is at stake, and what will decide it
1	Is the origin of life a rare accident or a generic chemical inevitability?	The largest uncertainty in quantitative habitability estimates
2	What carves the radius valley between super-Earths and sub-Neptunes?	Photoevaporation, core-powered mass loss, or distinct formation channels
3	When did Jupiter form?	Architect of the inner solar system: the NC-CC dichotomy and Earth-like system rarity
4	Was Mars ever inhabited?	Returned Mars samples, the most direct test; they recalibrate the prior on f_i
5	Is the solar system rare or typical?	PLATO, Gaia DR4/DR5 and long-baseline RV give a probabilistic answer

The five biggest open questions, each with what is at stake or the test that will decide it.
Course figure.

Solar System in true imagery, color and size



The principal bodies of the solar system grouped by region at true relative size, from the terrestrial planets to the Kuiper belt objects.

Credit: CactiStaccingCrane (Wikimedia Commons, CC BY-SA 4.0); NASA/ESA/ISRO.

Summary

1. Planet formation and differentiation are universal physical processes; interiors are heat engines that drive tectonics, dynamos and outgassing over Gyr
2. Atmospheres evolve through escape, outgassing and photochemistry, and habitability is a coupled trajectory, not a static orbital condition
3. The solar system is one detailed reference in a diverse exoplanet population

Next: The final exam.

The final exam

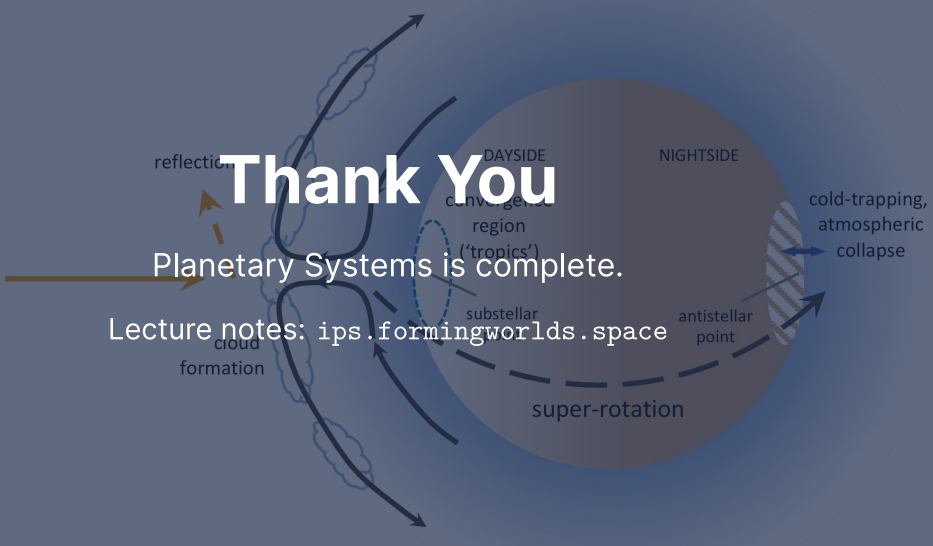
When and where

- Wed 28 Oct 2026, 15:00 to 17:00
- Exam Hall 4 (5263.0226)
- Closed book: bring a calculator and a pen
- Re-sit: Mon 25 Jan 2027, 15:00 to 17:00, Exam Hall 1 (5263.0102)

What to expect

- 6 questions of 10 points, 120 minutes
- Calculations in parts (a) to (c), as in the worksheets; each question spans two to three lectures
- The steps carry marks, not only the number: show your algebra
- Know the 12 relations of the formula list; every other formula and all data are printed

Prepare with the 7 worksheets and the 3 mock exams on the course website.



The diagram illustrates a tidally locked planet with a central brown star on the left. A thick orange arrow points from the star to the planet. The planet is divided into a 'DAYSIDE' (facing the star) and a 'NIGHTSIDE' (facing away). On the dayside, there is a 'convergence region ('tropics')' marked with a dashed blue circle, and a 'substellar point' indicated by a line. Clouds are shown on the dayside with arrows pointing to them labeled 'cloud formation'. A dashed line around the planet indicates 'super-rotation'. On the nightside, there is an 'antistellar point' and a region of 'cold-trapping, atmospheric collapse' shown with a hatched pattern and a blue arrow pointing to it. A dashed arrow labeled 'reflection' points away from the dayside. The background is a dark blue gradient.

Thank You

Planetary Systems is complete.

Lecture notes: ips.formingworlds.space