

Planetary Systems

WBAS002-05 · 5 ECTS · Semester 1a, 2026–2027

dr. Tim Lichtenberg (coordinator + lecturer) · tim.lichtenberg@rug.nl

dr. Mara Attia (lecturer, atmospheres) · m.attia@rug.nl

Teaching assistants:

Mariana Sastre villamilsastre@astro.rug.nl · Emma Postolec postolec@astro.rug.nl

Soumil Kelkar s.m.kelkar@rug.nl · Imre Kisvárdai kisvardai@astro.rug.nl

Kapteyn Astronomical Institute, University of Groningen

<https://ips.formingworlds.space>

What this course is about

A physics-based introduction to the solar system's planets and to extrasolar planetary systems: how they form and evolve, how atmospheres, surfaces, and interiors couple, and what both reveal about planetary diversity and habitability.

At the end of this course, you are able to:

1. Describe planetary-system formation and evolution, and place the solar system among exoplanets.
2. Explain heat generation and energy transport in planetary interiors and atmospheres.
3. Describe the structure and dynamics of atmospheres, surfaces, interiors, and magnetospheres.
4. Apply orbital mechanics, thermodynamics, and radiative transfer to quantitative problems.
5. Compare the major classes of solar-system bodies in formation, structure, and observables.
6. Evaluate exoplanet detection methods and interpret demographics and characterisation data.
7. Synthesise across these fields to assess planetary diversity and habitability.

Course overview

14 lectures + 7 tutorials, grouped as:

- L1–L2: setting the stage; disks, orbits
- L3–L4: heat, interiors, differentiation
- L5–L7: atmospheres, climate, surfaces
- L8–L10: Earth, Venus, Mercury, Mars
- L11–L12: giants, moons, small bodies
- L13–L14: exoplanets, astrobiology, outlook

Assessment: final written exam (100%); ungraded worksheets as preparation.

Three driving questions

1. How did our solar system form, and is it typical?
2. What determines whether a planet becomes habitable?
3. Are we alone?

Participation: nothing is mandatory; lectures and tutorials are opt-in. The only requirement is passing the exam with a grade > 5.5.

Expectation

A normal completion of the course requires studying the lecture notes in addition to attending the lectures. Optimally, read the relevant notes *before* the lecture.

Course schedule: September

	Date	Time	Content
L1	Mon 7 Sep	15:00–17:00	Introduction & history of planetary science
L2	Thu 10 Sep	11:00–13:00	Planet formation & orbital dynamics
T1	Fri 11 Sep	13:00–15:00	Tutorial 1
L3	Mon 14 Sep	15:00–17:00	Planetary heat & energy transport
L4	Thu 17 Sep	11:00–13:00	Chemical differentiation & magnetospheres
T2	Fri 18 Sep	13:00–15:00	Tutorial 2
L5	Mon 21 Sep	15:00–17:00	Atmospheres I (<i>dr. Mara Attia</i>)
L6	Thu 24 Sep	11:00–13:00	Atmospheres II (<i>dr. Mara Attia</i>)
T3	Fri 25 Sep	13:00–15:00	Tutorial 3
L7	Mon 28 Sep	15:00–17:00	Planetary surfaces
L8	Thu 1 Oct	11:00–13:00	Planetary interiors
T4	Fri 2 Oct	13:00–15:00	Tutorial 4

Room 5419.0161 (Collegezaal). Lecturer: dr. Tim Lichtenberg unless noted.

Course schedule: October & exams

	Date	Time	Content
L9	Mon 5 Oct	15:00–17:00	Rocky planets: Earth & Venus
L10	Tue 6 Oct	17:00–19:00	Rocky planets: Mercury & Mars
T5	Fri 9 Oct	13:00–15:00	Tutorial 5
L11	Mon 12 Oct	15:00–17:00	Gas & ice giants
L12	Thu 15 Oct	11:00–13:00	Meteorites, asteroids & comets
T6	Fri 16 Oct	13:00–15:00	Tutorial 6
L13	Mon 19 Oct	15:00–17:00	Exoplanets
L14	Thu 22 Oct	11:00–13:00	Synthesis & astrobiology
T7	Fri 23 Oct	13:00–15:00	Tutorial 7
Exam	Wed 28 Oct 2026	15:00–17:00	Exam Hall 4 (5263.0226)
Re-sit	Mon 25 Jan 2027	15:00–17:00	Exam Hall 1 (5263.0102)

Note the Tuesday *evening* slot for L10. Lectures and tutorials: room 5419.0161 (Collegezaal).

Worksheets: seven problem sets, one per two-lecture block.

- Worksheets *and* full solutions are available on the course website.
- In addition, a few **mock exams** with full solutions are provided there.

Tutorials (Fridays):

- Start with a ~5–10 min **mini-recap** of the concepts most important for the worksheet.
- The TAs are there to **answer questions and discuss the problem sets** with you.
- They may put a few qualitative questions to the classroom to get discussion going.
- They will *not* present full solutions; you are given those in full already.

Suggestion: first try to solve each problem set alone and really think it through before looking at the solutions.

- The exam has the **exact same shape and level as the problem sets**.
- **Six questions**, each spanning two to three lectures; the central formula a question needs is **printed in the question**.
- **Everything is relevant**: all content in the course lecture notes (the website), the lectures, and the slides; no exceptions.
- **Closed book**: you can only bring a calculator and a pen; nothing else is needed.
- Regular **2-hour** written exam: Wed 28 October 2026, 15:00–17:00, Exam Hall 4.
- Practice with the worksheets and the mock exams; they define the level.

Lecture 1: Introduction & History of Planetary Science

Planetary Systems

Tim Lichtenberg

Kapteyn Astronomical Institute
University of Groningen

2026

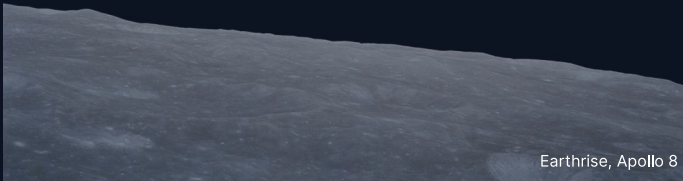
Learning objectives

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

- Describe the scope of planetary science and its three driving questions.
- Outline how the field evolved from antiquity through the space age into the exoplanet era.
- Identify the principal solar-system populations and their gross physical properties.
- Derive the stellar mass from a planet's orbital period and semi-major axis.

Planetary science is the comparative, physical study of planets, moons, and small bodies, in our solar system and beyond.

1. A pale blue dot



Earthrise, Apollo 8 (1968). Credit: NASA / W. Anders

A pale blue dot



Credit: NASA/JPL-Caltech, PIA00452 (1990)

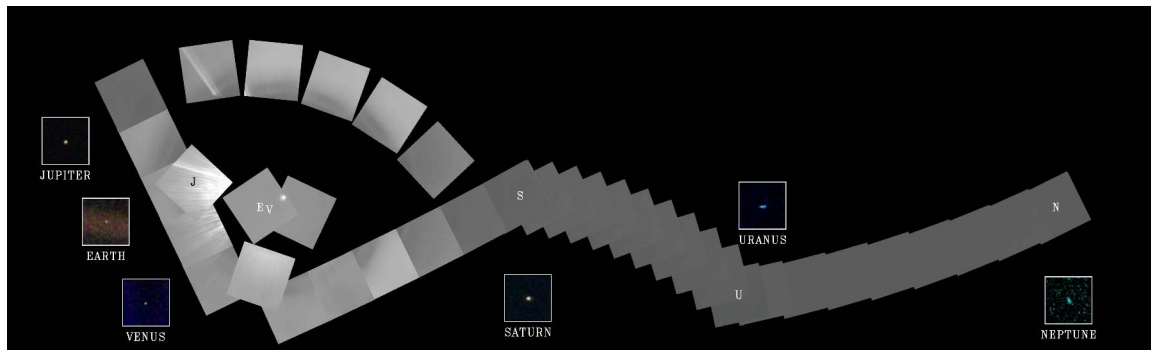
On 14 February 1990, **Voyager 1** turned its camera back toward the inner solar system from ~6 billion km (~40 AU).

Earth is a tiny bright speck, less than one pixel, suspended in a scattered sunbeam (right beam).

"Look again at that dot. That's here. That's home. That's us."

Carl Sagan, 1994

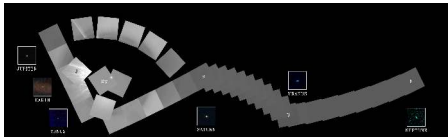
Minutes later, Voyager's cameras were switched off for good.



Voyager 1 "Family Portrait" mosaic, 14 February 1990. Credit: NASA/JPL-Caltech, PIA00451.

Reading the Family Portrait

60-frame mosaic spanning $\sim 70^\circ$ of sky, taken from ~ 6 billion km the same day as the Pale Blue Dot.



- Six of the eight planets are visible: **Venus, Earth, Jupiter, Saturn, Uranus, Neptune.**
- **Mercury** sat too close to the Sun's glare to be safely imaged.
- **Mars** showed only a thin sunlit crescent from Voyager 1's viewpoint and could not be detected.
- **Pluto** was too small and too distant.
- The only spacecraft image of our entire planetary system from outside.

Earthrise: a second perspective



Credit: NASA AS8-14-2383 / W. Anders (1968)

Apollo 8, 24 December 1968.

Earth rises above the lunar limb during the first crewed flight to leave Earth orbit.

Widely credited with shifting public perception of Earth as a finite, planetary system, an early articulation of the *comparative-planetology* view this course takes throughout.

The three driving questions of this course

1. **How did our solar system form, and is it typical?**

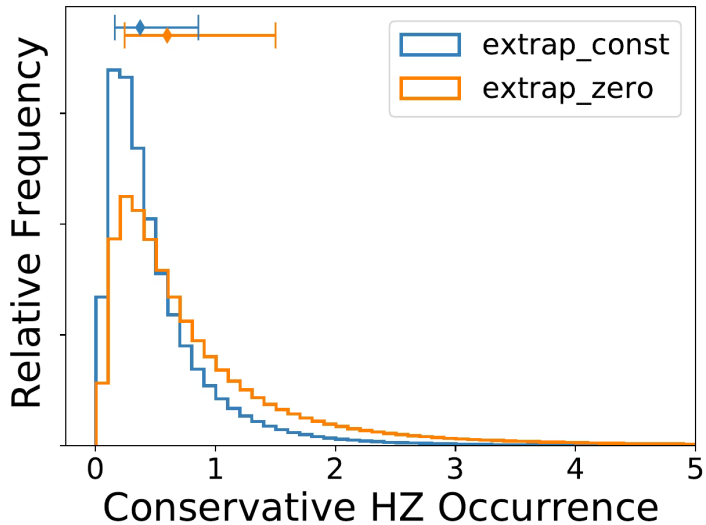
Pre-1992: zero known exoplanets. Today: > 6,000 confirmed planets in > 4,500 systems.

2. **What determines whether a planet becomes habitable?**

Venus, Earth, and Mars share a formation environment and possibly early liquid water, yet diverged across ~ 500 K in surface temperature and four orders of magnitude in surface pressure.

3. **Are we alone?**

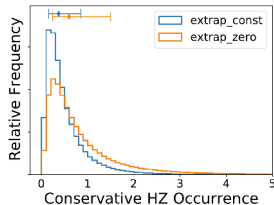
JWST is now characterising atmospheres of rocky worlds, including TRAPPIST-1. The question may become *partially* answerable in your careers.



Posterior on $\eta_{\oplus}$ from Kepler, for the conservative habitable zone. From Bryson et al. (2021).

Reading the $\eta_{\oplus}$ posterior

$\eta_{\oplus}$: average number of rocky habitable-zone planets per Sun-like star.



- Shown: *conservative* HZ (moist-greenhouse → maximum-greenhouse). Liquid water reliably maintained.
- The *optimistic* HZ (recent-Venus → early-Mars) is wider and includes transient surface water.
- Two coloured posteriors bracket the completeness extrapolation past Kepler's 500-day limit: blue = constant (*lower bound*); orange = drops to zero (*upper bound*).
- Diamonds above the panel: **posterior medians + 68% credible intervals.**
- Conservative HZ: $\eta_{\oplus} \approx 0.37 \rightarrow 0.60$. Optimistic HZ: $0.58 \rightarrow 0.88$.

Either way, habitable-zone rocky planets around Sun-like stars are *common*.



2. What is a planet?

Wanderers

Greek *planētēs* (πλανήτης) = “wanderer.”

Five naked-eye wanderers + Sun + Moon
→ **seven days of the week.**

Modern additions extended the list:

- 1781: Herschel discovers **Uranus** (first telescopic planet).
- 1846: Galle observes **Neptune** at a position predicted by Le Verrier and Adams from Uranus’s orbital perturbations.
- 1930: Tombaugh discovers **Pluto** at Lowell Observatory.

Why the definition of “planet” came under pressure:

- Pluto is small, icy, eccentric, inclined; crosses Neptune’s orbit.
- 1990s–2000s: many large trans-Neptunian objects discovered.
- **2005: Eris** (Brown et al., comparable size to Pluto) forced the question.
- Either Pluto + many TNOs are planets, or Pluto is not.

New Horizons reveals Pluto



Credit: NASA/JHUAPL/SwRI (July 2015)

Enhanced-colour view from the 2015 flyby:

- Dark reddish **Cthulhu Macula** (left).
- Bright nitrogen-ice plains, western edge of **Tombaugh Regio** (the “heart”).
- Water-ice mountains, glacial flows, possible cryovolcanism.
- Unexpectedly active for a body of Pluto’s size.

Reignited the planet-status debate *after* the 2006 IAU vote.

IAU 2006 definition of a planet

Resolution 5A: a planet is a body that

1. is in orbit around the Sun;
 2. has sufficient self-gravity to assume hydrostatic (nearly round) equilibrium;
 3. has **cleared the neighbourhood** around its orbit.
- Satisfies (1) + (2) but not (3) → **dwarf planet**.
 - Solar system: **8 planets; 5 officially recognised dwarf planets** (Ceres, Pluto, Eris, Makemake, Haumea); many additional Kuiper-belt candidates.

Is the IAU definition the right one?

Critique of (3) “cleared the neighbourhood”:

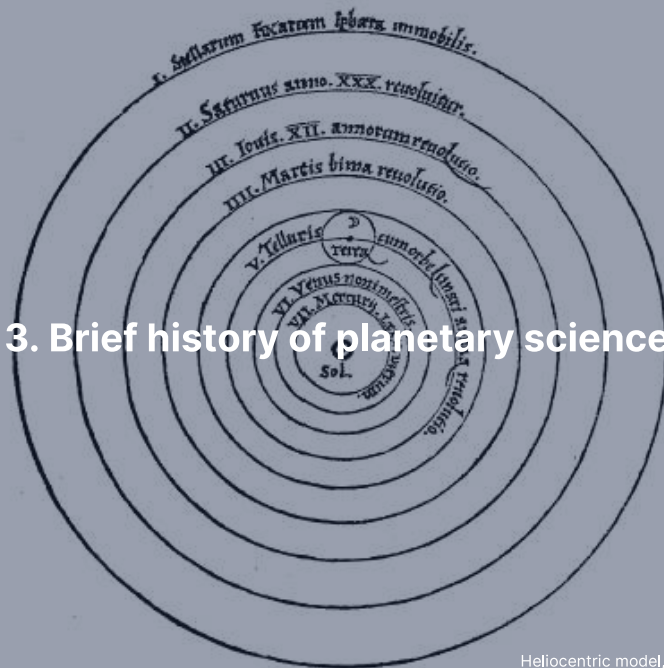
- Not precisely defined.
- Depends on heliocentric distance: Earth itself would *not* clear its zone if placed at Neptune's orbit.

Geophysical alternative (Runyon et al. 2017): any body massive enough to be in hydrostatic equilibrium counts as a planet, regardless of dynamics.

- Solar system would have > 100 planets under this rule.

For this course: the exact classification matters less than the *physics*. The solar system is a *continuous spectrum* of objects from dust grains to gas giants, all governed by the same laws.

3. Brief history of planetary science



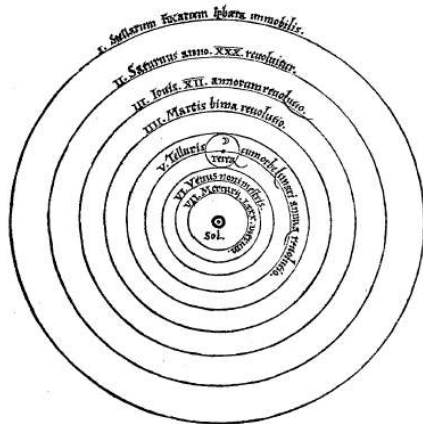
Ancient and pre-telescopic astronomy

- **Babylonian astronomers (~1800 BCE):** systematic planetary-position records; arithmetical prediction of conjunctions and oppositions.
- **Aristotle (~350 BCE):** geocentric system of nested spheres.
- **Ptolemy (~150 CE):** geocentric model with *epicycles*, the standard framework for > 1,400 years.

The Copernican revolution (1543):

- **Copernicus:** heliocentric model in *De revolutionibus*.
- **Kepler** (1609–1619): three empirical laws of planetary motion; circles replaced by ellipses.
- **Newton** (1687): all three Kepler laws follow from a single law of universal gravitation, the first grand unification in physics.

Copernicus, *De revolutionibus* (1543)



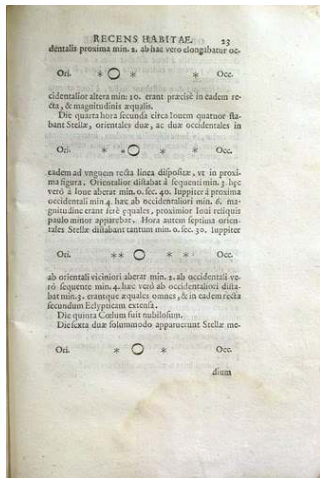
Credit: Public domain

Reading the woodcut from the centre out:

- *Sol* (Sun) at the centre
- *Mercurius*, *Venus*
- *Terra* (Earth) with the Moon as a small attached orbit
- *Mars*, *Iupiter*, *Saturnus*
- Outer band: *Stellarum Fixarum Sphaera Immobilis* (the immobile sphere of the fixed stars)

Conceptual shift from geocentric cosmology, dominant for over a millennium.

The telescopic era opens (1610)



Credit: Galileo, *Sidereus Nuncius* (1610). Public domain

Galileo's telescope turned planetary science from a *mathematical* into a *physical* science.

- Discovered four moons orbiting Jupiter (the *Medicea Sidera*; figure rows record successive nights).
- Resolved the phases of Venus, confirming heliocentrism.
- Resolved Saturn's rings, but could not interpret them.

Marius (1614) proposed the names **Io, Europa, Ganymede, Callisto** (L11).

Later centuries: **spectroscopy** (19th c.) opened remote composition; **photography** enabled systematic surveys.

The space age opens

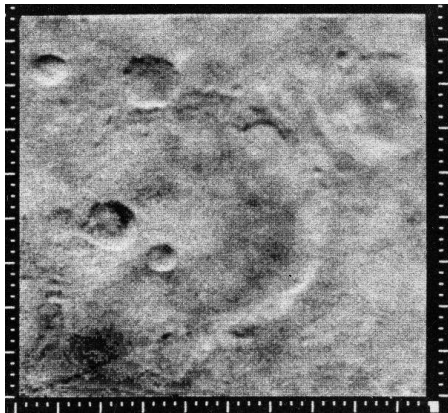
14 December 1962: Mariner 2 flies past Venus.

- First successful spacecraft visit to another planet.
- Measured Venus's extreme surface temperature, overturning earlier "habitable Venus" speculations.

The pace accelerates:

- 1965: Mariner 4 returns the first close-up images of Mars (cratered, Moon-like).
- 1970: Venera 7 makes the first successful planetary landing (Venus).
- 1976: NASA Viking landers conduct first life-detection experiments on Mars.
- 1977–1989: **Voyager grand tour** of Jupiter, Saturn, Uranus, Neptune.

Mariner 4 ends the Mars-canals era (1965)

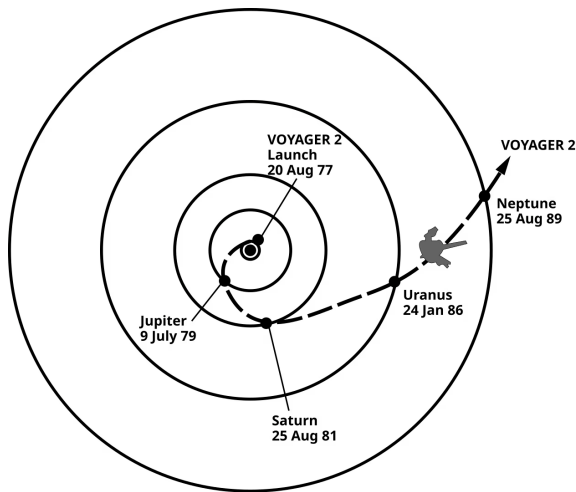


Credit: NASA/JPL (15 July 1965)

First close-up image of another planet's surface.

- 21 frames returned during the brief Mars encounter.
- Heavily cratered, Moon-like terrain.
- **Decisively ended** speculation about Martian canals and surface vegetation.
- Mars geology and atmosphere revisited in L10.

Voyager 2's grand tour of the outer solar system



Credit: NASA/JPL, public domain

Gravity assists at **Jupiter (1979), Saturn (1981), Uranus (1986), Neptune (1989).**

Made possible by a rare alignment of the outer planets that recurs only ~once every 175 years.

Voyager 1 took a faster trajectory: Jupiter (1979), Saturn (1980), then deflected north out of the ecliptic.

Both spacecraft are now in interstellar space: Voyager 1 crossed the heliopause in 2012, Voyager 2 in 2018.

The exoplanet revolution

1992: Wolszczan & Frail announce planets orbiting a pulsar; the first confirmed exoplanets.

1995: Mayor & Queloz detect **51 Pegasi b** around a Sun-like star: a hot Jupiter with a 4.2-day orbit. Challenged every existing formation theory.

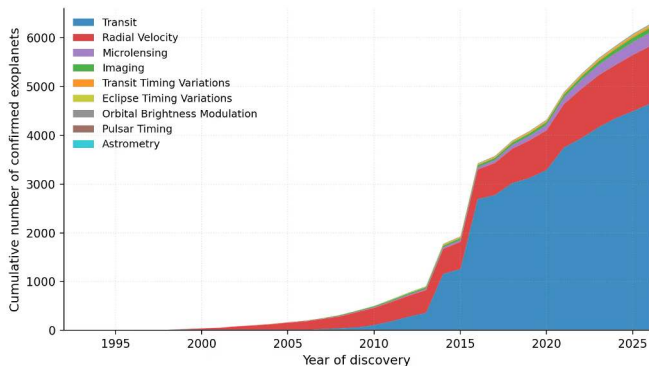
2009: CoRoT-7b, the first *transiting rocky* exoplanet, $1.58 R_{\oplus}$, 0.85-day orbit (Léger et al.).

2009–2018: NASA **Kepler** mission discovers thousands of transiting planets.

2018–: TESS surveys the brightest nearby stars.

2021–: JWST characterises exoplanet atmospheres via transmission and emission spectroscopy (L13).

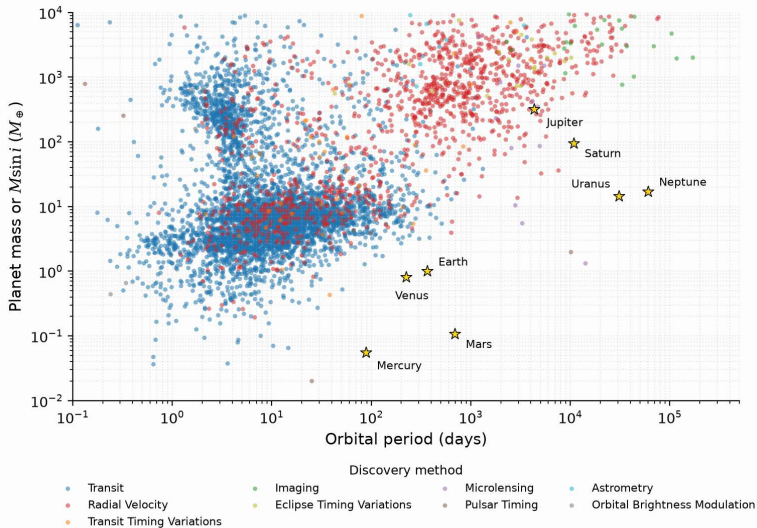
Cumulative exoplanet discoveries by method



Credit: NASA Exoplanet Archive, accessed 2026-05-08

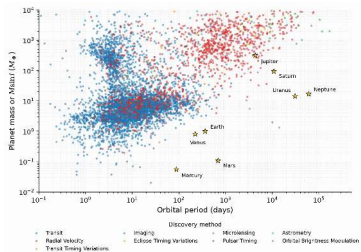
Steps visible:

- 1992 pulsar timing.
- Late 1990s–2000s: radial-velocity revolution.
- Post-2009: transit explosion driven by Kepler.
- **2014 and 2016 jumps:** Kepler batch validations: hundreds (2014) and > 1,000 (2016) candidates promoted at once.

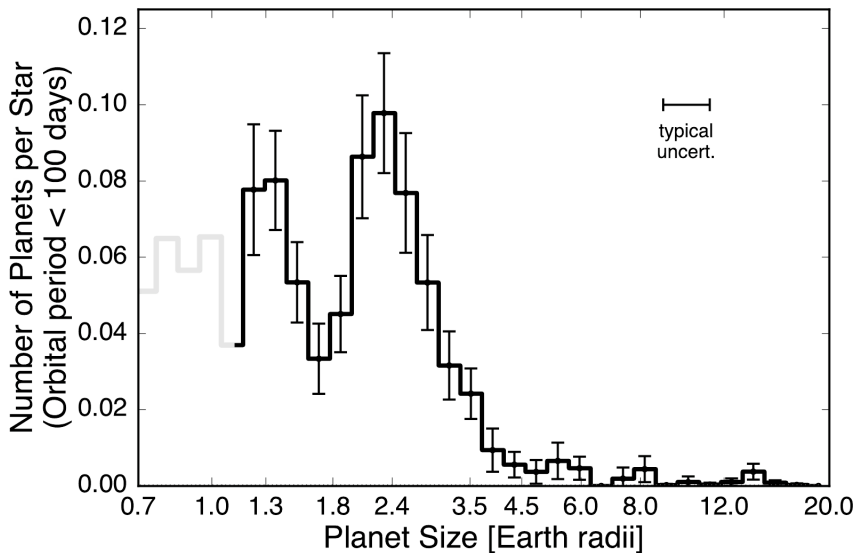


Planet mass (or $M \sin i$) vs orbital period, coloured by detection method. Solar-system planets shown as gold stars. NASA Exoplanet Archive (2026-08-21).

Reading the mass-period diagram



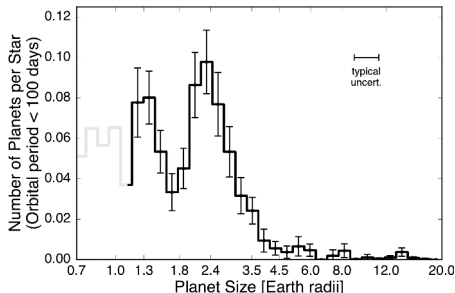
- **Upper-left:** hot Jupiters and other large, short-period planets. Easiest to detect; *selection effects* dominate this region.
- **Lower-middle:** the Earth-analogue regime ($\sim 1 M_{\oplus}$, period ~ 1 yr). Sparsely populated.
- Radial-velocity and transit surveys need *multi-year baselines* to access long periods.
- **Future direct-imaging missions** (HWO, LIFE) are designed to fill the Earth-analogue region by spatially separating planet light from stellar light.
- Detection method colours reveal which technique works where (e.g. transits at short periods, microlensing at intermediate periods).



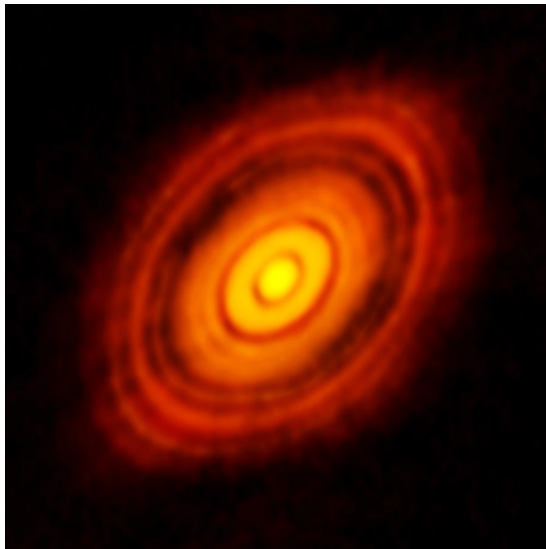
Completeness-corrected radius distribution, California-Kepler Survey. Reproduced from Fulton et al. (2017), Fig. 7 (top panel).

Reading the radius valley

Restricted to orbital periods < 100 d around FGK stars.

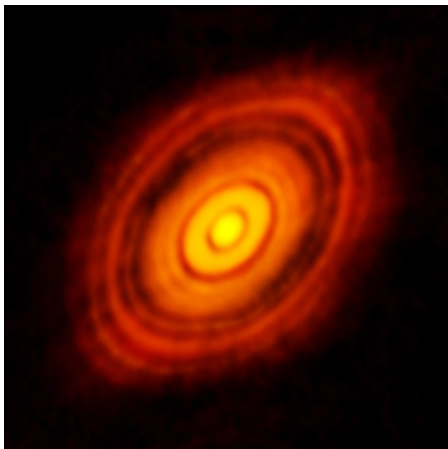


- Two peaks: **super-Earths** at $\sim 1.3 R_{\oplus}$ and **sub-Neptunes** at $\sim 2.4 R_{\oplus}$.
- Separated by the **radius valley** near $1.8 R_{\oplus}$.
- Interpreted as the boundary between *rocky* planets and those with a thin H/He envelope.
- Error bars: 1- σ Poisson on bin counts.
- **Light-grey segment** below $\sim 1.1 R_{\oplus}$: low completeness, occurrence unreliable.
- Atmospheric escape and the radius valley revisited in L13.



ALMA 1.3 mm continuum image of HL Tauri. Credit: ALMA (ESO/NAOJ/NRAO); ALMA Partnership et al. (2015).

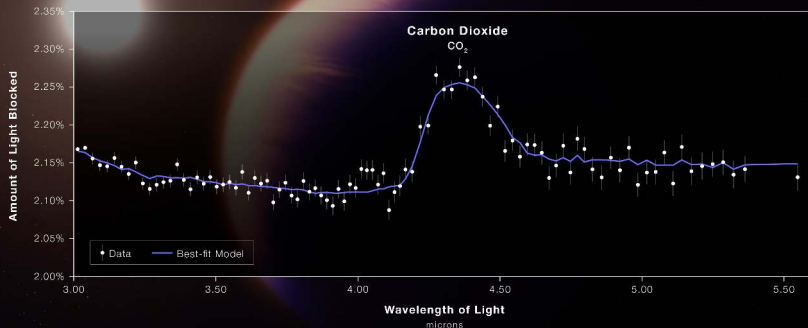
Reading HL Tau



- Protoplanetary disk around the young star **HL Tauri** (~ 140 pc).
- Concentric **dark gaps** are widely interpreted as carved by forming protoplanets.
- Alternative interpretations remain in play: local dust pile-ups at **ice lines**, MRI-dead-zone substructures.
- ALMA's ~ 5 AU angular resolution at HL Tau's distance is what made this multi-ringed substructure visible for the *first time*.
- Disks and planet formation: L2.

HOT GAS GIANT EXOPLANET WASP-39 b ATMOSPHERE COMPOSITION

NIRSpec | Bright Object Time-Series Spectroscopy

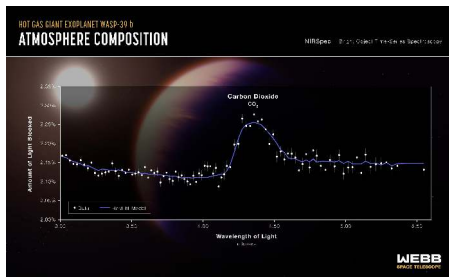


WEBB
SPACE TELESCOPE

First unambiguous CO₂ detection in an exoplanet atmosphere. NASA, ESA, CSA, J. Olmsted (STScI). Data: Rustamkulov et al. (2023).

Reading WASP-39 b's CO₂ detection

WASP-39 b: hot Saturn, 0.28 M_J (Saturn-mass).



- JWST/NIRSpec transmission spectrum, July 2022.
- Plotted as **transit depth vs wavelength**, 3.0–5.5 μm .
- Prominent peak near **4.3 μm** is the CO₂ absorption band.
- White points = data with error bars; blue curve = best-fit atmospheric model.
- **First unambiguous** CO₂ detection in any exoplanet atmosphere.
- Prototype result for the wider JWST atmospheric programme (L13).

Solar System in true imagery, color and size

- Sedna
- — Gonggong Xiangliu
- — Eris Dysnomia
- — Orcus Vanth
- — Quaoar Weywot
- — Makemake S/2015 (136472) 1
- — Haumea Namaka, Hi'iaka
- — Pluto Charon, * Styx, * Nix, * Kerberos, * Hydra

— Ceres

4. Overview of the solar system

Neptune
Triton
* and more...

Uranus
Miranda
Ariel
Umbriel
Titania
Oberon
* and more...

Saturn
Mimas
Enceladus
Tethys
Dione
Rhea
Titan
* and more...

Jupiter
Io
Europa
Ganymede
Callisto
* and more...

Mars
* Phobos
* Deimos

Earth
Moon

Venus
Mercury

Sun

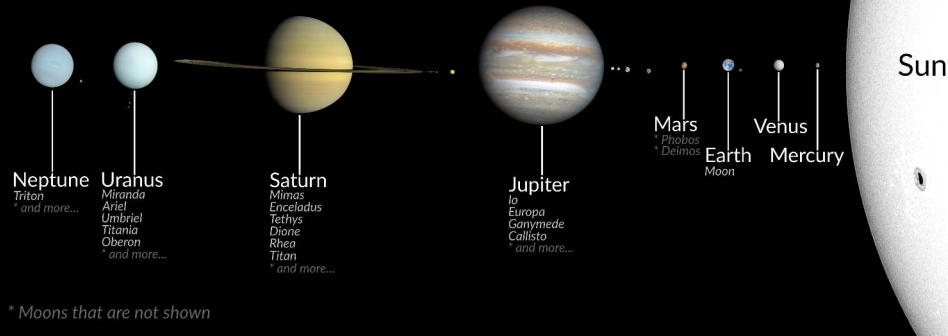
* Moons that are not shown

Architecture and scale, inside out

- **Inner solar system:** four rocky (*terrestrial*) planets, $a = 0.39\text{--}1.52$ AU. Small, dense, rock + metal.
- **Asteroid belt:** rocky/metallic bodies, $\sim 2.1\text{--}3.3$ AU; dominated by dwarf planet **Ceres** (~ 940 km). Total mass only $\sim 4 \times 10^{-4} M_{\oplus}$.
- **Outer solar system:** four *giant* planets, $a = 5.2\text{--}30.1$ AU. Massive H/He envelopes, extensive moon systems.
 - Gas giants: Jupiter, Saturn.
 - Ice giants: Uranus, Neptune.
- **Kuiper belt + scattered disk:** icy bodies beyond Neptune.
 - Classical Kuiper belt $\sim 30\text{--}50$ AU (Pluto, Makemake, Haumea).
 - Scattered disk extends much farther on eccentric orbits (Eris).
 - Inner Oort cloud / detached: Sedna and others.
- **Oort cloud:** hypothetical spherical shell at $10^4\text{--}10^5$ AU; source of long-period comets. Inferred from cometary orbits, not directly observed.

Solar System in true imagery, color and size

- Sedna
- Gonggong Xiangliu
- Eris Dysnomia
- Orcus Vanth
- Quaoar Weywot
- Makemake S/2015 (136472) 1
- Haumea Namaka, Hi'iaka
- Pluto Charon, * Styx, * Nix, * Kerberos, * Hydra



Solar system composite at *true relative size*. Distances not to scale. Credit:
CactiStaccingCrane (Wikimedia, CC BY-SA 4.0).

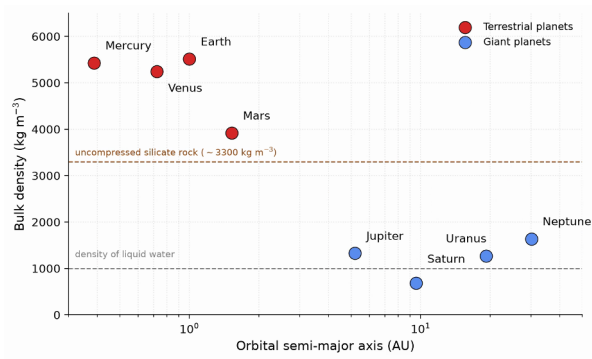
Key properties of the eight planets

Planet	$M (M_{\oplus})$	$R (R_{\oplus})$	a (AU)	P (yr)	e	ρ (kg m ⁻³)
Mercury	0.055	0.383	0.387	0.241	0.206	5427
Venus	0.815	0.949	0.723	0.615	0.007	5243
Earth	1.000	1.000	1.000	1.000	0.017	5514
Mars	0.107	0.532	1.524	1.881	0.093	3934
Jupiter	317.8	11.21	5.203	11.86	0.049	1326
Saturn	95.16	9.45	9.537	29.46	0.054	687
Uranus	14.54	4.01	19.19	84.01	0.047	1271
Neptune	17.15	3.88	30.07	164.8	0.009	1638

Data: JPL Solar System Dynamics (Planetary Physical Parameters).

Jupiter is > 5,700× more massive than Mercury. Saturn is less dense than water.

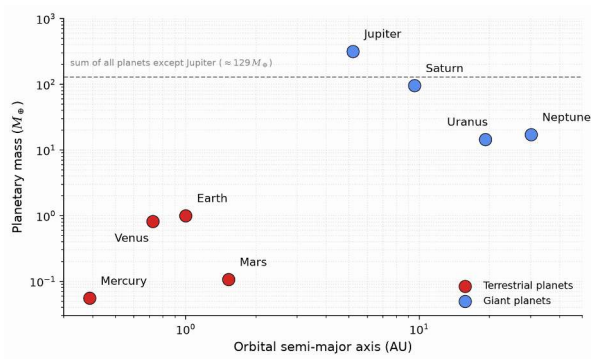
Pattern 1: density decreases with distance



Credit: Data: JPL SSD Planetary Physical Parameters

- Terrestrials (red): $\rho > 3900$; giants (blue): $\rho < 1700 \text{ kg m}^{-3}$.
- **Saturn:** 687 kg m^{-3} , below liquid water (grey dashed).
- Tan dashed: uncompressed rock density $\sim 3300 \text{ kg m}^{-3}$.
- Mars sits at the tan line; Earth, Venus, Mercury exceed it: iron cores + self-compression raise ρ .
- Interpretation: disk *condensation gradient* (L2).

Pattern 2: mass is concentrated in Jupiter



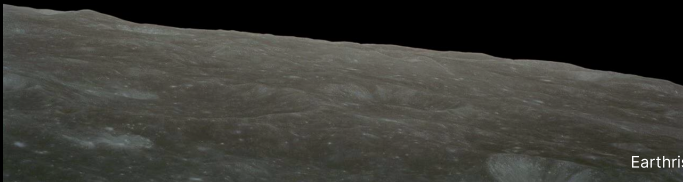
Credit: Data: JPL SSD Planetary Physical Parameters

- Same x-axis as the density plot.
- Grey dashed: sum of *all non-Jupiter* planetary masses $\approx 129 M_{\oplus}$.
- **Jupiter alone** ($317.83 M_{\oplus}$) exceeds this sum by $\sim 2.5\times$.
- Jupiter + Saturn together $\gtrsim 90\%$ of all planetary mass.
- We will quantify this in the next section.
- Formation context developed in L2.

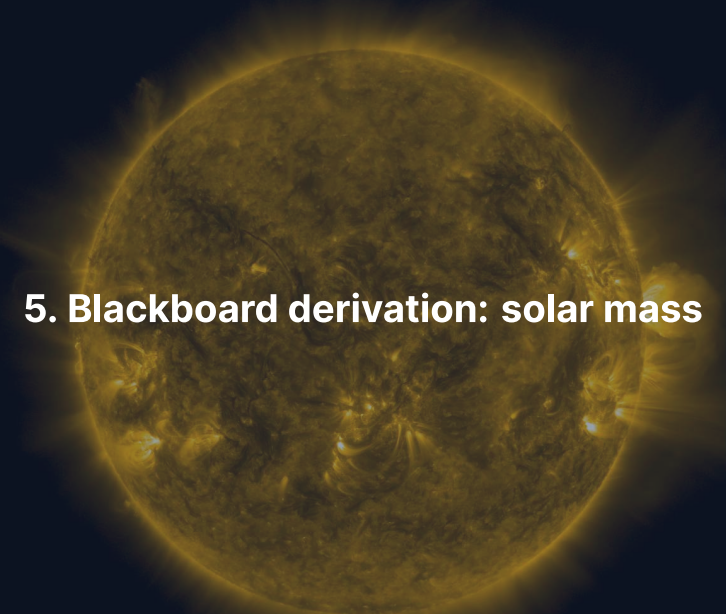
Composition-based classification

- **Terrestrial planets** (Mercury, Venus, Earth, Mars):
 - Rocky surfaces, iron cores, thin or no atmospheres (Venus excepted).
 - Treated in L9 (Earth, Venus) and L10 (Mercury, Mars).
- **Gas giants** (Jupiter, Saturn):
 - Massive H/He envelopes, no well-defined solid surface, likely rocky/icy cores at high P .
 - Treated in L11.
- **Ice giants** (Uranus, Neptune):
 - Interiors dominated by heavier volatiles (H_2O , NH_3 , CH_4) under extreme P .
 - Topped by H/He atmospheres. Also L11.

Break



Earthrise, Apollo 8 (1968). Credit: NASA



5. Blackboard derivation: solar mass

Setup

Planet of mass M_p in a **circular** orbit of radius r around a star of mass M_* .

Gravitational attraction provides the centripetal acceleration:

$$\frac{GM_*M_p}{r^2} = \frac{M_p v^2}{r}$$

with orbital velocity

$$v = \frac{2\pi r}{P}, \quad P = \text{orbital period.}$$

Substitute and cancel

Substituting $v = 2\pi r/P$:

$$\frac{GM_* M_p}{r^2} = \frac{M_p}{r} \left(\frac{2\pi r}{P} \right)^2$$

Cancelling M_p on both sides:

$$\frac{GM_*}{r^2} = \frac{4\pi^2 r}{P^2}$$

Crucial: the planet's mass cancels. The orbital period depends only on the *central* mass and the orbital radius.

Newton's form of Kepler's third law

Solving for M_* :

$$M_* = \frac{4\pi^2 r^3}{GP^2}$$

Valid in the limit $M_p \ll M_*$.

For *elliptical* orbits, replace r with the semi-major axis a . General case requires the **vis-viva equation**, covered in L2.

Apply to the Sun-Earth system

Quantity	Value
Semi-major axis $a_{\oplus}$	$1.496 \times 10^{11} \text{ m}$
Orbital period $P_{\oplus}$	$3.156 \times 10^7 \text{ s}$
Newton's constant G	$6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$

$$M_{\odot} = \frac{4\pi^2 (1.496 \times 10^{11})^3}{6.674 \times 10^{-11} (3.156 \times 10^7)^2} \approx 1.99 \times 10^{30} \text{ kg}.$$

Accepted value: $M_{\odot} = 1.989 \times 10^{30} \text{ kg}$. **Agreement to three figures from two measurable quantities.**

Why the approximation $M_* + M_p \approx M_*$ is justified

More precisely, $P^2 = 4\pi^2 a^3 / [G(M_* + M_p)]$.

Test on the heaviest planet:

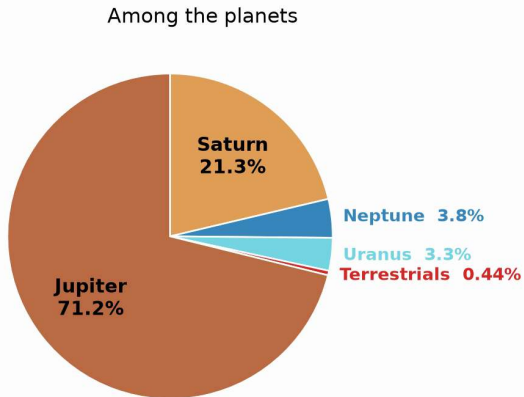
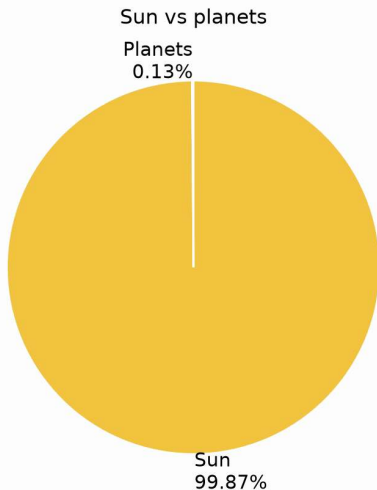
- Jupiter: $M_J \approx 318 M_\oplus \approx 1.90 \times 10^{27} \text{ kg}$
- $M_J/M_\odot \approx 9.5 \times 10^{-4}$

All eight planets together:

- $M_{\text{planets}} \approx 446 M_\oplus \approx 2.7 \times 10^{27} \text{ kg}$
- $M_{\text{planets}}/M_\odot \approx 1.3 \times 10^{-3}$

The Sun contains **99.87%** of the solar system's mass. Jupiter alone accounts for **71%** of the planetary mass.

Mass budget of the solar system



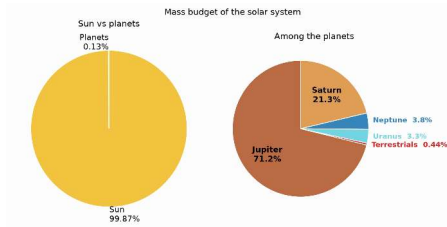
Mass budget of the solar system. Data: JPL SSD Planetary Physical Parameters.

Reading the mass budget

Left pie: the Sun contains 99.87% of total mass; the eight planets together contribute the remaining 0.13%.

Right pie (planetary mass only):

- Jupiter: ~ 71%
- Saturn: ~ 21%
- Neptune: 3.8% Uranus: 3.3%
- All four terrestrials together: 0.44% (one wedge for legibility)



This extreme mass concentration in the central star is a fundamental property of planetary systems, and any formation theory must explain it (L2).

A horizontal arrangement of four celestial bodies against a dark blue background. From left to right: a small, grey, cratered sphere (Mercury); a large, yellowish-brown sphere with horizontal cloud bands (Venus); a large sphere with blue oceans, white clouds, and brown landmasses (Earth); and a medium-sized, reddish-brown sphere with darker patches (Mars). The text "6. Comparative planetology" is centered over the Venus and Earth spheres.

6. Comparative planetology

Why comparative planetology?

We cannot perform controlled experiments on entire worlds.

Comparative planetology treats planets as a set of natural experiments: similar objects subjected to different conditions.

Compare planets to isolate which differences arise from:

- distance to the Sun (insolation)
- planetary mass (gravity, internal heat budget)
- internal activity (tectonics, dynamos)
- historical contingency (impacts, atmosphere loss)

This is the methodology we apply throughout the course.



Mercury, Venus, Earth, Mars at approximate relative scale. Credit: NASA/JPL (public domain).

Reading the four terrestrial planets

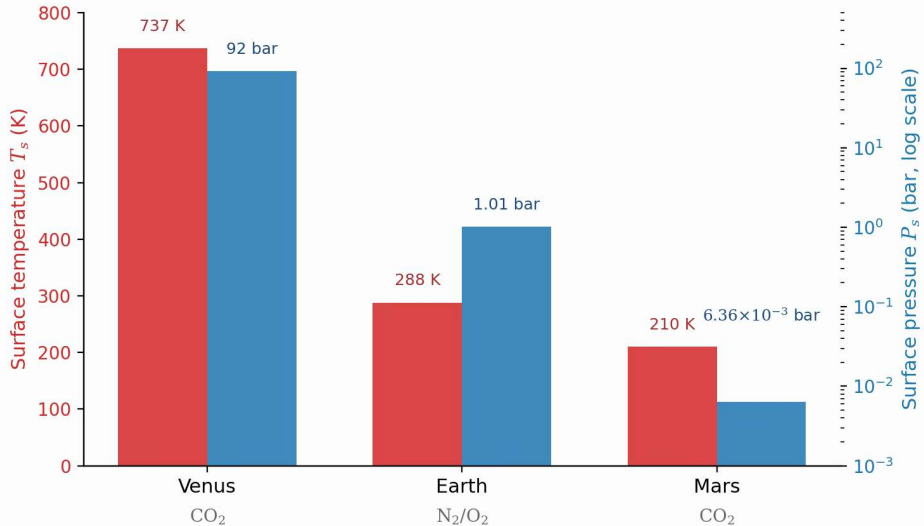


- Span a factor of ~ 18 in mass.
- Same protoplanetary disk, broadly similar bulk compositions.
- Dramatically different evolutionary paths.
- Earth, Venus: detailed in L9.
- Mercury, Mars: detailed in L10.

The Venus-Earth-Mars divergence

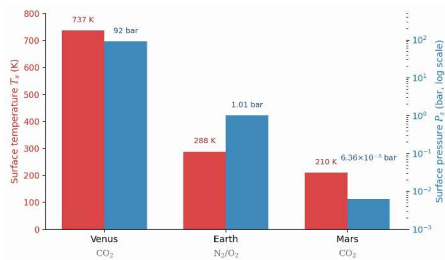
Property	Venus	Earth	Mars
Surface temperature	464 °C	15 °C	-63 °C
Surface pressure	92 bar	1 bar	0.006 bar
Dominant atmosphere	CO ₂ (96.5%)	N ₂ /O ₂ (99%)	CO ₂ (95%)
Magnetic field	none	strong dipole	remnant crustal
Tectonic mode	episodic resurfacing	plate tectonics	stagnant lid

Three planets, broadly similar starting materials, four orders of magnitude apart in surface pressure and ~ 500 K in surface temperature.

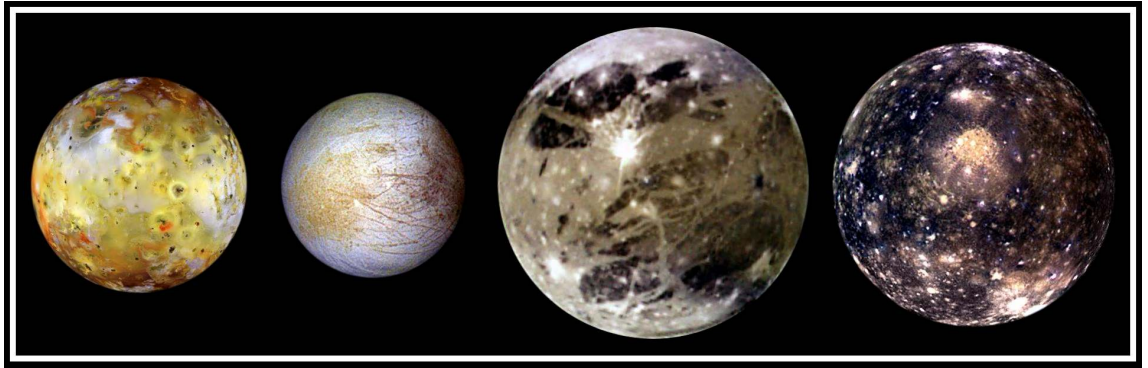


Surface T and P for Venus, Earth, Mars. Data: JPL SSD Planetary Physical Parameters.

Reading the atmospheric divergence



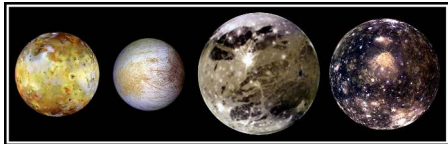
- **Red bars (left axis):** surface temperature.
- **Blue bars (right axis, log scale):** surface pressure.
- Dominant atmospheric species labelled below each planet.
- Despite similar bulk compositions and shared formation environment:
 - factor of $\sim 10^4$ in surface pressure;
 - ~ 500 K range in surface temperature.
- Drives the L9–L10 case studies: why did three sibling planets diverge?



Io, Europa, Ganymede, Callisto at correct relative size. Credit: NASA/JPL/DLR, Galileo mission.

Reading the Galilean comparison

Four moons, common formation environment around Jupiter.



- **Io:** most volcanically active body in the solar system.
- **Europa:** icy crust over a global liquid-water ocean.
- **Ganymede:** *largest moon in the solar system*, 5262 km (vs. Mercury, 4880 km); intrinsic magnetic field.
- **Callisto:** heavily cratered, geologically inert.

Tidal heating + ice content drive vastly different outcomes. Moon systems revisited in L11.

Comparative method generalises to exoplanets

The same logic now extends to thousands of exoplanets.

We can study how planetary properties vary as a function of:

- stellar type (M dwarf, K dwarf, FGK)
- orbital distance (insolation)
- system architecture (single vs. resonant chain)

Solar system as one sample within a wider exoplanet population: L13.



7. Observational techniques

Telescopes: a multi-wavelength toolkit

Ground-based:

- Optical imaging: surface and atmospheric features.
- Infrared spectroscopy: thermal emission, atmospheric composition.
- Radio: subsurface and atmospheric dynamics.
- **Adaptive optics** on 8–10 m telescopes (VLT, Keck, Subaru): angular resolutions approaching space-based.

Space-based: avoid atmospheric absorption and distortion.

ESO's Very Large Telescope (Paranal)



Credit: G. Hühdepohl (atacamaphoto.com) / ESO

Four **8.2 m** Unit Telescopes on Cerro Paranal, Atacama Desert.

Solar-system science highlights:

- SPHERE-ZIMPOL: shapes of large main-belt asteroids.
- NACO, SINFONI: Titan hazes, Saturn / Jupiter storms.
- Comet 67P monitoring in support of **Rosetta**.

Hubble Space Telescope



Credit: NASA, STS-125 (May 2009)

Launched 1990; five servicing missions (1993–2009) replaced instruments, gyros, batteries, solar arrays.

The image is from SM4 release; that mission added **WFC3** and **COS**, both still operating today.

Planetary-science use:

- **OPAL programme** (Outer Planets Atmospheres Legacy): annual monitoring of Jupiter Great Red Spot, Saturn polar hexagon, Uranus / Neptune cloud variability since 2014.

James Webb Space Telescope



Credit: NASA / D. Stover (April 2017)

6.5 m primary mirror, 18 gold-coated beryllium hexagons. Operates from **Sun-Earth L2**, 1.5 million km from Earth.

~ 25 m² collecting area, cryogenic ($T < 50$ K) optics, optimised for near- and mid-IR spectroscopy.

Primary planetary use: **exoplanet atmospheric characterisation** (L13).

Already seen earlier: WASP-39 b CO₂; coming later in this lecture: TRAPPIST-1 b dayside thermal emission.

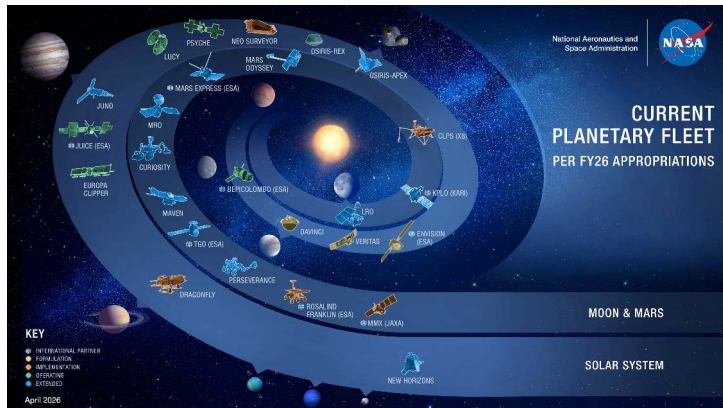
Spacecraft give the most detailed data

NASA fleet (next slide) and **ESA fleet (after)** together span the solar system from Sun to interstellar medium.

Mission types, in order of increasing cost and complexity:

- **Flyby:** one brief encounter. *Voyager 2 at Neptune (1989)*.
- **Orbiter:** long-term monitoring. *Cassini at Saturn (2004–2017)*.
- **Lander:** in-situ surface measurements. *Viking 1 on Mars (1976)*.
- **Rover:** mobile lander. *Perseverance on Mars (2021–)*.
- **Sample return:** material brought back for lab analysis. *Hayabusa2 at Ryugu (2020)*.

NASA's planetary fleet (FY26 appropriations)



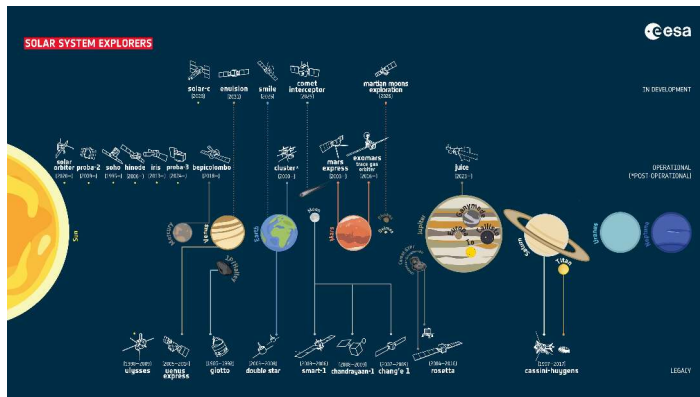
Credit: NASA SVS / GSFC, J. Mottar (May 2026)

Organised by target:

- Inner solar system
- Mars program
- Asteroids and small bodies
- Outer planets
- Heliopause (Voyagers)

Reflects *budgeted* mission state; some extended-mission and concept-stage projects omitted.

ESA's Solar System exploration fleet



Credit: ESA (CC BY-SA 3.0 IGO, September 2025)

Planetary highlights:

- Giotto at Halley (1986)
- Huygens lands on Titan (2005)
- Rosetta + Philae at 67P (2014–2016)
- Venus Express (2006–2014)
- Mars Express (2003–)
- BepiColombo to Mercury
- JUICE to Jupiter system
- Upcoming: EnVision, ExoMars Rosalind Franklin, Comet Interceptor

Remote-sensing methods

- **Spectroscopy:** characteristic absorption / emission features identify materials. Reveals atmospheric composition, surface mineralogy, thermal properties.
- **Radar:** penetrates clouds, maps surface topography (*Magellan* at Venus), detects subsurface structures (*MARSIS* at Mars).
- **Gravimetry:** orbit perturbations map the gravity field → interior density variations and mass concentrations.
- **Magnetometry:** magnetic-field measurements constrain dynamo activity and interior conductivity.

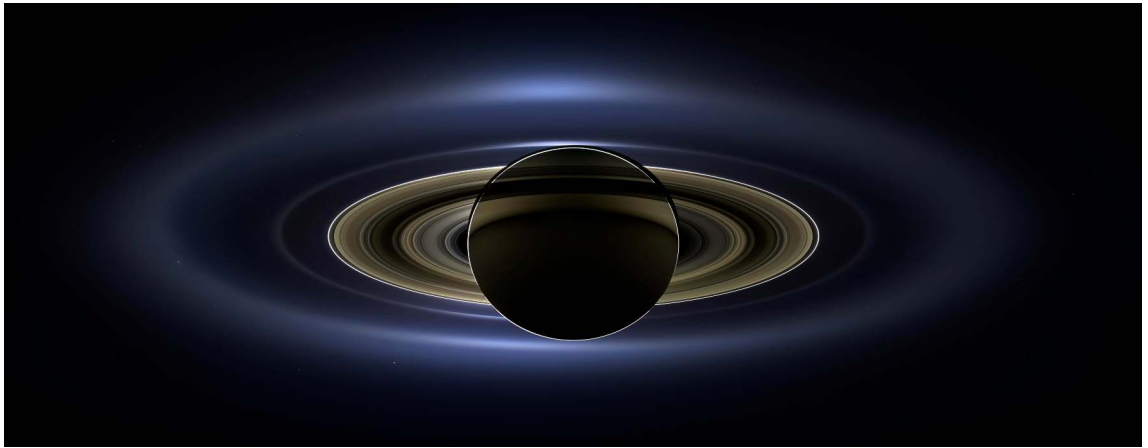


8. Key spacecraft missions

Perseverance, Jezero crater (2021). Credit: NASA/JPL-Caltech

Selected landmark planetary missions

Mission	Agency	Year(s)	Target	Key achievement
Mariner 2	NASA	1962	Venus	First successful planetary flyby
Mariner 4	NASA	1965	Mars	First close-up images of another planet
Apollo 11	NASA	1969	Moon	First crewed landing on another world
Venera 7	USSR	1970	Venus	First successful planetary landing
Viking 1/2	NASA	1976	Mars	First Mars landers; life-detection tests
Voyager 1/2	NASA	1977–89	Outer pl.	Grand tour of the four giant planets
Giotto	ESA	1986	1P/Halley	First close-up images of a comet nucleus
Galileo	NASA	1995–2003	Jupiter	First Jupiter orbiter; Europa's ocean
Mars Express	ESA	2003–	Mars	First ESA planetary orbiter; subsurface ice
Cassini-Huygens	NASA/ESA	2004–17	Saturn	Huygens lands on Titan; Enceladus plumes
Spirit / Opp.	NASA	2004–18	Mars	Long-duration rovers; past-water evidence
Venus Express	ESA	2006–14	Venus	Long-term monitoring of Venus's atmosphere
Rosetta / Philae	ESA	2014–16	67P	First comet orbiter; first comet landing
New Horizons	NASA	2015	Pluto	First Pluto flyby; geological complexity
Hayabusa2	JAXA	2014–20	Ryugu	Returned carbonaceous-asteroid sample
Juno	NASA	2016–25	Jupiter	First Jupiter polar orbiter; deep interior
BepiColombo	ESA/JAXA	2018–	Mercury	Two orbiters; Mercury arrival Nov 2026
Perseverance	NASA	2021–	Mars	Sample caching; Ingenuity helicopter
JWST	NASA/ESA/CSA	2021–	Exoplanets	Atmospheric characterisation
Chang'e 6	CNSA	2024	Moon	First lunar far-side sample return
Europa Clipper	NASA	2024–	Europa	Habitability of Europa's ocean



Backlit Saturn with Earth in the rings (lower right). Credit: NASA/JPL-Caltech/SSI (19 July 2013).

Reading “The Day the Earth Smiled”



- Cassini imaged Saturn from *inside* the planet's shadow on 19 July 2013.
- Earth visible as a faint pale point through the rings (lower right).
- **First Earth portrait from deep space pre-announced to the public;** Voyager Pale Blue Dot and Family Portrait were unannounced.
- Cassini operated in Saturn orbit 2004–2017.
- Discovered Enceladus's global subsurface ocean and Titan's hydrocarbon lakes.
- Saturn rings, Enceladus, Titan revisited in L11.

Perseverance's first colour view of Mars



Credit: NASA/JPL-Caltech (18 February 2021)

Hazard-avoidance camera, immediately after landing in **Jezero crater**.

The plain ahead is part of an ancient lake-delta system that filled Jezero during the *Noachian*, ~ 3.6 Ga ago.

Perseverance is *caching* samples for return via **Mars Sample Return**.

MSR architecture is being re-baselined; Jezero stratigraphy and the sample-return programme are returned to in L10.

Coming decade: missions in flight or planned

- **ESA JUICE** (launched April 2023):
 - Jupiter-system arrival 2031.
 - Ganymede orbit insertion 2034.
- **Mars Sample Return** campaign (architecture under re-baselining).
- **NASA Dragonfly**: nuclear-powered rotorcraft to Titan, launch ~2028, arrival 2034 (L11, L14).
- Plus EnVision (Venus), ExoMars Rosalind Franklin, Comet Interceptor, BepiColombo, Europa Clipper science phase.

The background of the slide is a deep-field astronomical image from the James Webb Space Telescope, showing a vast field of galaxies. The galaxies are mostly orange and red, with some blue and white stars. The image is a mosaic of many smaller images, creating a grid-like pattern. The text "9. Recent advances" is centered in the middle of the image.

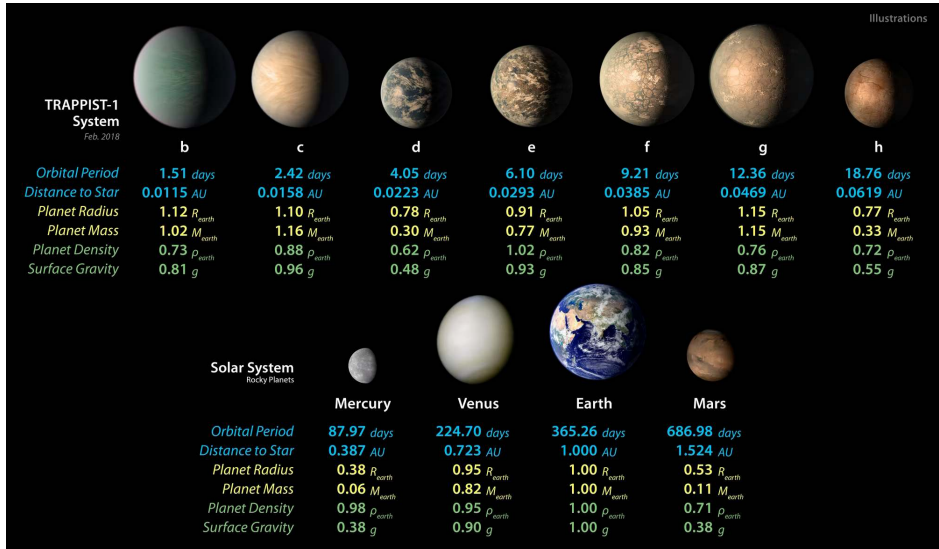
9. Recent advances

JWST is now characterising rocky-planet atmospheres

TRAPPIST-1: nearby ultra-cool dwarf star, ~ 12 pc from Earth.

- Seven roughly Earth-sized planets (b through h).
- Chain of **six mean-motion resonances** locking orbital-period ratios into integer relations.
- Three planets (e, f, g) inside conservative HZ; a fourth (d) near its inner edge.
- JWST is testing whether any of them retain atmospheres.

Greene et al. (2023) reported the first such measurement, for TRAPPIST-1 b.

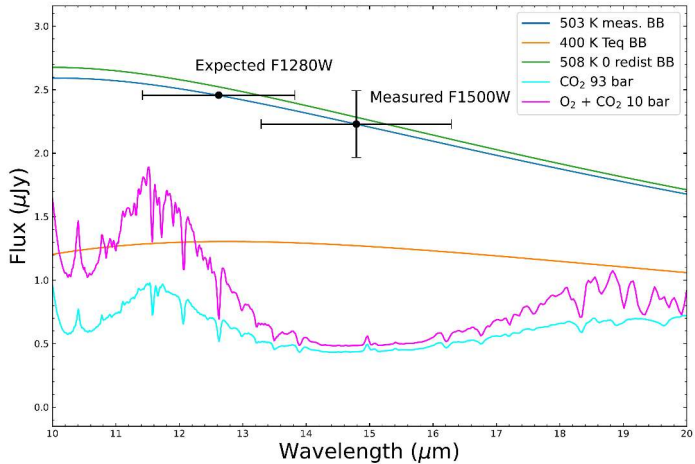


TRAPPIST-1 planets (top row) vs. the inner solar system (bottom row). Credit: NASA/JPL-Caltech.

Reading the TRAPPIST-1 comparison

- Top row: TRAPPIST-1 b through h; *artist's illustrations* (the planets are too small and too faint to be spatially resolved).
- Bottom row: inner solar system, *spacecraft photographs*.
- Orbital periods: 1.5 days (b) to 19 days (h). The entire system fits inside Mercury's 88-day orbit.
- Measured / estimated values shown: period, distance, radius, mass, density, surface gravity.
- Six-link resonance chain locks the periods (Gillon et al. 2017, Luger et al. 2017).
- This is the closest available *laboratory* for testing M-dwarf habitability.



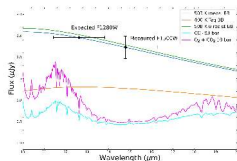


JWST MIRI F1500W secondary eclipse of TRAPPIST-1 b. Reproduced from Greene et al. (2023).

Reading the M-dwarf atmosphere test

First thermal measurement of a rocky exoplanet around an M dwarf.

- x-axis: wavelength (μm); y-axis: planet spectral flux density (μJy).
- Two black data points: F1280W (*expected*, $12.8 \mu\text{m}$) and F1500W (*measured*, $15 \mu\text{m}$).
- Five model curves: blue: $503 \pm 27 \text{ K}$ dayside blackbody; orange: 400 K equilibrium with full heat redistribution; green: 508 K bare-rock prediction (zero albedo, no redistribution); cyan: 93-bar CO_2 -dominated atmosphere; magenta: 10-bar $\text{O}_2 + \text{CO}_2$ atmosphere.
- CO_2 absorbs at $\sim 15 \mu\text{m}$; atmospheric models would suppress flux there.



F1500W point sits on the *bare-rock* blackbody and well above the atmospheric models. Rules out thick CO_2 -rich atmospheres on TRAPPIST-1 b. (L13.)

OSIRIS-REx samples Bennu (20 October 2020)



Credit: NASA / Goddard / Univ. of Arizona, SamCam

SamCam recorded the **Touch-and-Go (TAG)** event at site *Nightingale*:

- TAGSAM head visibly crushes porous regolith on contact.
- Bright pulse ~1 s after contact: nitrogen-gas jet that mobilised the sample material.
- Returned **121.6 g** on 24 September 2023: the largest asteroid sample ever brought to Earth.
- Hydrated minerals + organics identified in initial analysis.

Asteroids and small bodies: L12.

10. Three central questions of this course

Q1. How do planetary systems form?

Clues we have already met:

- Mass concentration in Jupiter and Saturn (mass-budget pie).
- Dust gaps in HL Tau (ALMA).
- Small-planet radius valley (Fulton 2017).

Mapped onto the course:

- **L2:** the protoplanetary disk and orbital dynamics.
- **L3:** energy budget of accretion; short-lived radionuclides.
- **L12:** small bodies that preserve the formation epoch (asteroids, comets, KBOs).

Q2. What makes a planet habitable?

Venus, Earth, Mars share an origin and yet diverge by four orders of magnitude in pressure and 500 K in temperature.

Coupled ingredients to disentangle:

- **Interiors and dynamos** (L4, L8): heat and volatile fluxes from depth.
- **Atmospheres and climate** (L5, L6): surface T , escape, available chemistry.
- **Surfaces** (L7): closing the volatile cycle back into the interior.

Case studies put numbers on each ingredient:

- **L9**: Earth, Venus.
- **L10**: Mercury, Mars.

Q3. Does life exist beyond Earth?

Motivates much of the current mission queue.

- JWST atmospheric spectra of rocky M-dwarf planets (e.g. TRAPPIST-1 b dayside).
- JUICE and Europa Clipper at the icy moons.
- Dragonfly at Titan.
- ELT, GMT, TMT for direct imaging in the 2030s.

Mapped onto the course:

- **L11:** giant planets + ocean worlds in their moon systems.
- **L13:** solar system inside the exoplanet population; habitable zone revisited.
- **L14:** biosignatures, Drake equation, search programmes of the next two decades.

Next time: Lecture 2

This lecture has been a panoramic tour: bodies, history, missions, three questions.

L2 begins the actual physics. We walk back to the molecular cloud and follow the collapse step by step:

- Angular momentum conservation → rotating disk rather than spherical infall.
- Disk temperature gradient → the **snow line** separating rocky and icy material.
- Dust grains → planetesimals via coagulation, settling, the streaming instability.
- Kepler's laws + the **vis-viva equation** + orbital resonances govern subsequent dynamics.

The story of how the solar system came to look the way it does begins not with the planets but with the disk that made them.

Summary

1. **Planetary science is comparative:** studying planets, moons, and small bodies as a set of natural experiments.
2. **Three driving questions** organise the course: how systems form, what makes them habitable, and whether we are alone.
3. **The solar system has structure:** density falls with distance, mass is concentrated in Jupiter + Saturn, the Sun holds 99.87% of the total.
4. **Newton's form of Kepler's third law** ($M_* = 4\pi^2 r^3 / GP^2$) recovers $M_\odot$ to three figures from Earth's a and P .
5. **Comparative planetology applies to exoplanets too:** > 6,000 confirmed; bimodal small-planet radius distribution; first CO₂ detections and first rocky M-dwarf thermal measurements landing now.

Questions?

Next: Lecture 2, Protoplanetary disks & orbital dynamics

Thu 10 Sep, 11:00–13:00, room 5419.0161 (Collegezaal)

Next tutorial: Fri 11 Sep, 13:00–15:00, room 5419.0161 (Collegezaal)

<https://ips.formingworlds.space>