

Exoplanets

Lecture 6

Fall 2025/2026

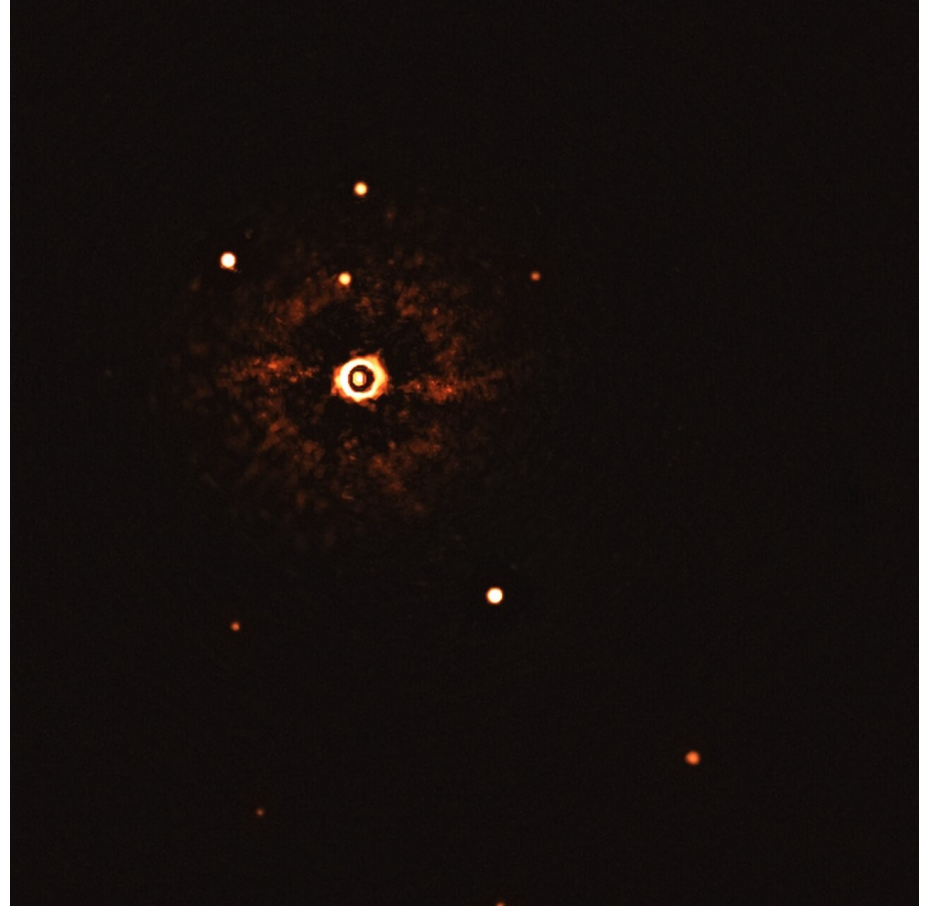
06 November 2025

Outline

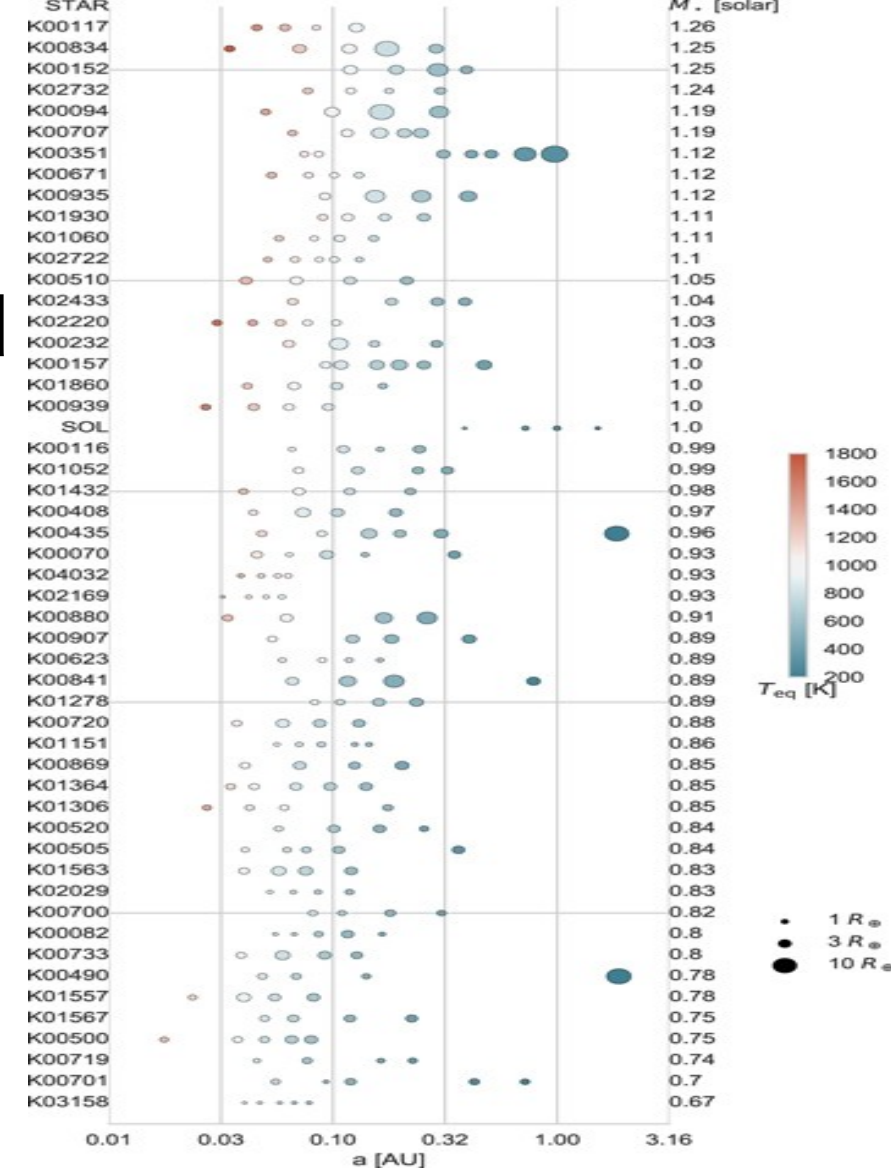
- Formation of Solar system
- Formation of exoplanetary systems
- Compariosn of planetary systems

What's the status?

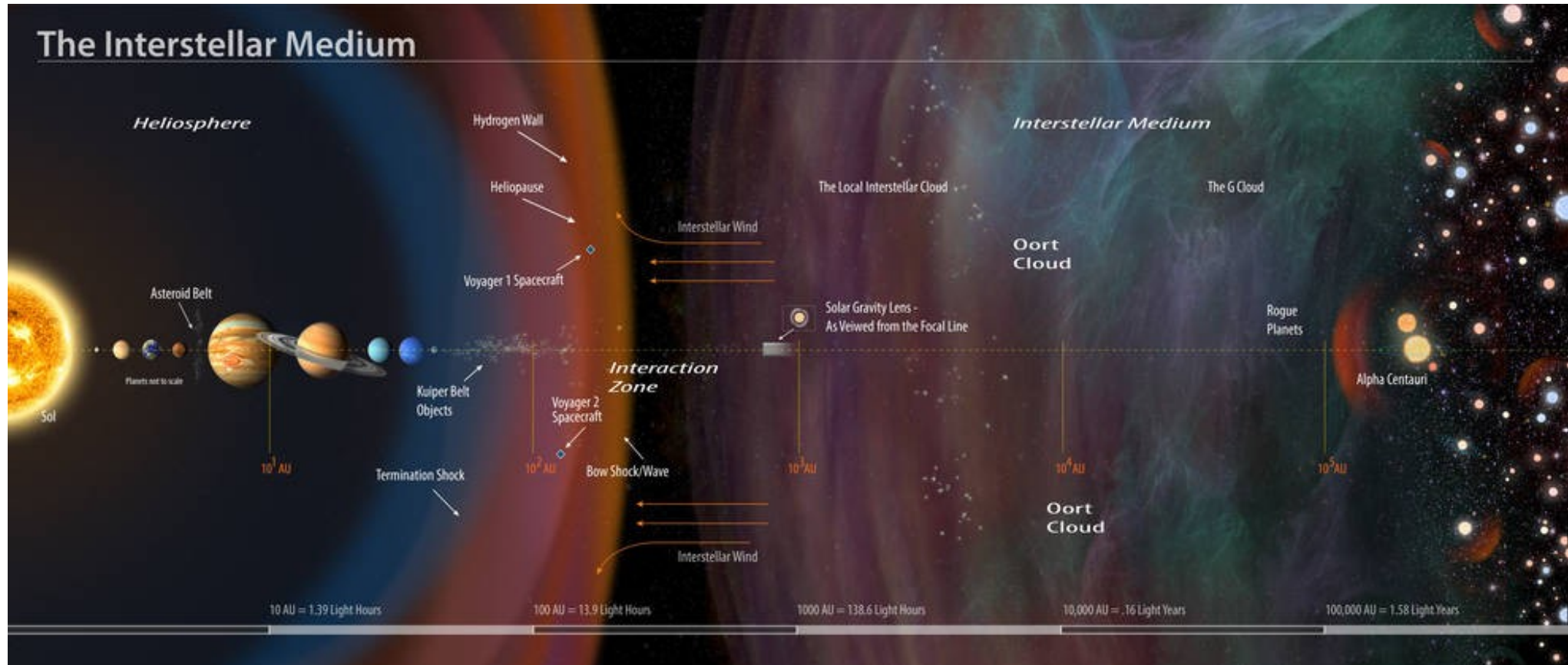
- TYC 8998-760-1
- Sun-like star
- Imaged by ESO VLT
SPHERE
- <https://arxiv.org/pdf/2007.10991.pdf>
- Planets: 6 & 14 Mjupiter masses
- 160AU and 480 au
- First detection of multiple system around
1Msun masss star! 2020!



- Multiple systems compared to Solar System
- Are we unique?
- PLATO will answer this question

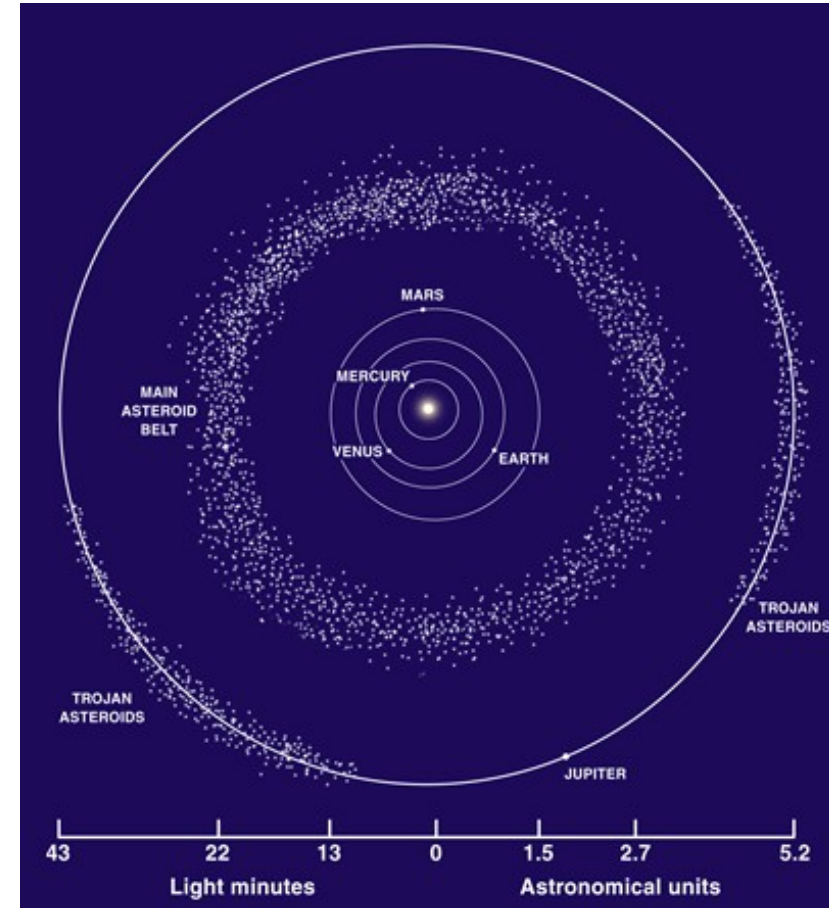


Architecture of the solar system



Main asteroid belt

- Between Mars and Jupiter
- Contains most of the asteroids
- Formed about 4.6 billion years ago
- Currently +1 million asteroids known
- Radii ranges of asteroids:
10m-530km (Vesta)
- Info:
 - <https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/in-depth/>



Credit: NASA Lunar and Planetary Institute

Type of asteroids

- C (chondrite) – clay, silicate rocks (from confirmation time of Solar System)
- S (stony) - nickel-iron
- M (nickel-iron) – partly melted, iron in the core

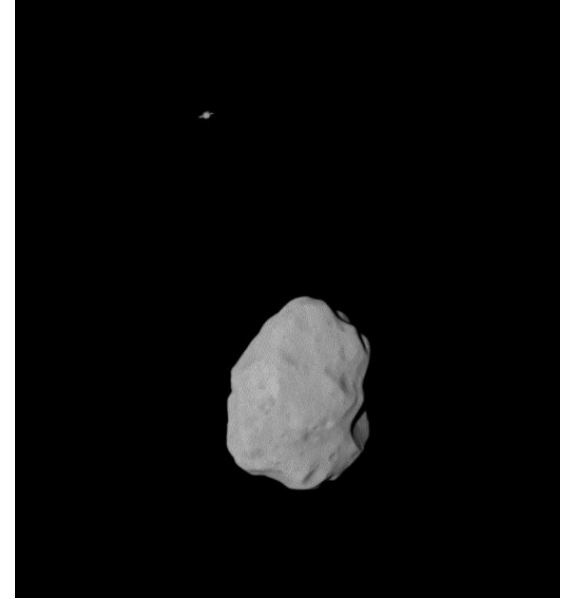
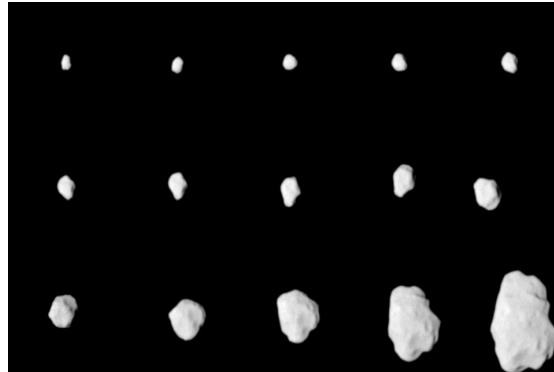
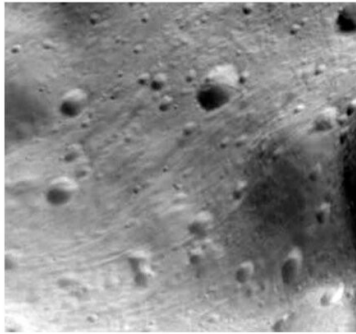


Credit images: NASA



Types of asteroids

- C/M? type Lutetia
- Flyby by ROSETTA in 15 km/s speed!
- Composition test sample needed

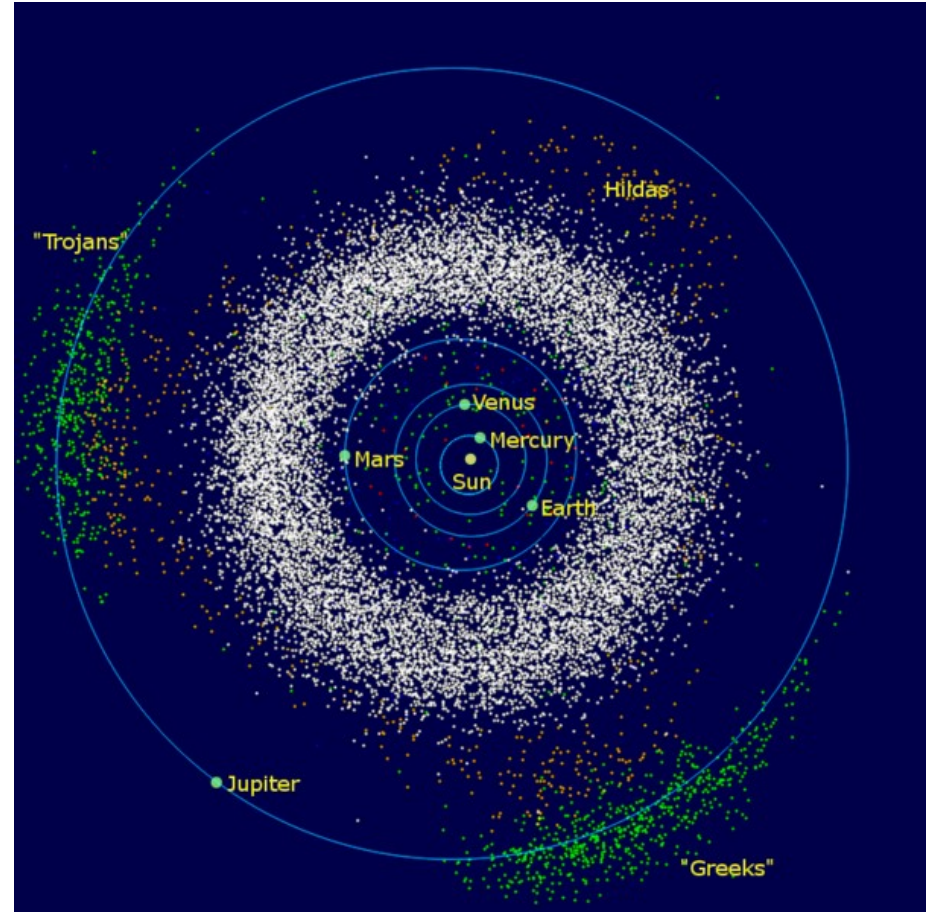
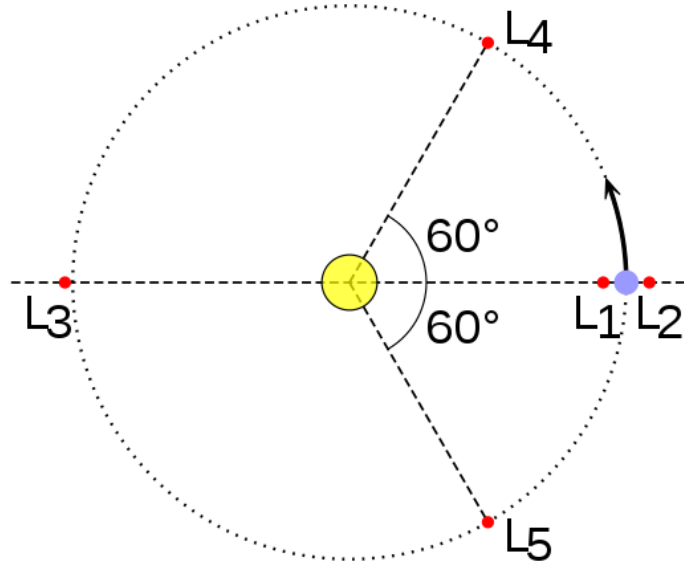


All images credit: ESA

https://www.esa.int/Science_Exploration/Space_Science/Rosetta/Rosetta_triumphs_at_asteroid_Lutetia

Trojans

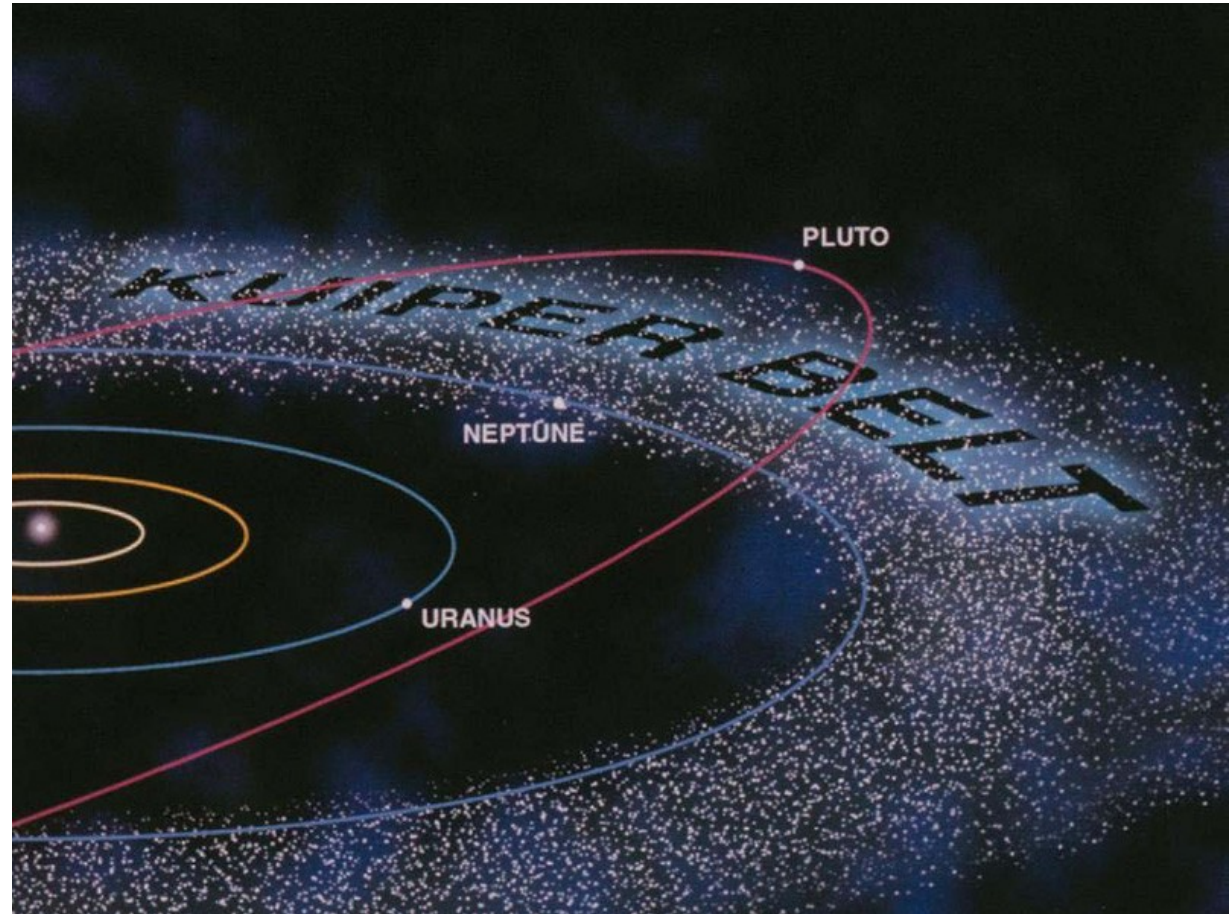
- Asteroids located on trailing and leading edges of planetary orbits
- Location is in L4/L5



Images based on NASA data from Wikipedia

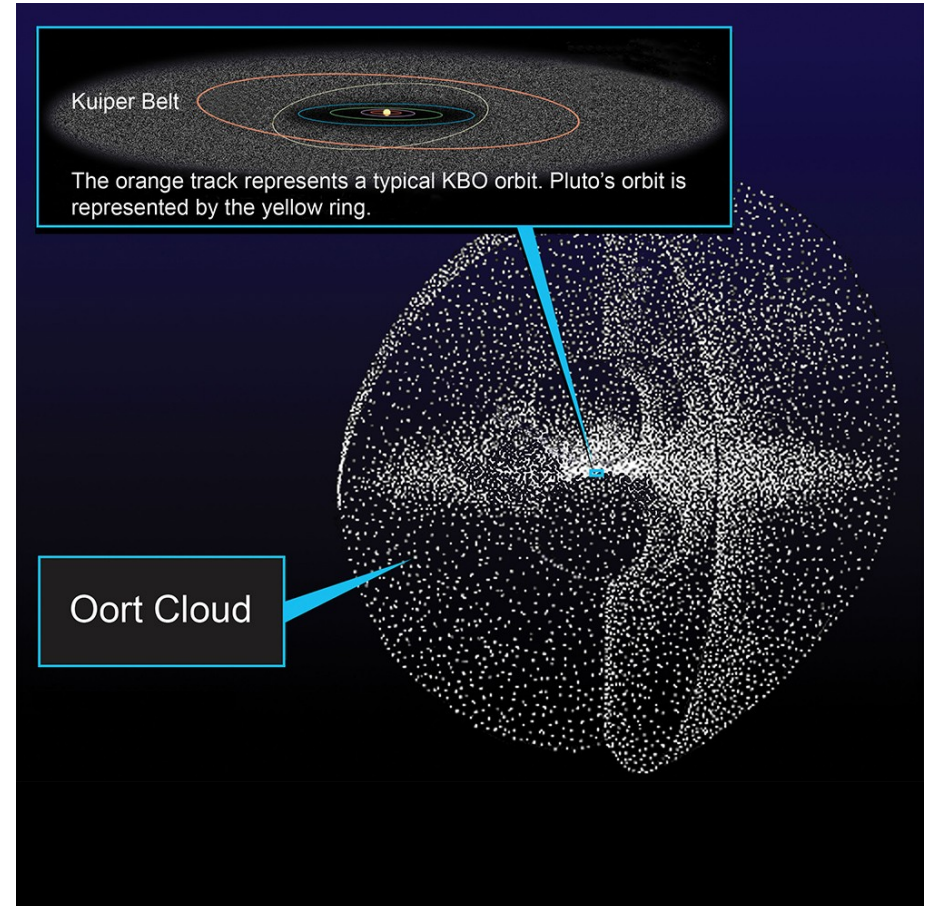
Kuiper belt

- It spans from 30AU to 50 AU
- Hosts dwarf planets
 - Pluto
 - Make Make
 - Haumea
 - Sedna
 -
- Composition mainly icy, frozen methane etc.
- Nice review:



Oort cloud

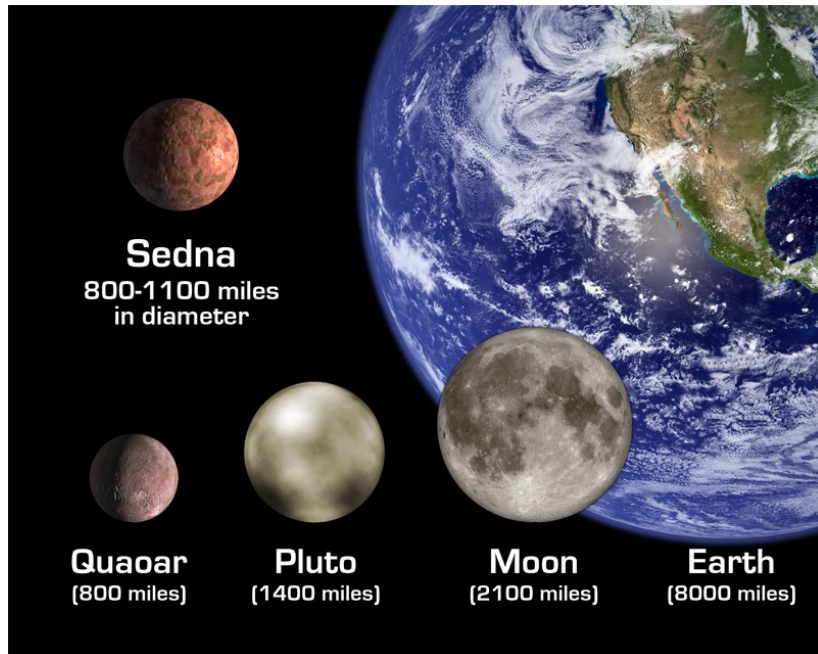
- Spherical not disc
- Range 2000 up to 100k Aus from the Sun
- Long period comets originate here
- Review reading:
<https://www.lpi.usra.edu/books/CometsII/7031.pdf>



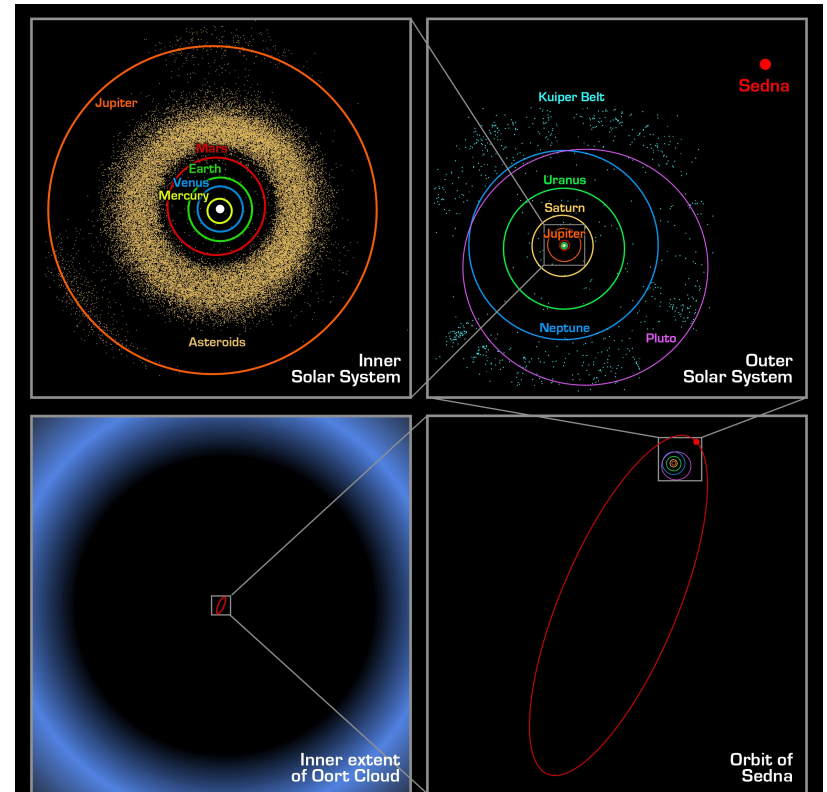
Credit: NASA

Sedna

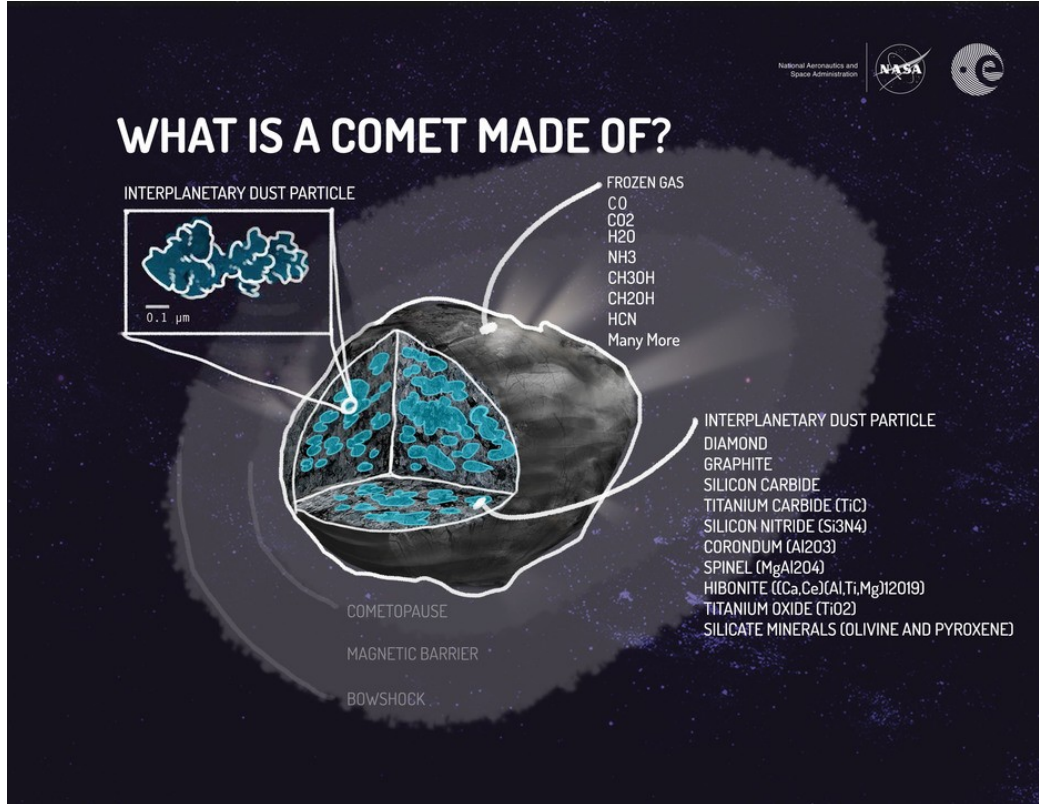
- First object from the Oorts cloud
- Brown et al 2004, ApJL



<http://web.gps.caltech.edu/~mbrown/sedna/>



Comets



Credit: NASA JPL

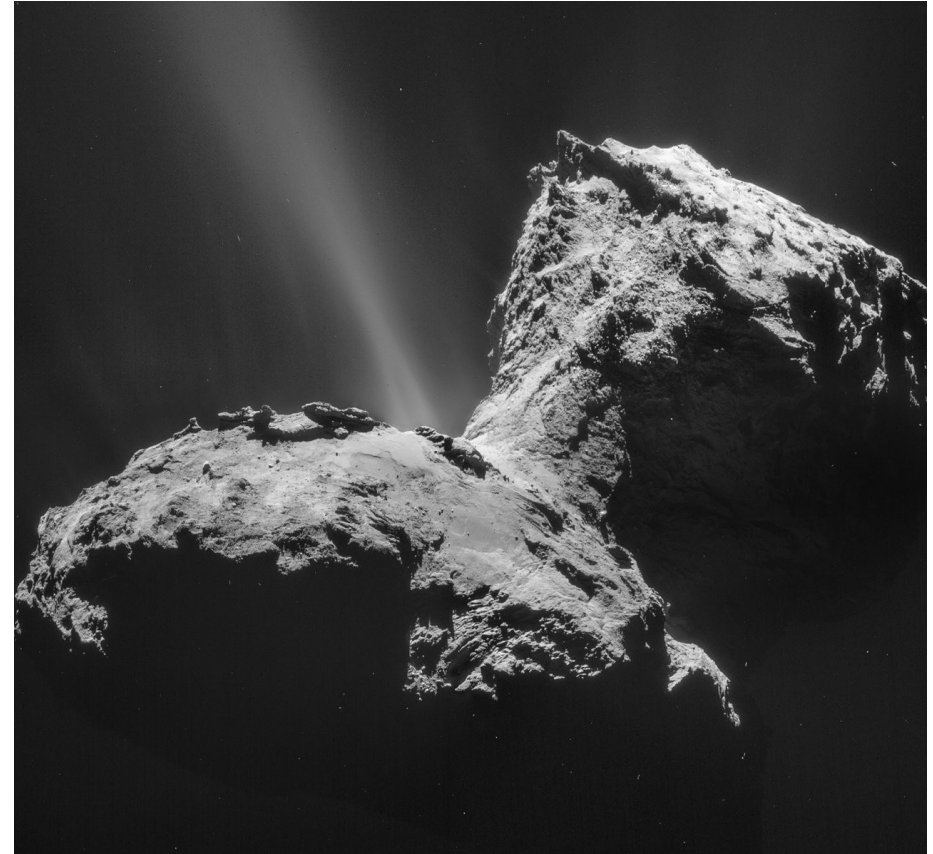


Image: NASA 67P/Churyumov-Gerasimenko

Mysterious Kepler star KIC8462852

- Why is so unique?
- Why caught attention?
 - IRREGULARITY

KIC8462852

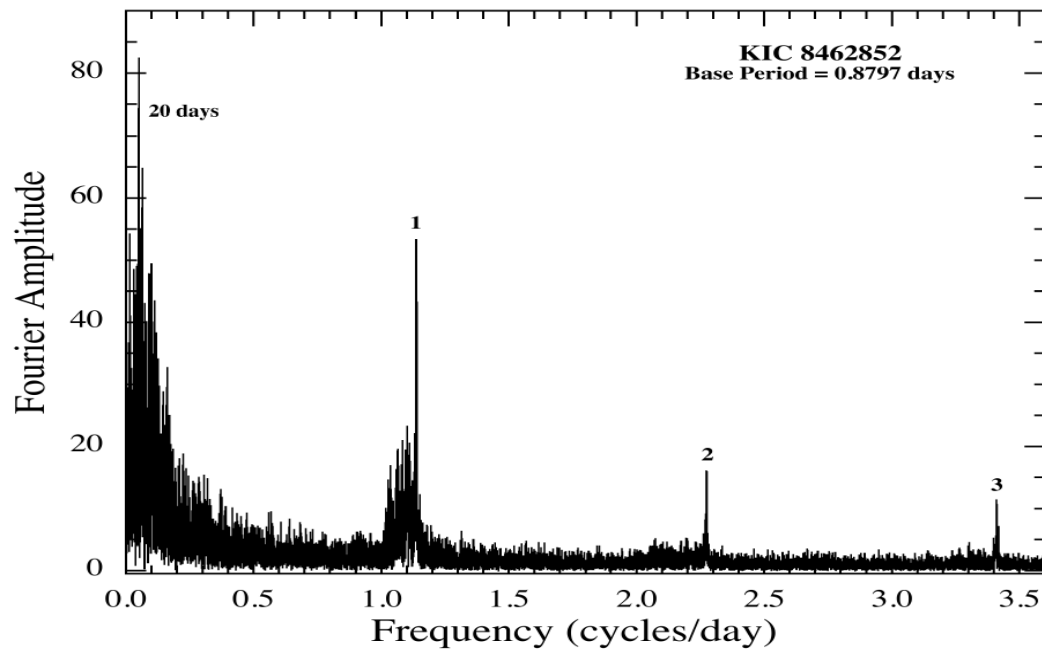


Figure 2. Fourier transform for KIC 8462852. The peaks are labeled with the harmonic numbers starting with 1 for the base frequency. Refer to Section 2.1 for details.

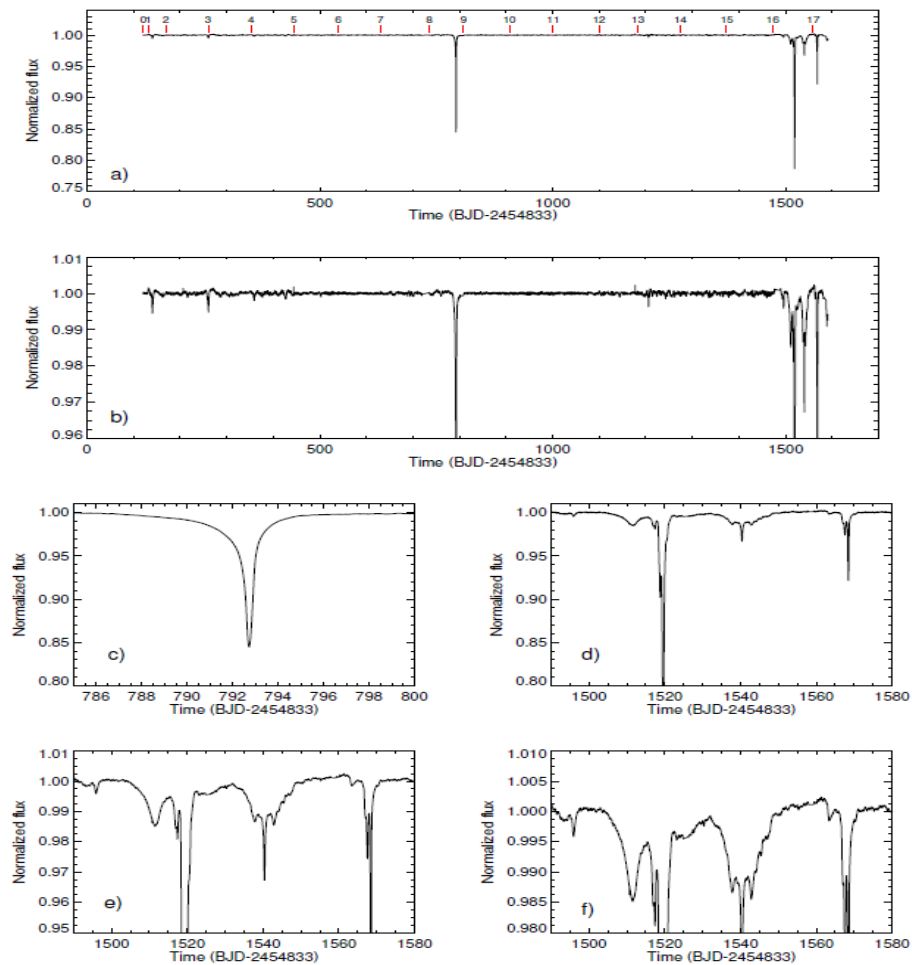


Figure 1. Montage of flux time series for KIC 8462852 showing different portions of the 4-year *Kepler* observations with different vertical scalings. The top two panels show the entire *Kepler* observation time interval. The starting time of each *Kepler* quarter is marked and labeled with a red vertical line in the top panel ‘(a)’. Panel ‘(c)’ is a blowup of the dip near day 793, (D800). The remaining three panels, ‘(d)’, ‘(e)’, and ‘(f)’, explore the dips which occur during the 90-day interval from day 1490 to day 1580 (D1500). Refer to Section 2.1 for details. See Section 2.1 for details.

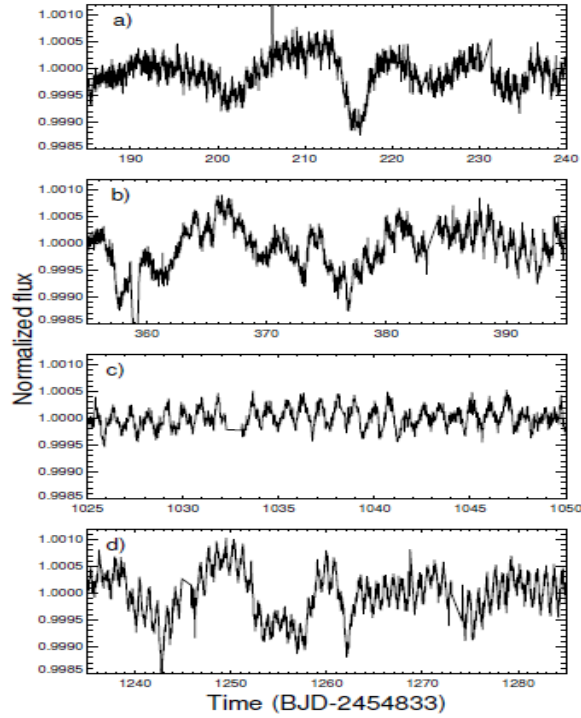


Figure 4. Stacked plots showing a zoomed-in portion of the *Kepler* light curve. The star's rotation period of 0.88 d is seen in each panel as the high-frequency modulation in flux. With the exception of panel 'c', a longer term (10–20 day) brightness variation is observed, also present in the FT shown in Figure 2. Refer to Section 2.1 for details.

tional velocity, and rotation period (Section 2.1), we determine a stellar rotation axis inclination of 68 degrees.

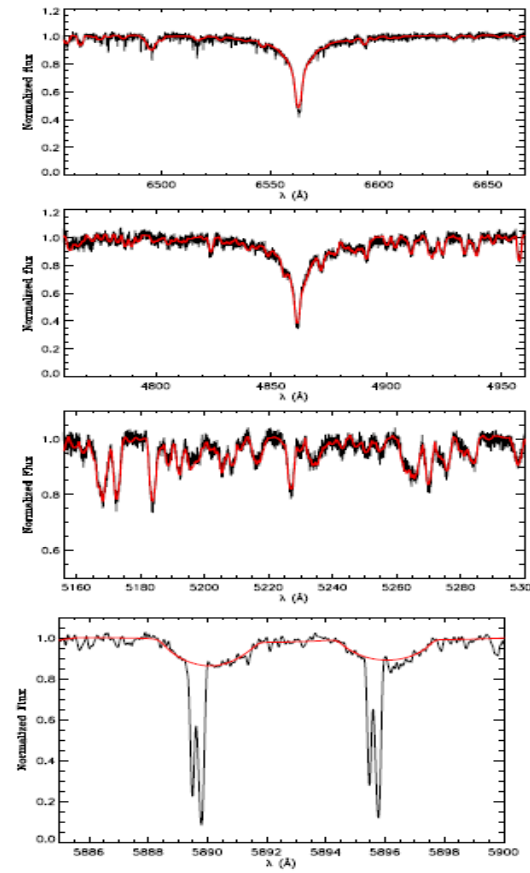


Figure 5. NOT spectrum closeups for KIC 8462852, the best fit stellar model shown in red. Panels show region near $H\alpha$, $H\beta$, Mg, and Na D (top to bottom). The bottom panel shows both the stellar (broad) and interstellar (narrow) counterparts of the Na D lines. Refer to Section 2.2 for details.

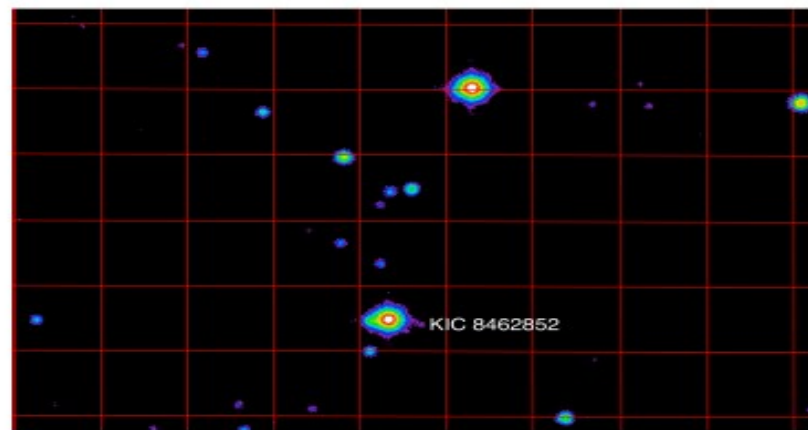


Figure 6. UKIRT image for KIC 8462852 and another bright star for comparison, showing that it has a distinct protrusion to the left (east). For reference, the grid lines in the image are $10'' \times 10''$. Refer to Section 2.3 for details.

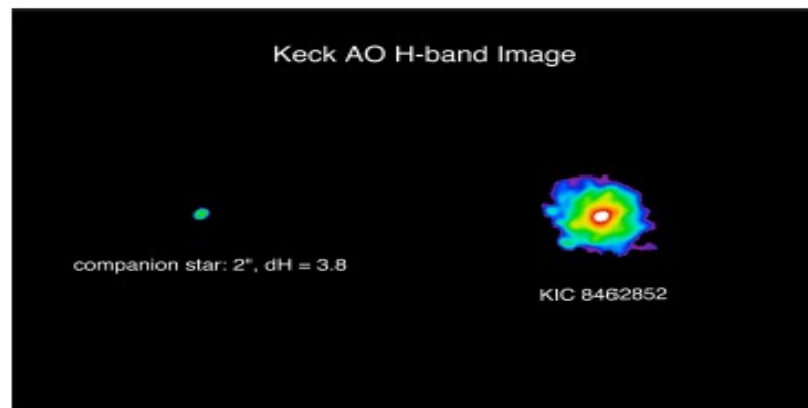


Figure 7. Keck AO H -band image for KIC 8462852 showing the companion was detected with a $2''$ separation and a magnitude difference $\Delta H = 3.8$. Refer to Section 2.3 for details.

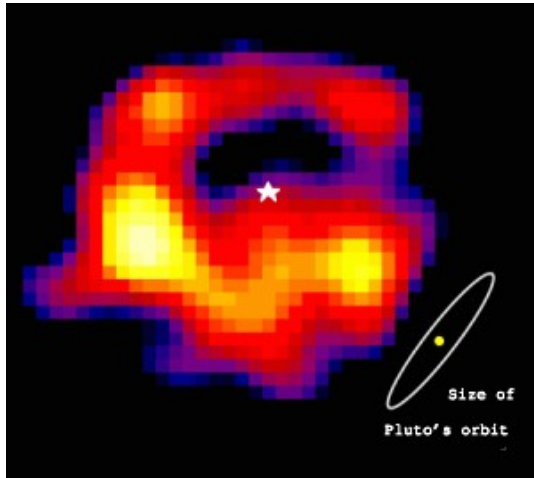
Explanations of a Kepler star mystery?

- A comet which broke apart and now is orbiting a star?
- Disc around the star
- A result of a collision of large bodies – however no IR excess observed
- Aliens? - perhaps not, not yet

Reading - <https://arxiv.org/pdf/2002.10370.pdf>

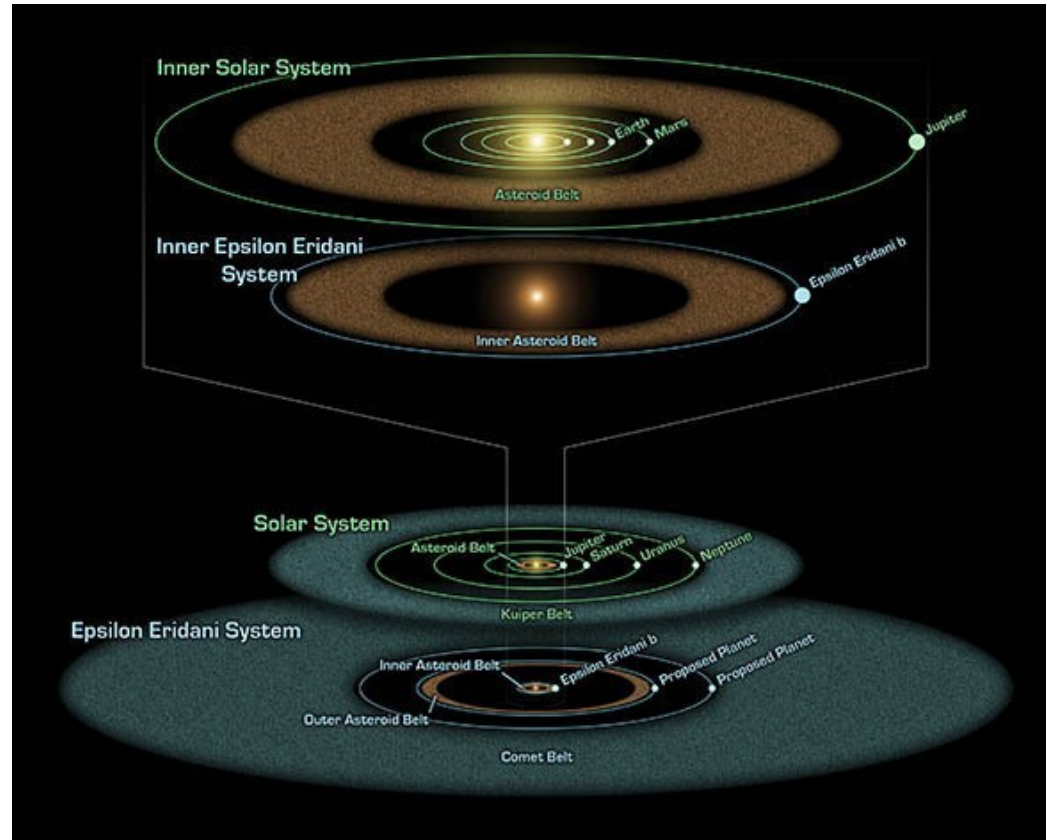
Solar System and alien worlds

- Epsilon Eri



Credit:

Jane Greaves - Joint Astronomy Center (JAC), Hawaii



Credit NASA JPL

Benedict et al. 2006 <https://arxiv.org/abs/astro-ph/0610247>

55 Cnc A system

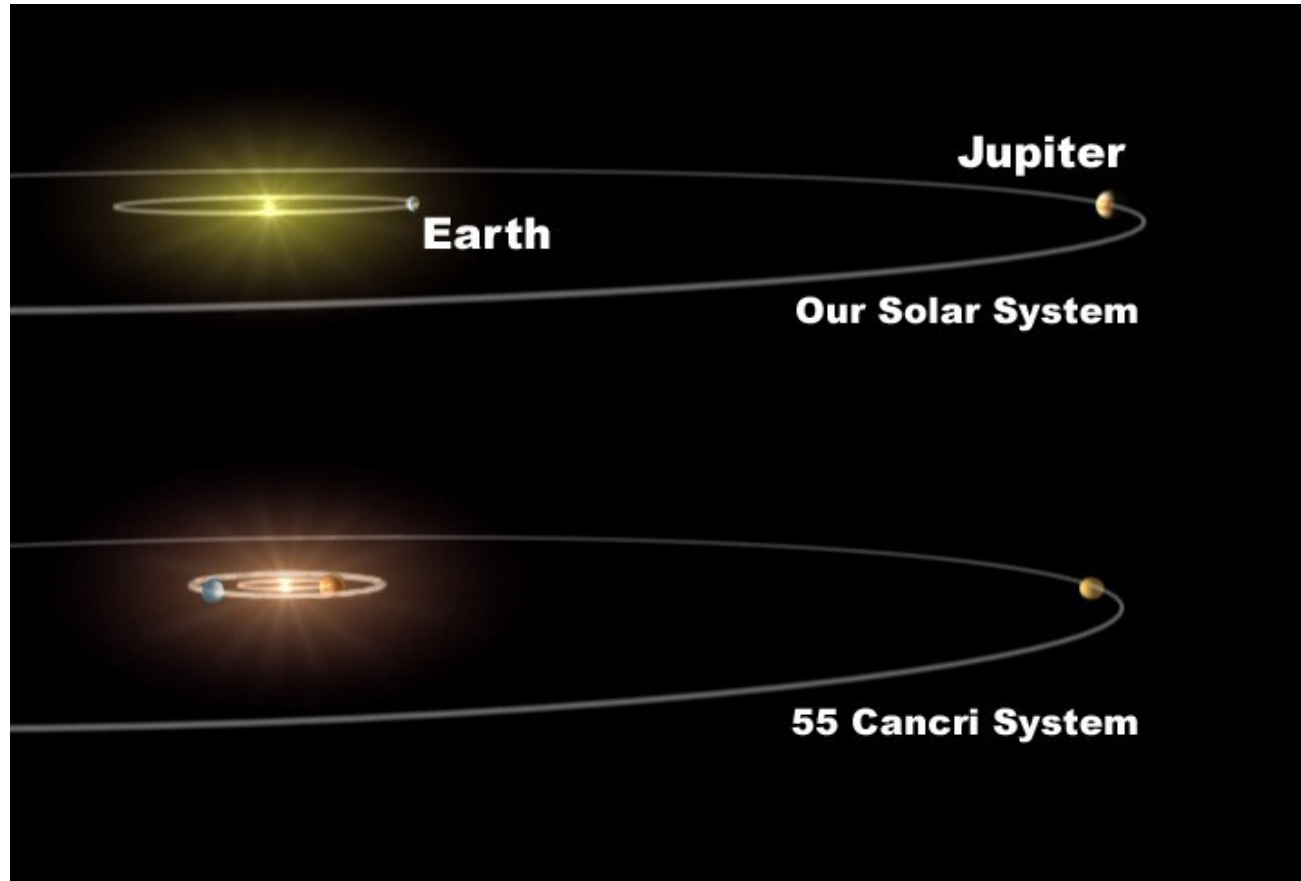


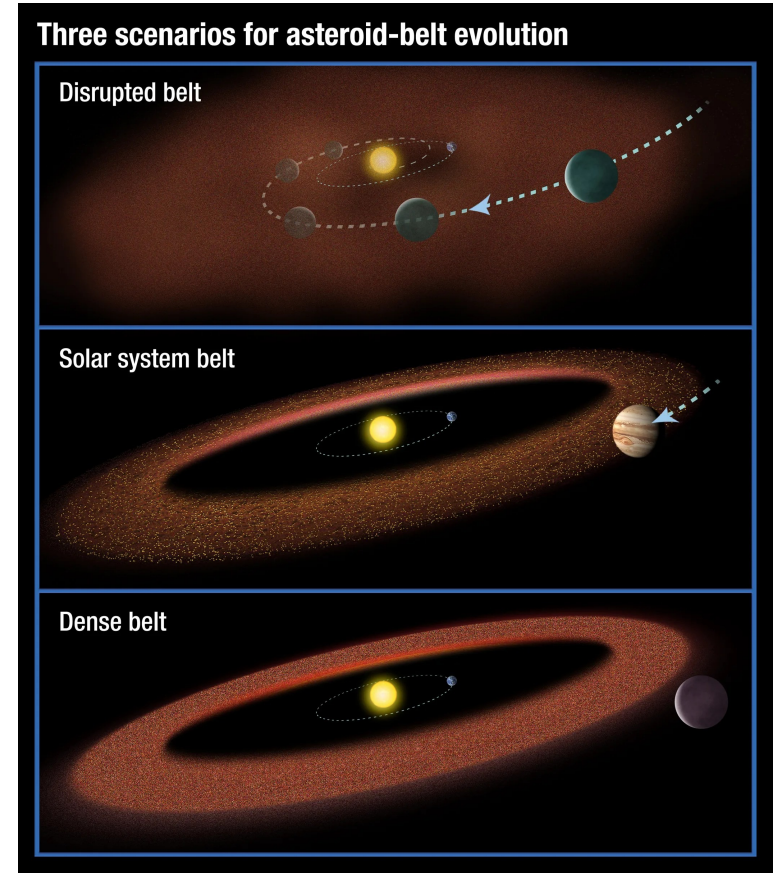
Image: NASA

Moutu et al. 2025, <https://arxiv.org/pdf/2510.11523>

The asteroid belt and life?

- Importance of asteroid belt for life
- Material for bombardment of inner planets
- Migration/non migration perhaps crucial

Image credit: NASA

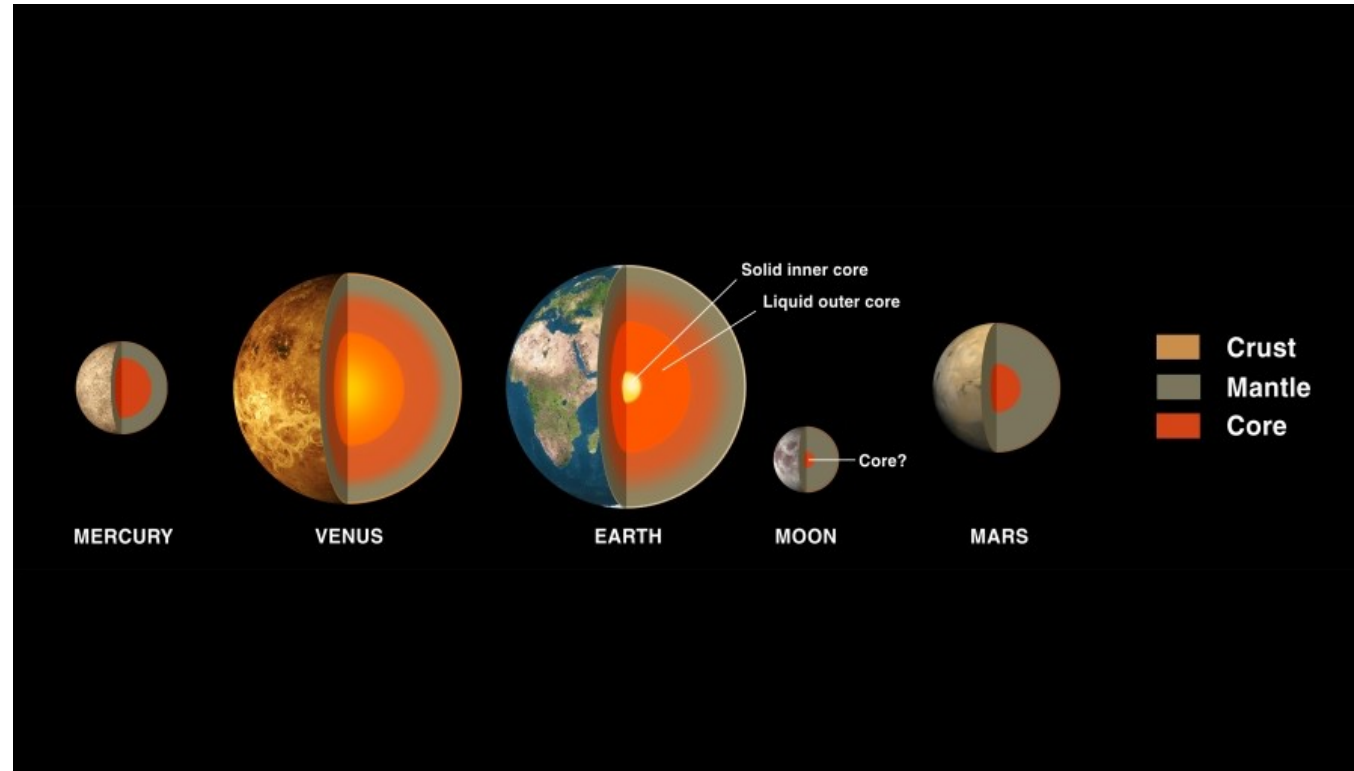
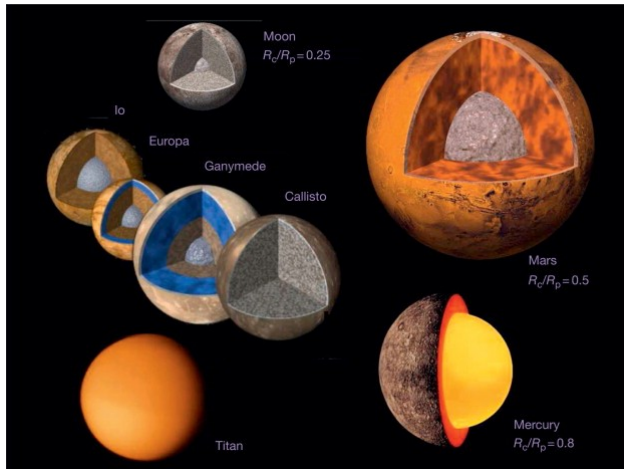


Terrestrial planets and moons



Terrestrial planets composition

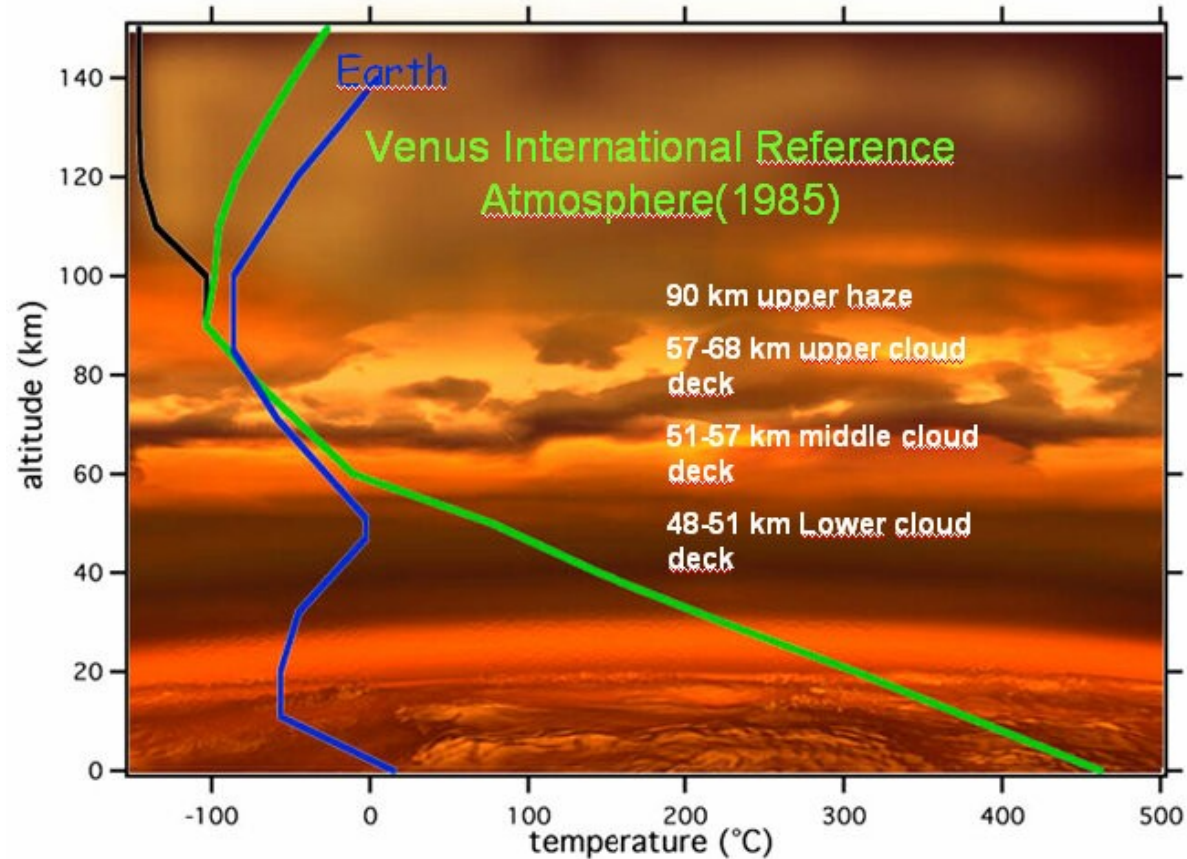
- Solid core
- Rocky surface
- Thin atmosphere



Credit: NASA JpL

Atmosphere of Earth, Venus and Mars

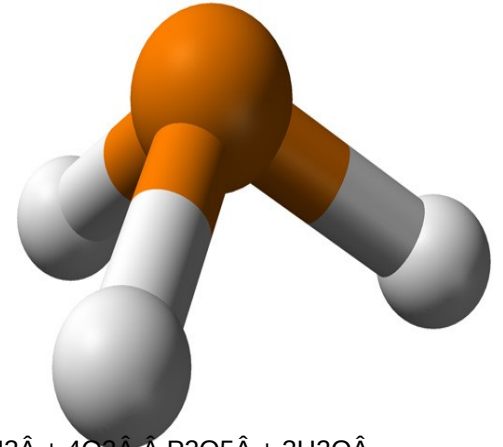
Atmosphere of Venus



Credit: ESA

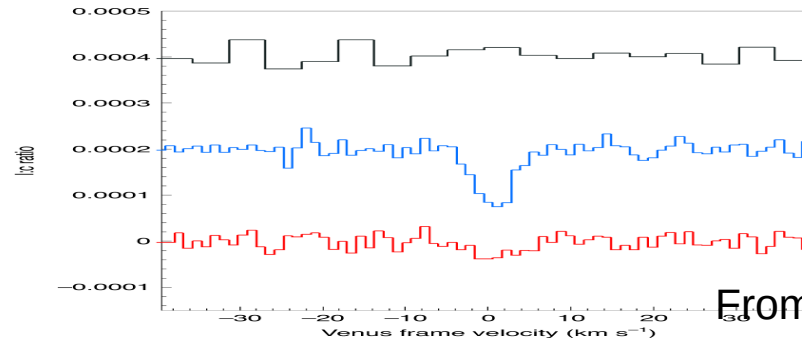
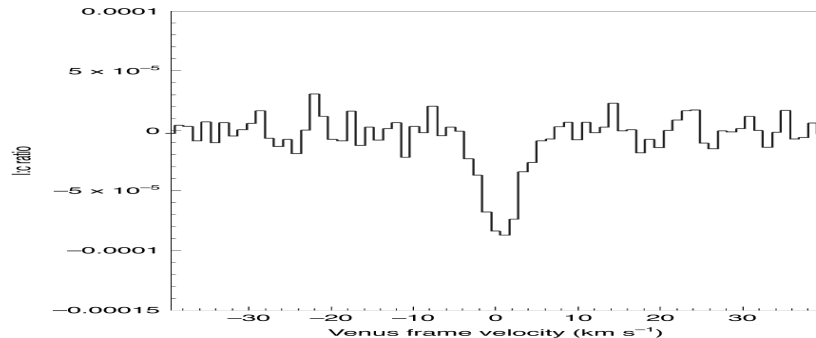
Phosphine in Venus's atmosphere

- JCMT & ALMA observations indicate PH₃ in the clouds
- Greaves et al. 2020, Phosphine gas in the cloud decks of Venus. *Nat Astron* (2020).
<https://doi.org/10.1038/s41550-020-1174-4>



Source: <https://chemiday.com/en/reaction/3-1-0-807>

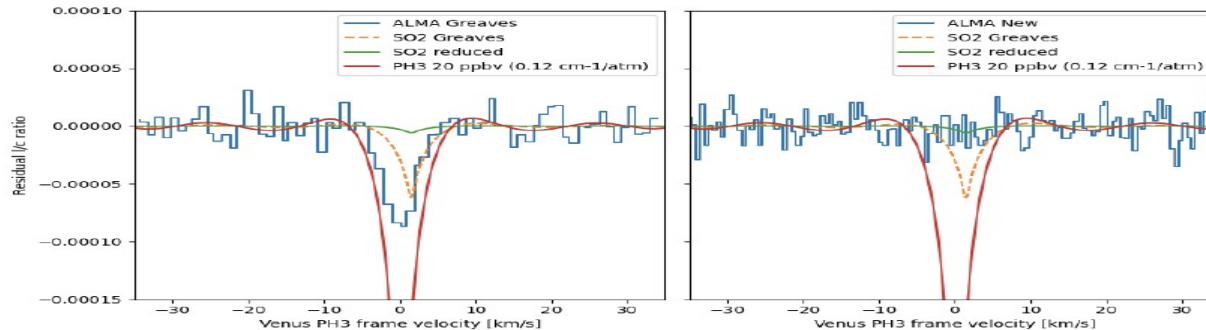
- Lingam & Loeb, 2020, <https://arxiv.org/pdf/2009.07835.pdf> - microbial Phosphine possible?



From Greaves 2020

Or no Phosphine?

- Villanueva et al 2020,
<https://arxiv.org/abs/2010.14305>
- JCMT can be explained by SO₂ contamination
- ALMA by calibration issues



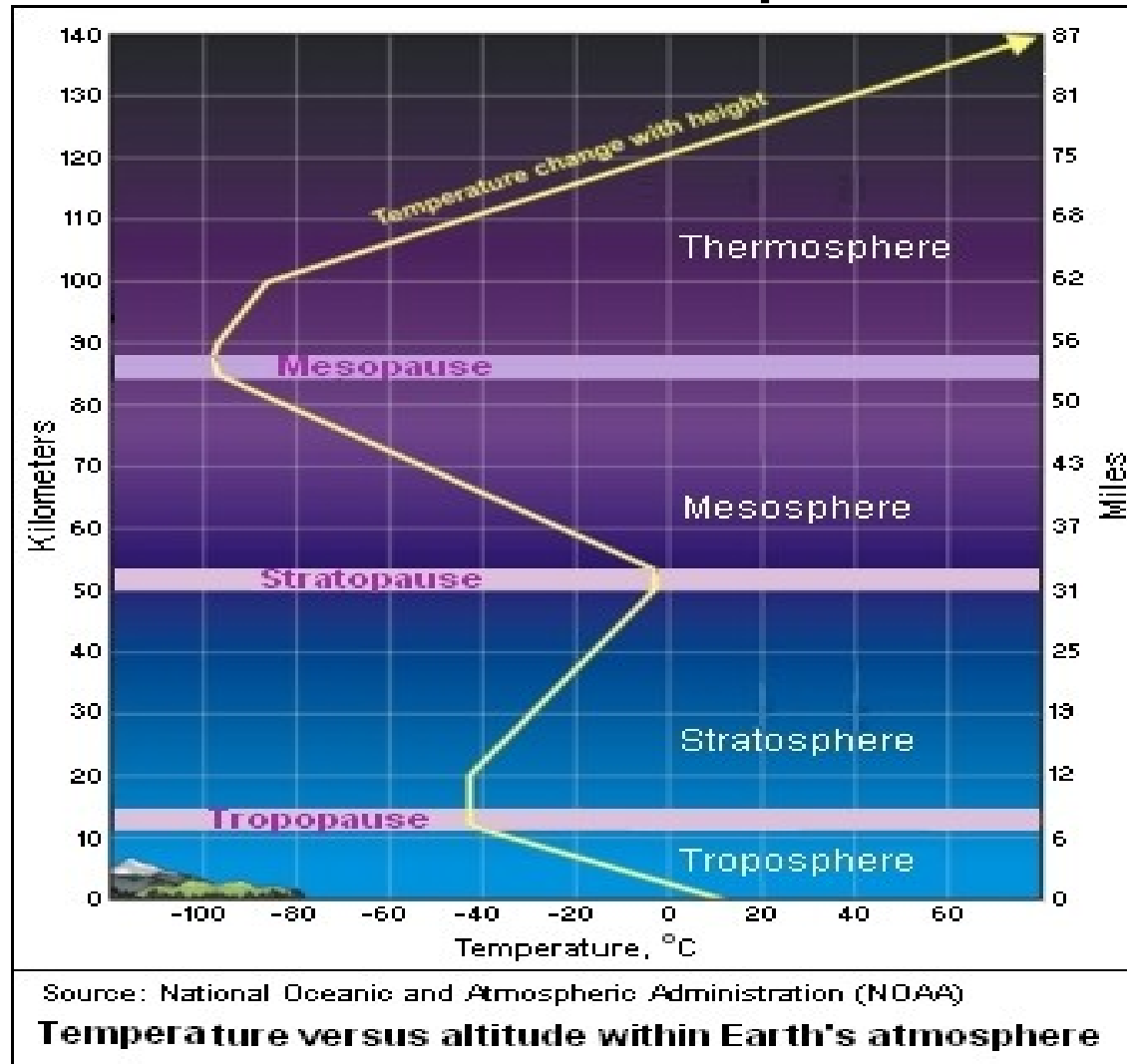
Detectability of Phosphine

- Sousa Silva et al. <https://arxiv.org/pdf/1910.05224.pdf>

Atmospheric Scenario	Required Mixing Ratio for Detection	Minimum Observation Hours (in-transit + out-of-transit)	Associated Confidence Interval for Phosphine Detection (σ)
H ₂ -dominated, Sun-like star	780 ppm	56	3
H ₂ -dominated, active M-dwarf (Fig. 3)	220 ppb	91	3
H ₂ -dominated, active M-dwarf	220 ppb	200	4.4
H ₂ -dominated, active M-dwarf	5 ppb	200	2.5
H ₂ -dominated, active M-dwarf	0.28%	3	5
CO ₂ -dominated, Sun-like star	N/A	Not detectable	N/A
CO ₂ -dominated, active M-dwarf (Fig. 4)	310 ppm	200	2.7
CO ₂ -dominated, active M-dwarf	7.6%	32	3

Potential PH ₃ Production Pathway on Venus	Quantitative Barriers for Production Pathway	Method
Equilibrium thermodynamics of chemical reactions between chemical species in the atmosphere and on the surface	Chemical reactions in Venusian environment are on average 100 kJ/mol too energetically costly (10 - 400 kJ/mol) to proceed spontaneously	Calculation of free energy from known or modeled gas concentrations
Equilibrium thermodynamics of chemical reactions in the subsurface	Oxygen fugacity of plausible crust and mantle rocks 8 - 15 orders of magnitude too high to support reduction of phosphate	Calculation of subsurface oxygen fugacity (fO ₂)
Photochemical production by photochemically-generated reactive species	The required forward reaction rates are too low by factors of 10 ⁴ - 10 ⁶	UV production of radicals followed by forward kinetic modelling from known and estimated reaction rates
Production by lightning	Limited frequency of lightning and low abundance of both atmospheric P species and reducing gases. Less than ppt of PH ₃ is produced. PH ₃ production is ~7 orders of magnitude too low to explain detected amounts	Calculations of the maximal efficiency of formation of PH ₃ upon complete atomization of atmospheric and cloud components containing phosphorus. Literature review of lab experiments on the efficiency of formation of PH ₃ by lightning discharges.
Meteoritic delivery as a source of phosphides and phosphine	The estimated maximal yearly meteoritic delivery of phosphine is ~8 orders of magnitude too low to explain detected amounts	Calculation of the maximum possible amounts of reduced P species delivered assuming their 100% conversion to PH ₃
Large-scale comet/asteroid impact	Radar mapping of the surface of Venus shows no evidence of a recent large impact	
Other endergonic processes as potential sources of phosphine	Solar wind protons and large tribochemical processes cannot be responsible	

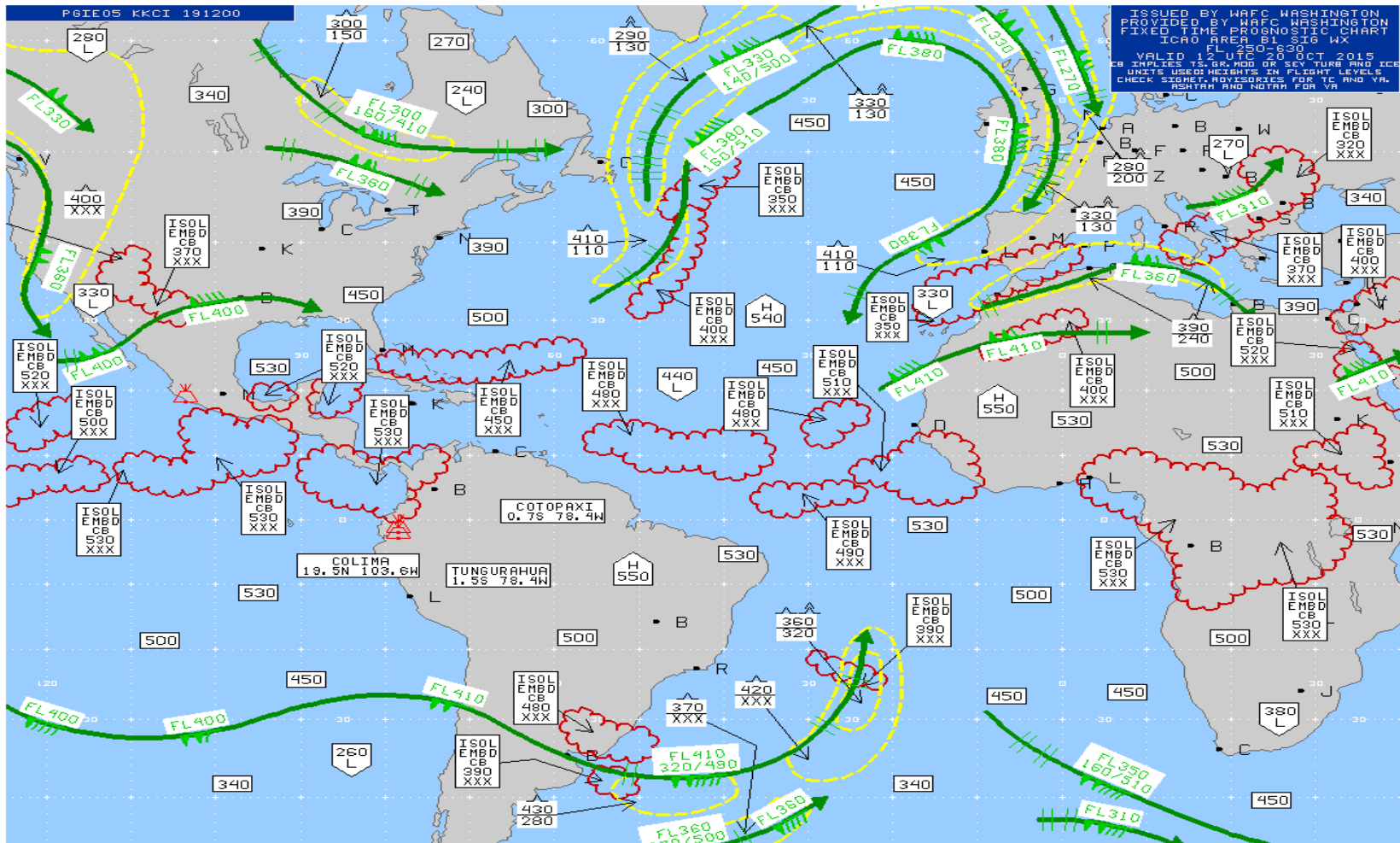
Earth's atmosphere



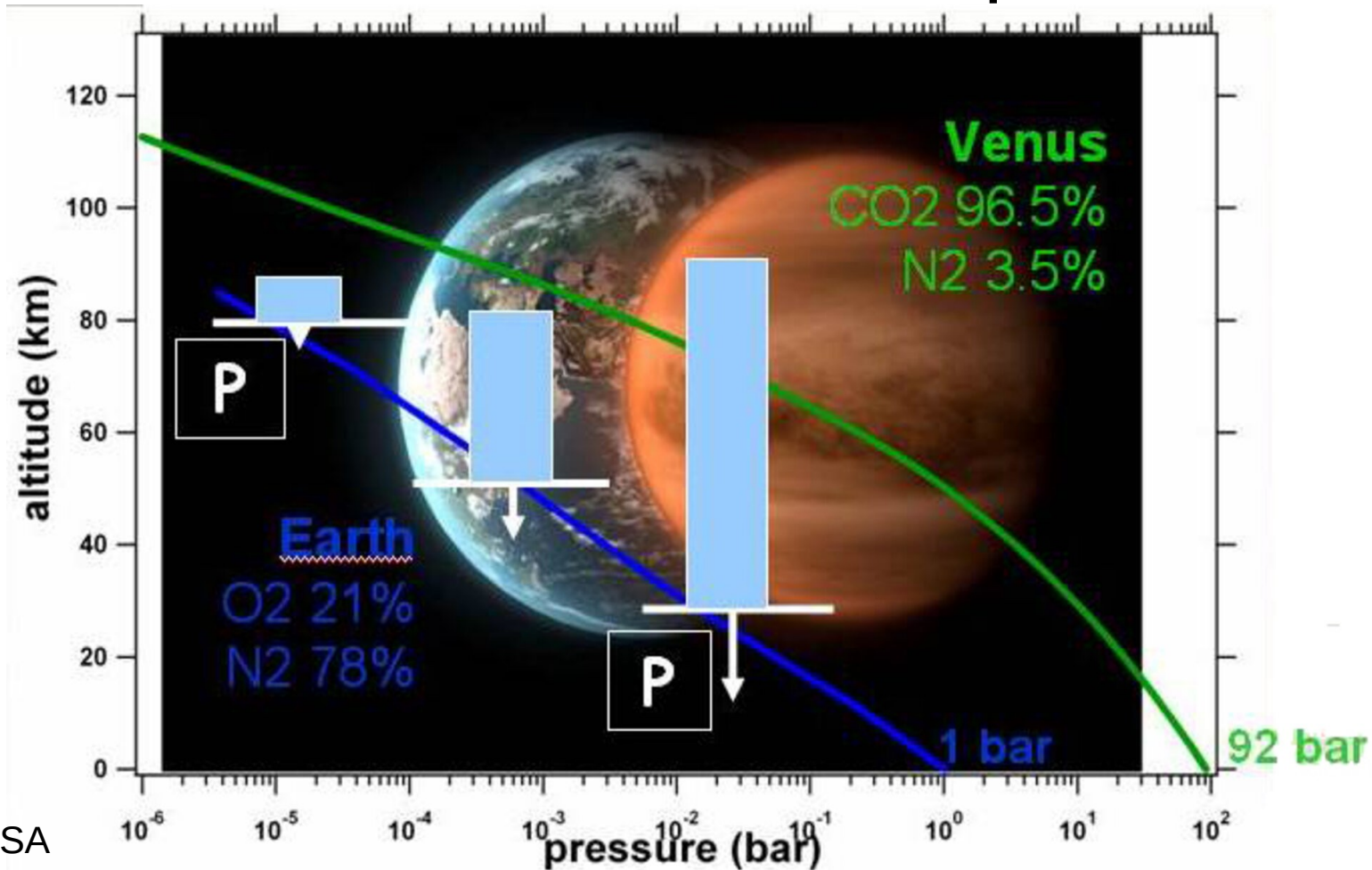
The weather



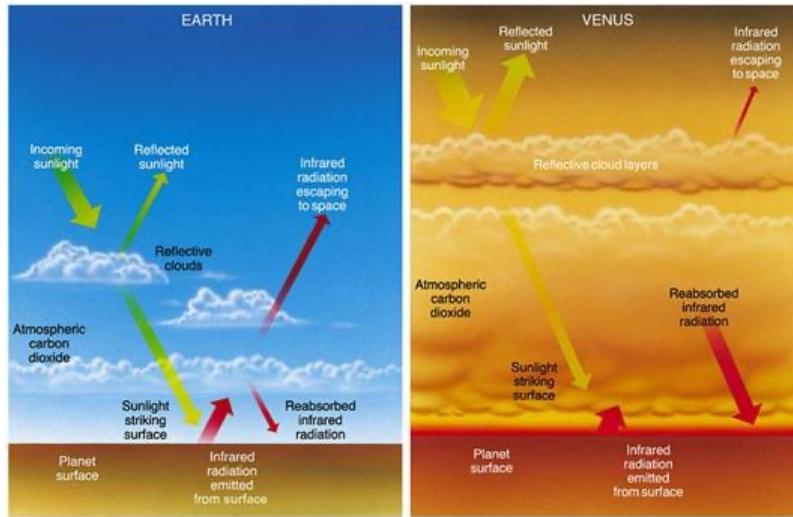
Jet streams



Venus and Earth compared



Difference between Earth and Venus



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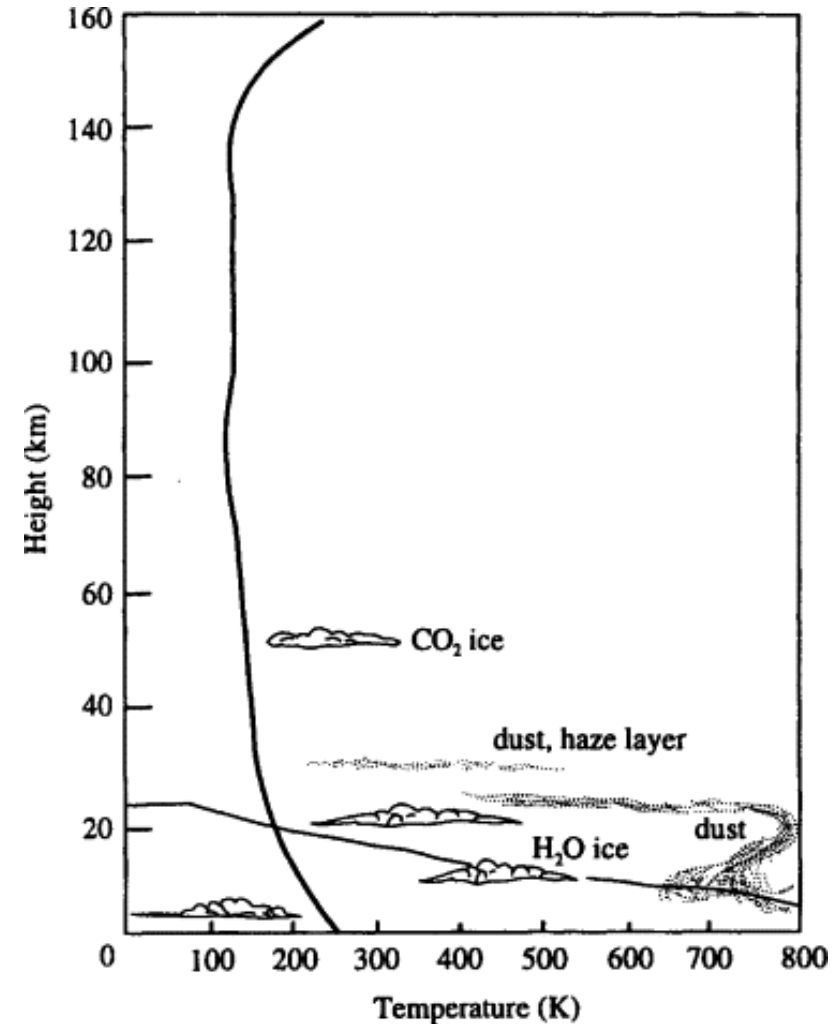
Credit: Pearson Education

	Venus	Earth
Average surface temperature	737 K	288 K
Effective Temperature = Apparent radiative temperature (from space)	232 K	254 K
Excess in temperature due to greenhouse effect	+ 505 K	+ 34 K

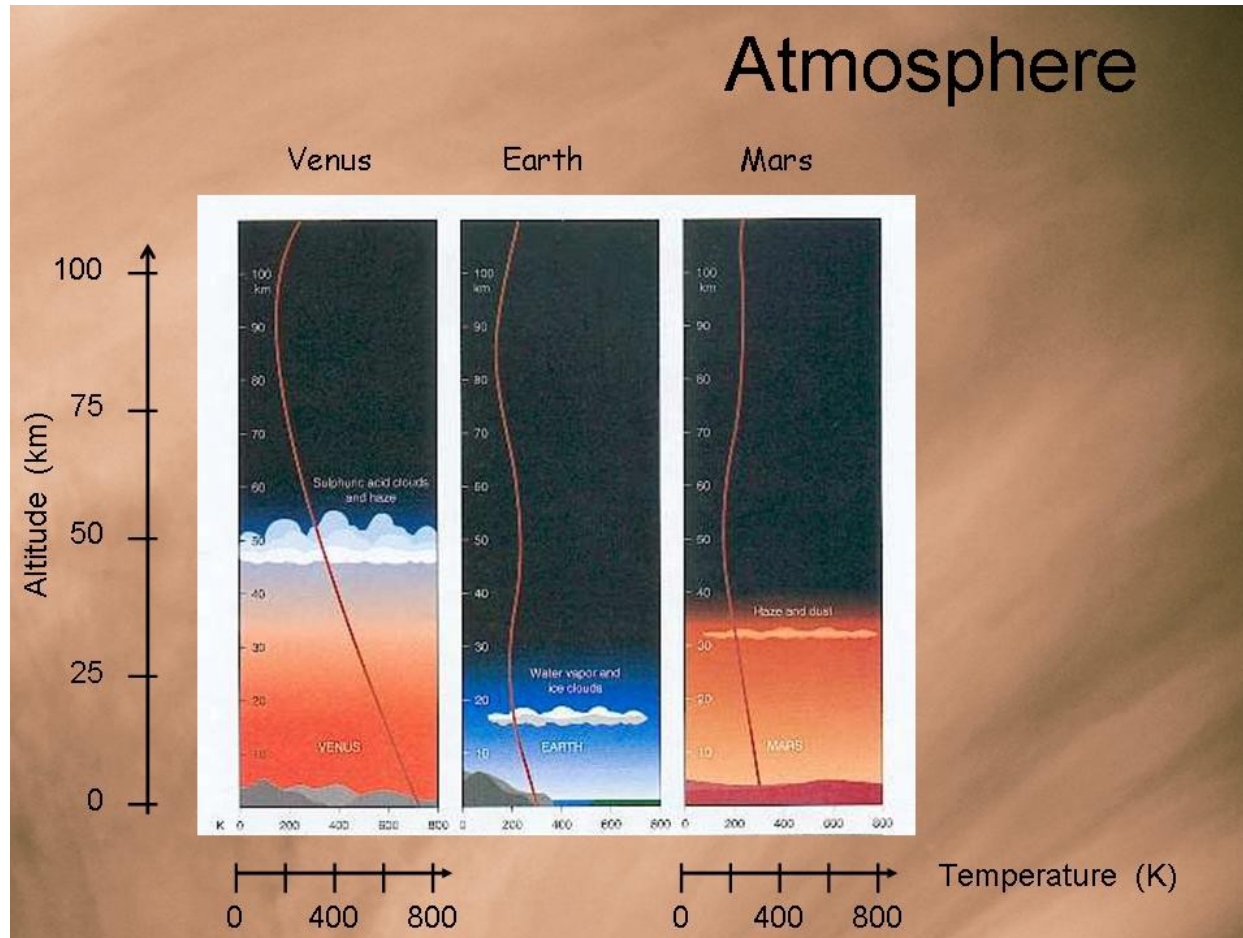
Credit: BISA

Mars

- 96% CO₂ atmosphere
- 0.02% water vapor
- Atmospheric pressure 6-7mb
- Dust storms
- <https://www.sciencedirect.com/topics/earth-and-planetary-sciences/martian-atmosphere>
- Mahaffy et al., 2013
<https://science.sciencemag.org/content/341/6143/263>



Venus, Earth and Mars compared

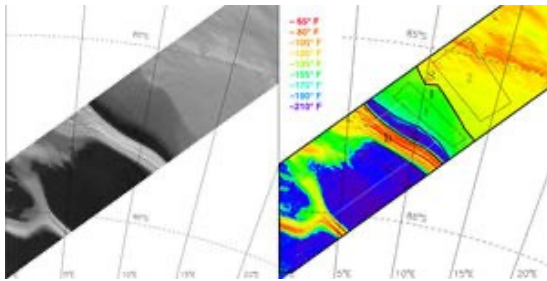


Water on Mars?

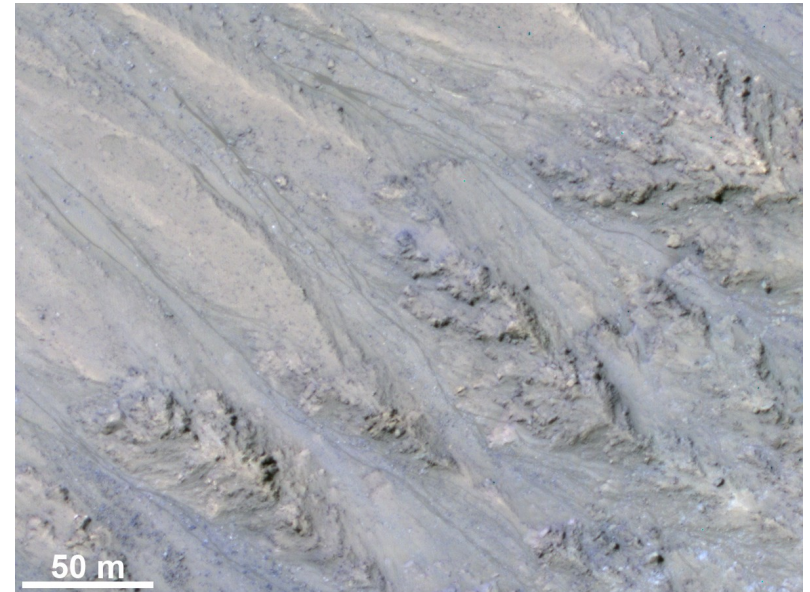
- Lakes below surface?

<https://www.nature.com/articles/s41550-020-1200-6>

- Sand or water? See credit below.
- Polar caps from CO₂ but also with patches of water ice

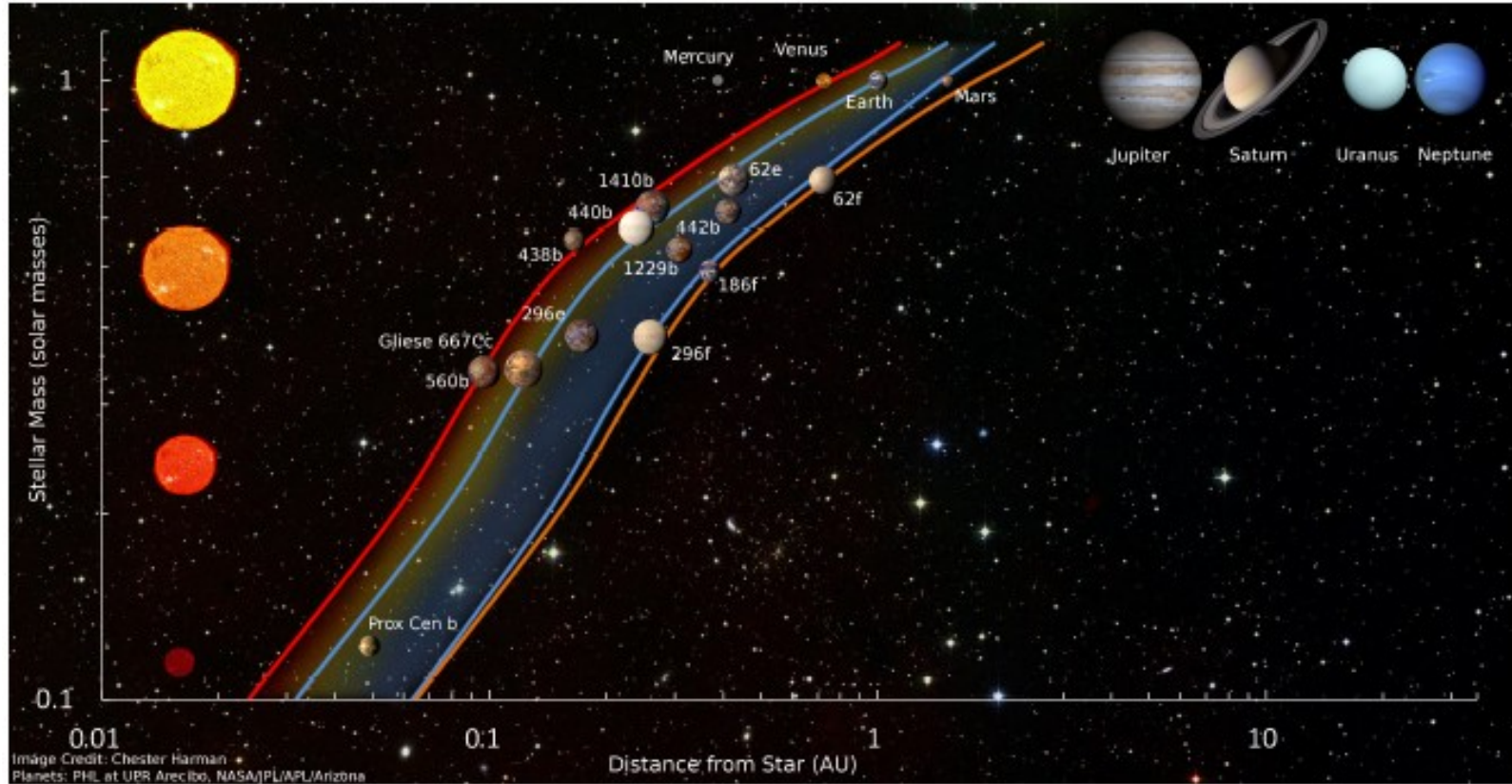


NASA JpL
THEMIS
(left Figure)



https://www.nasa.gov/sites/default/files/thumbnails/image/pia22070fig1_esp_023184_1335_cutout_scalebar.jpg

Habitability

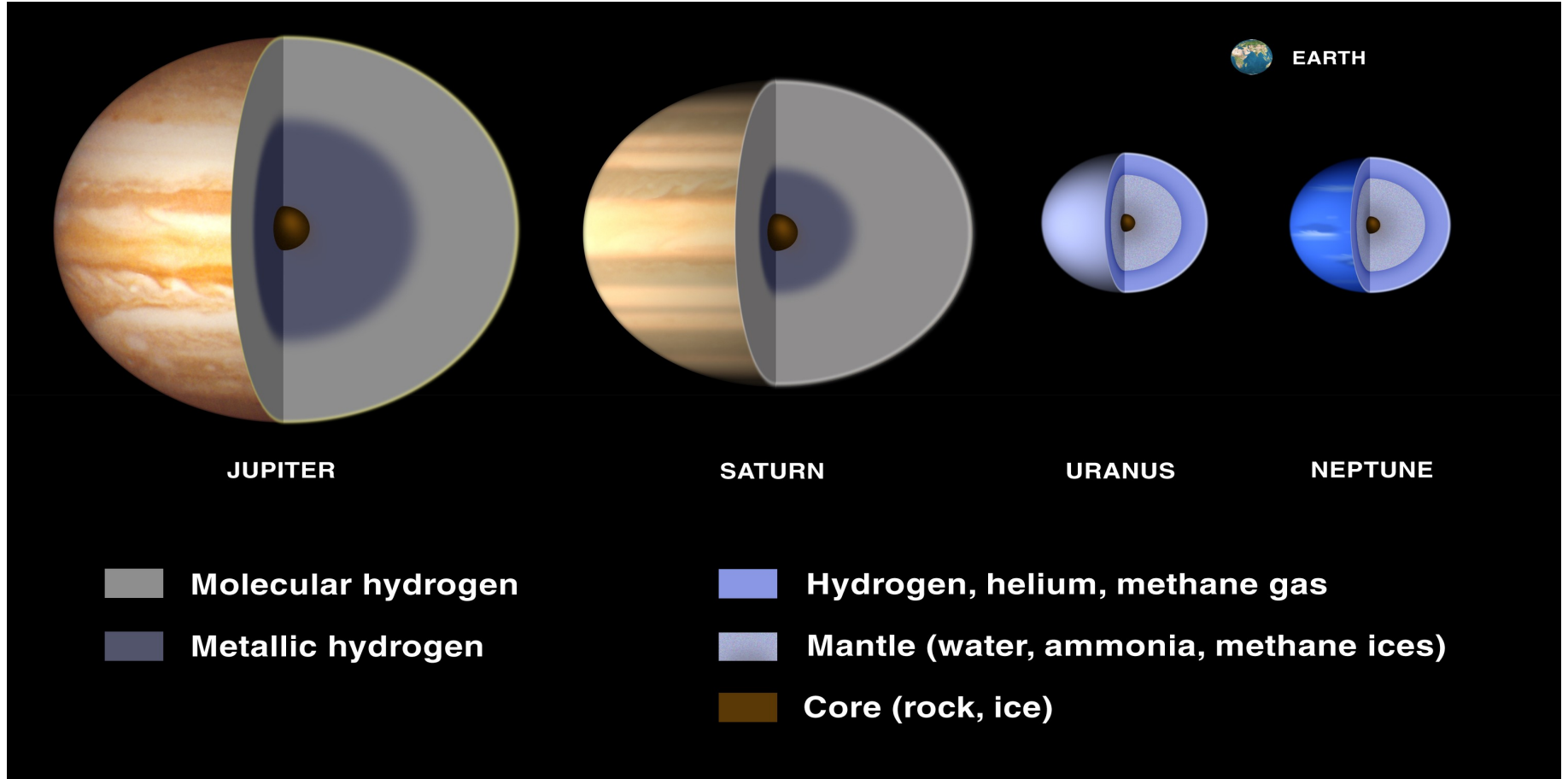


Shields et al. https://www.researchgate.net/publication/309288637_The_Habitability_of_Planets_Orbiting_M-dwarf_Stars/figures?lo=1

Parameters of Solar System planets

Celestial Object	Mean Distance from Sun (million km)	Period of Revolution (d=days) (y=years)	Period of Rotation at Equator	Eccentricity of Orbit	Equatorial Diameter (km)	Mass (Earth = 1)	Density (g/cm ³)
SUN	—	—	27 d	—	1,392,000	333,000.00	1.4
MERCURY	57.9	88 d	59 d	0.206	4,879	0.06	5.4
VENUS	108.2	224.7 d	243 d	0.007	12,104	0.82	5.2
EARTH	149.6	365.26 d	23 h 56 min 4 s	0.017	12,756	1.00	5.5
MARS	227.9	687 d	24 h 37 min 23 s	0.093	6,794	0.11	3.9
JUPITER	778.4	11.9 y	9 h 50 min 30 s	0.048	142,984	317.83	1.3
SATURN	1,426.7	29.5 y	10 h 14 min	0.054	120,536	95.16	0.7
URANUS	2,871.0	84.0 y	17 h 14 min	0.047	51,118	14.54	1.3
NEPTUNE	4,498.3	164.8 y	16 h	0.009	49,528	17.15	1.8
EARTH'S MOON	149.6 (0.386 from Earth)	27.3 d	27.3 d	0.055	3,476	0.01	3.3

Gas giants



Credit: NASA JpL

Jupiters atmosphere

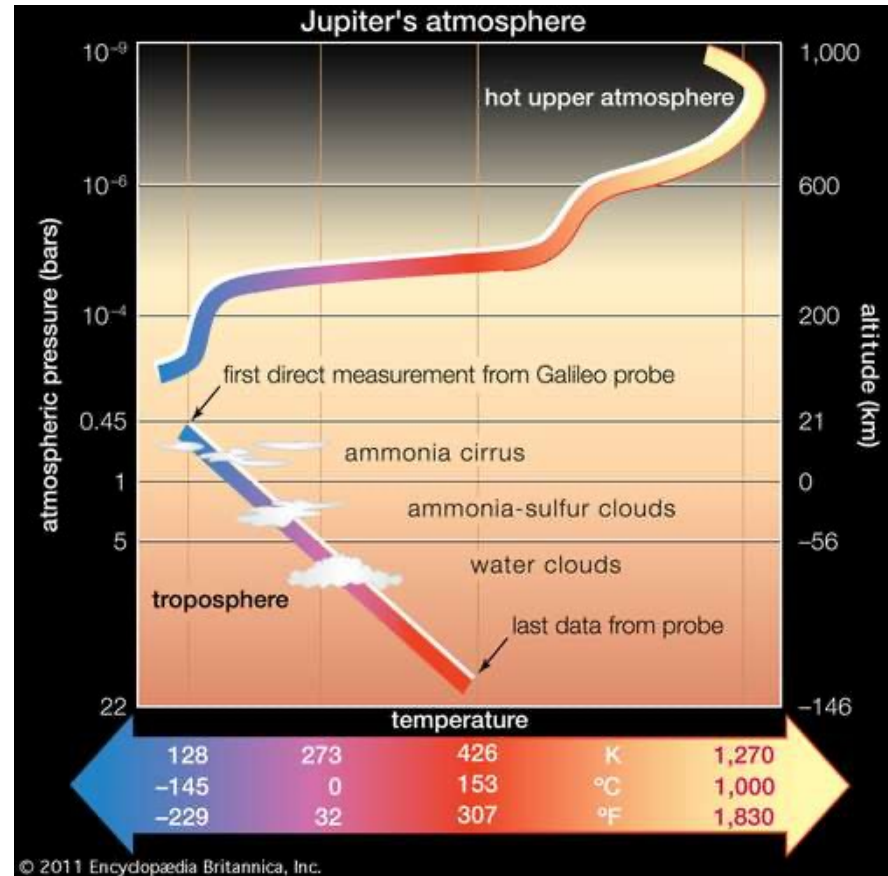
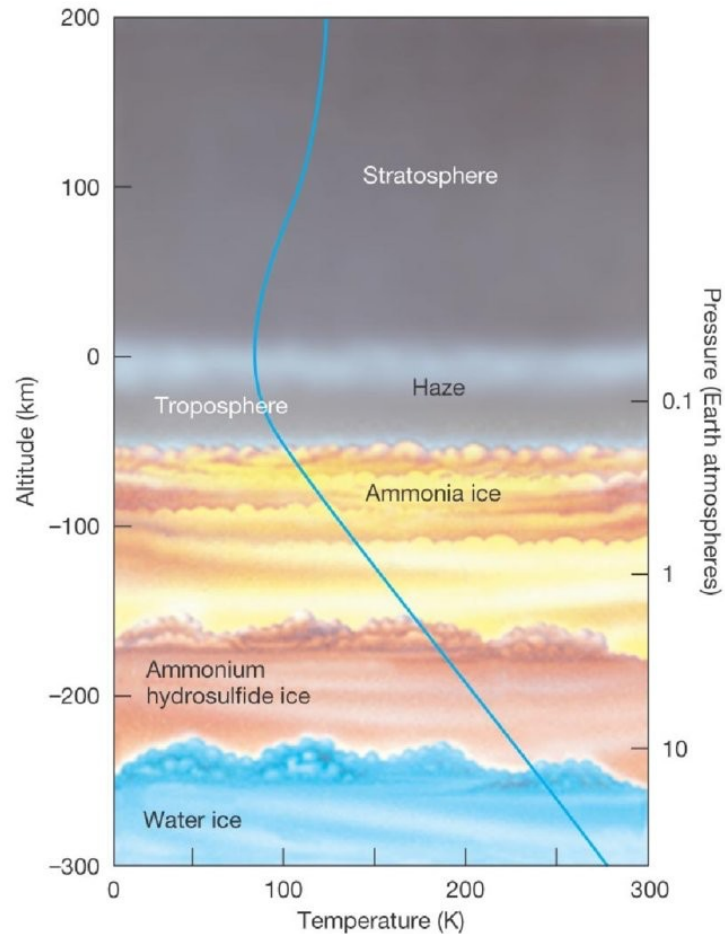
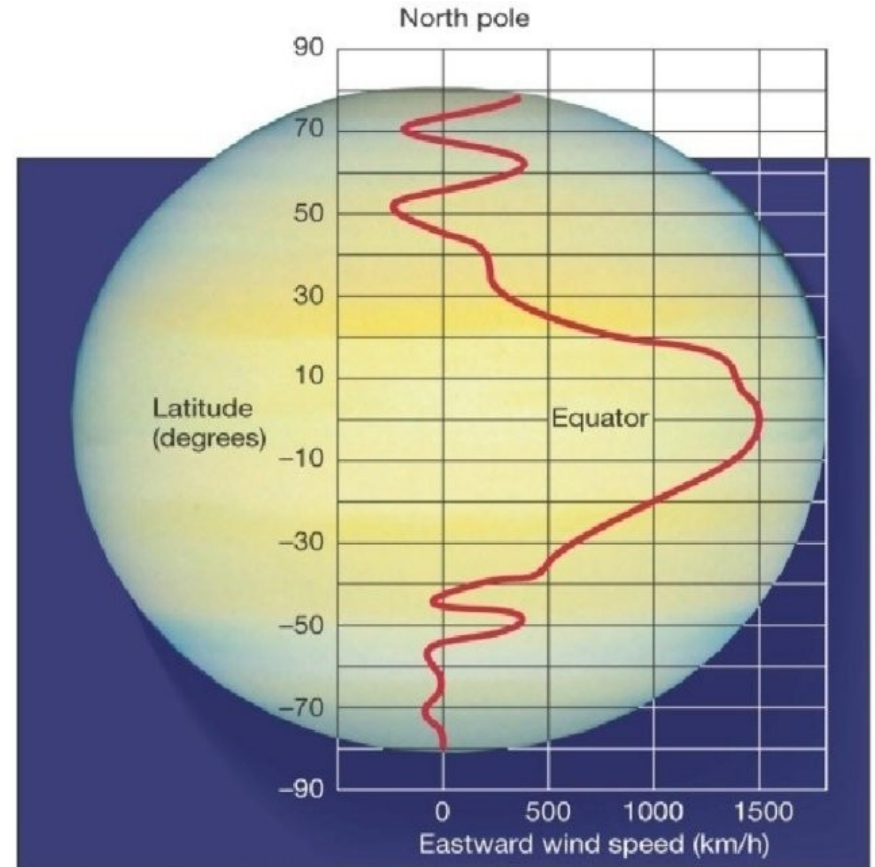


Image: Brittanica

Saturn's atmosphere



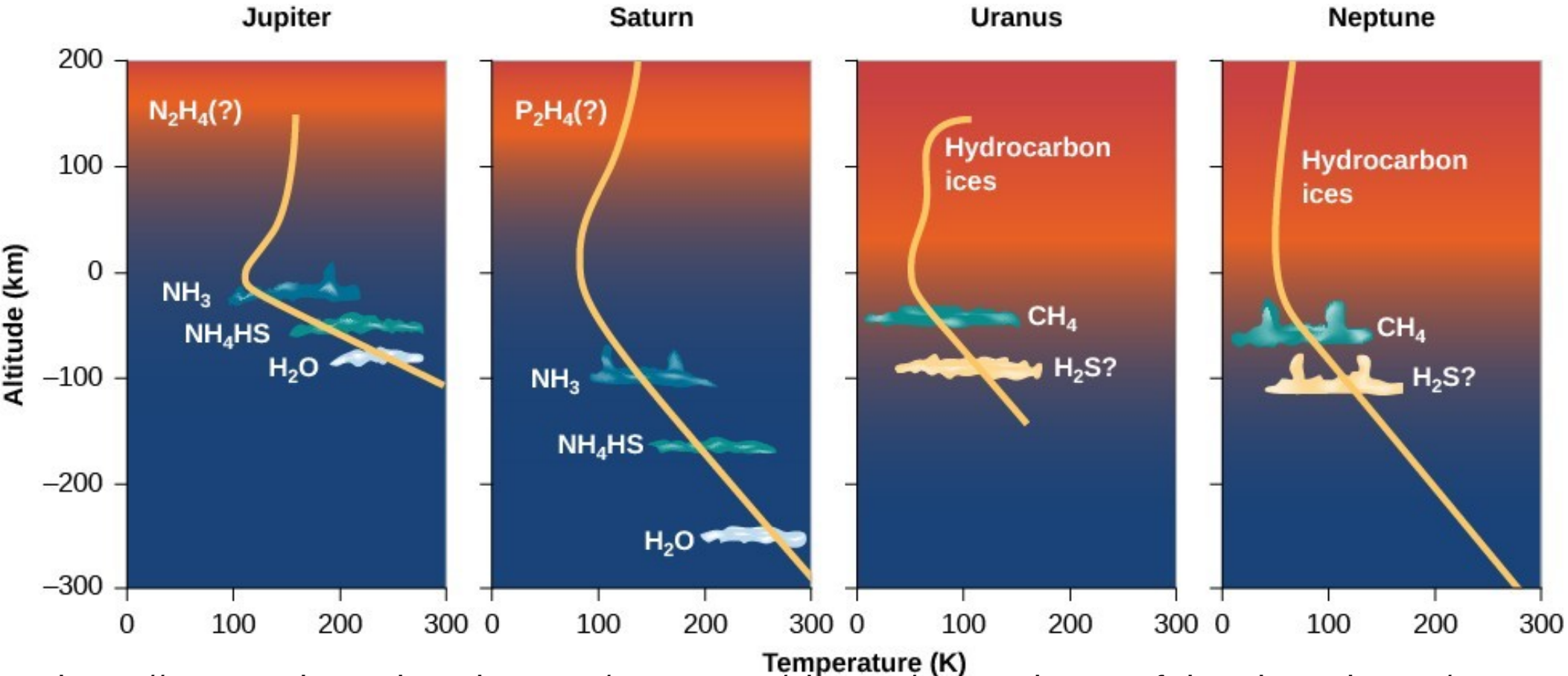
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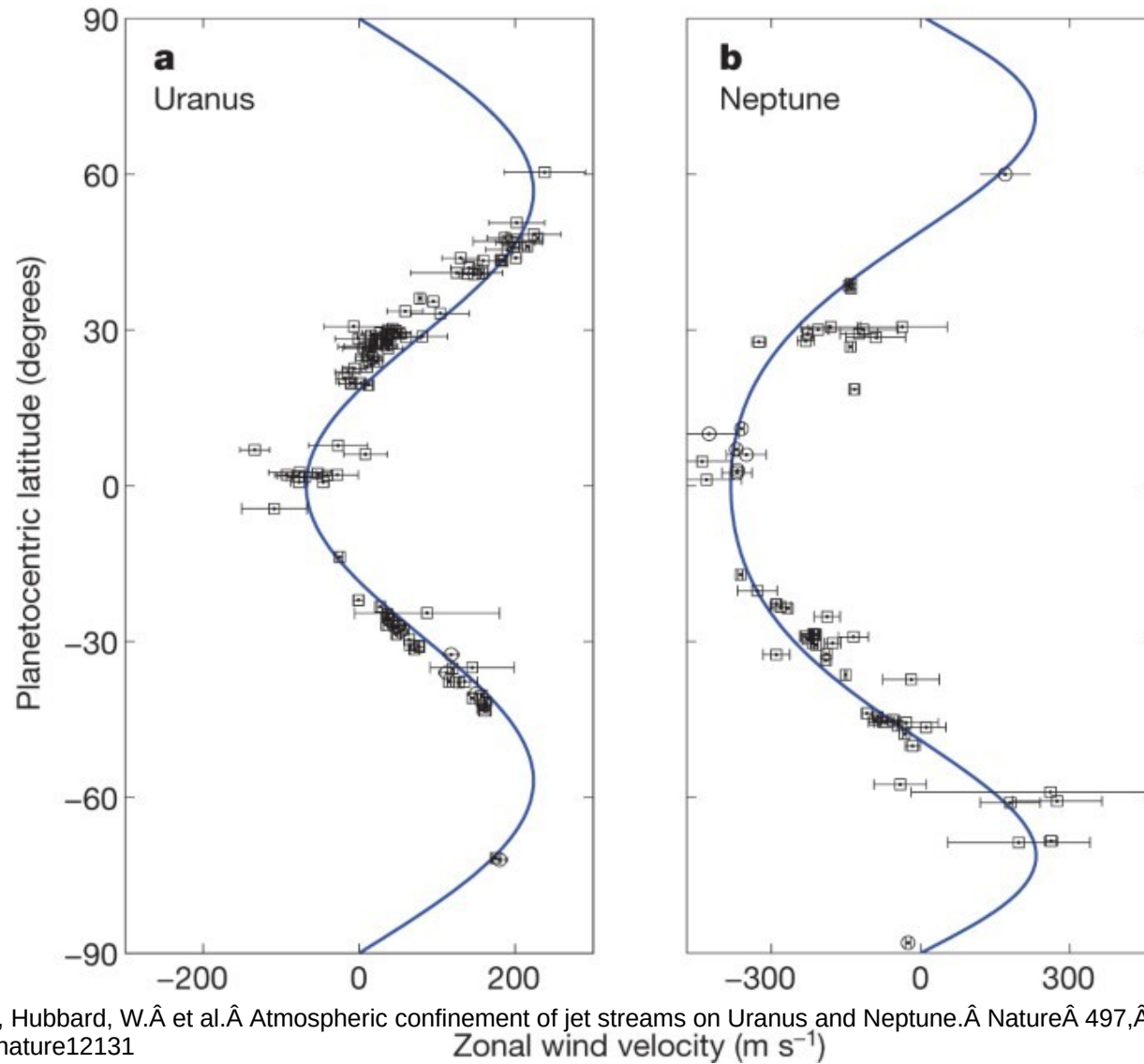


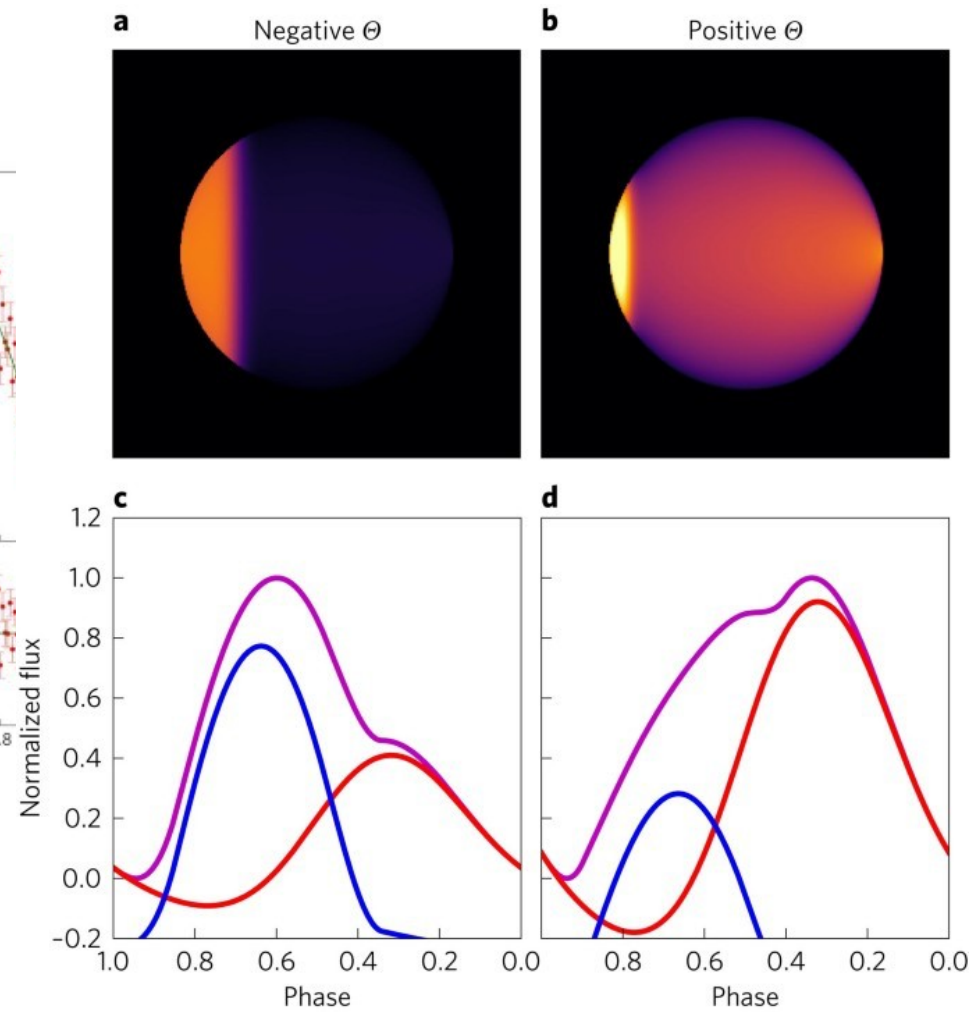
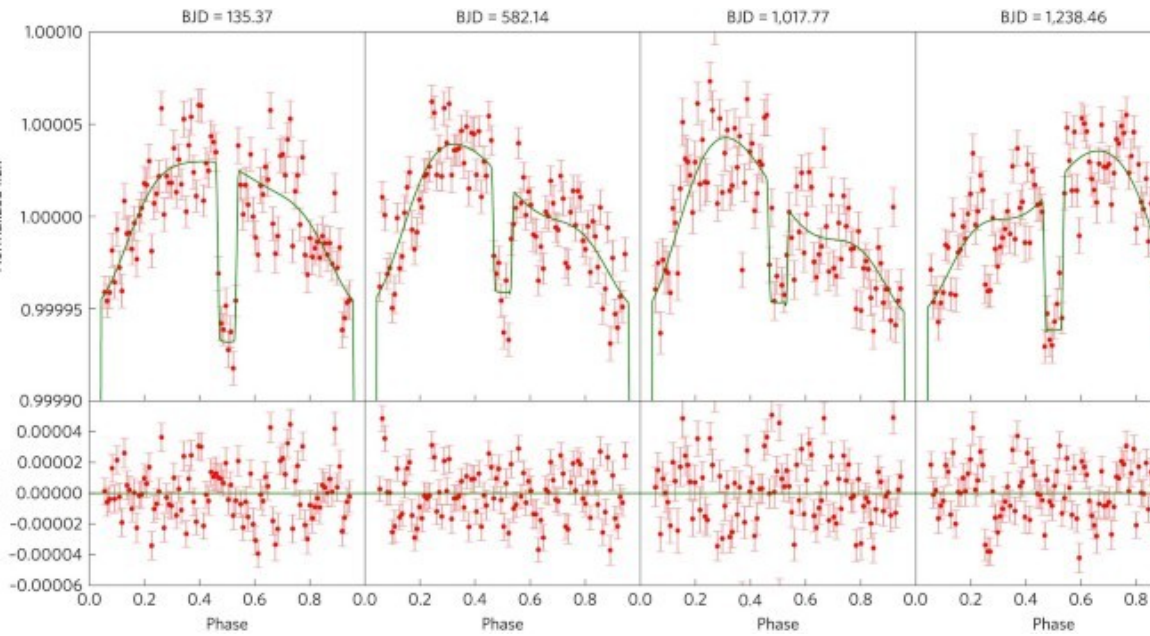
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Credit: Persons Education

Comparison of gas planets

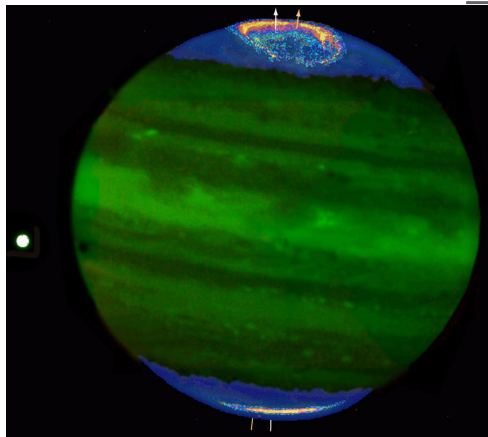




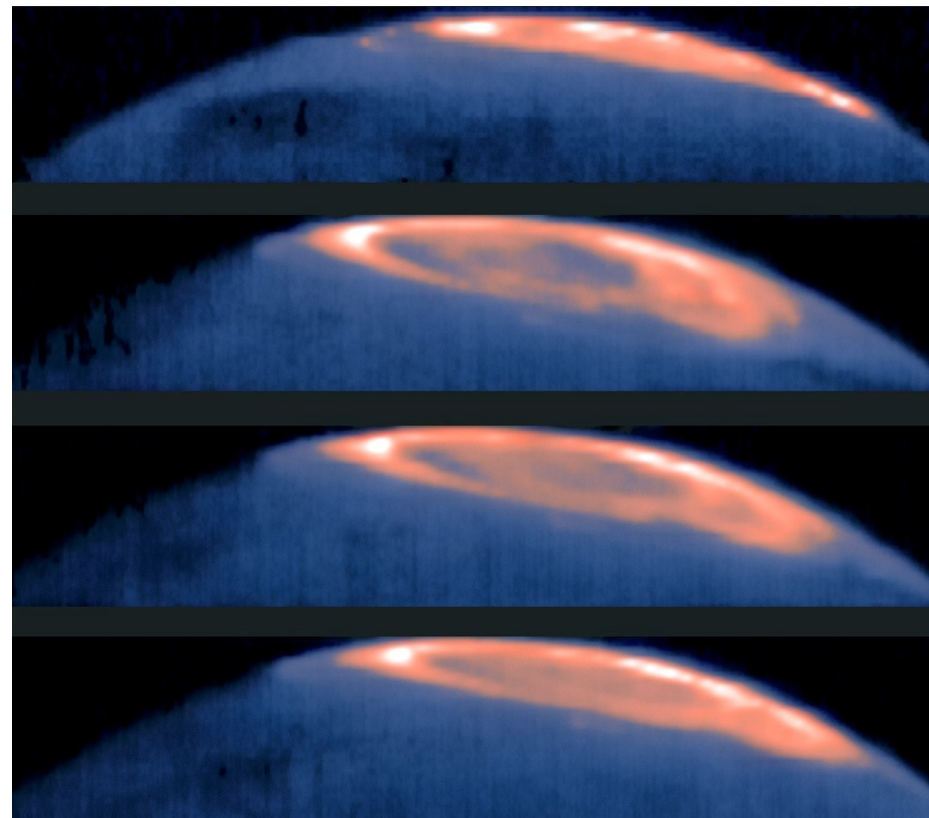


Aurorae

- Observed on Jupiter
- Rotation of 10 hrs plays role
- Great cold spot (right hand image)
- Stallard et al 2017 [10.1002/2016GL071956](https://doi.org/10.1002/2016GL071956)



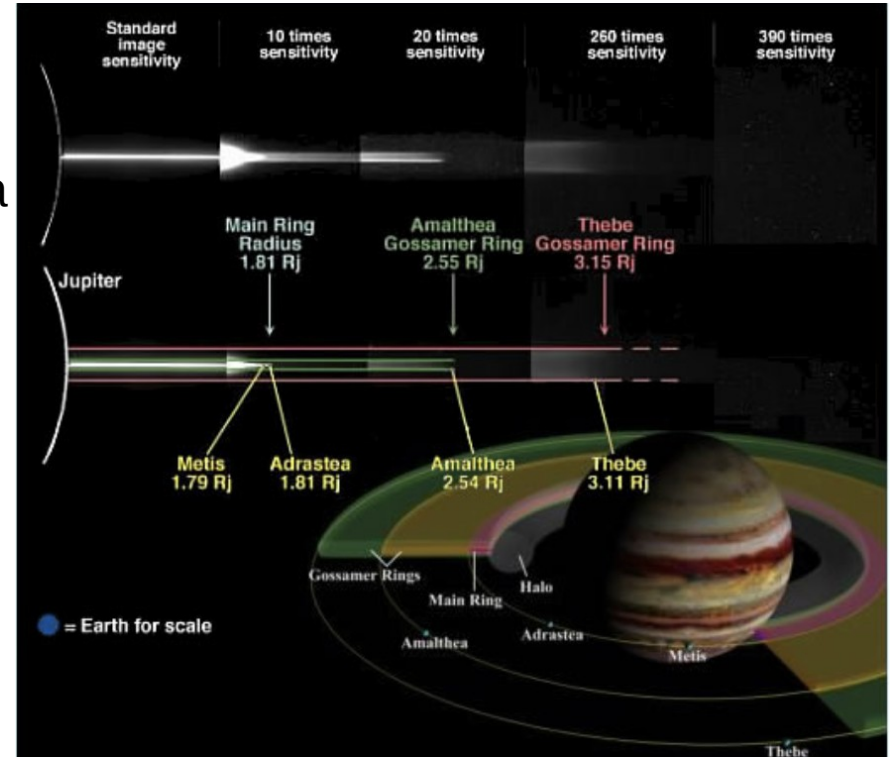
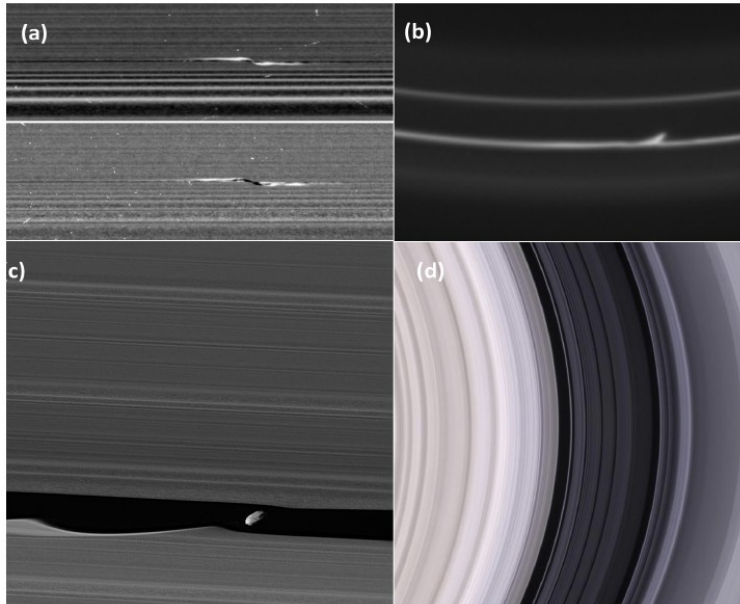
<https://www.eso.org/public/news/eso0123/#1>



<https://www.eso.org/public/images/potw17>

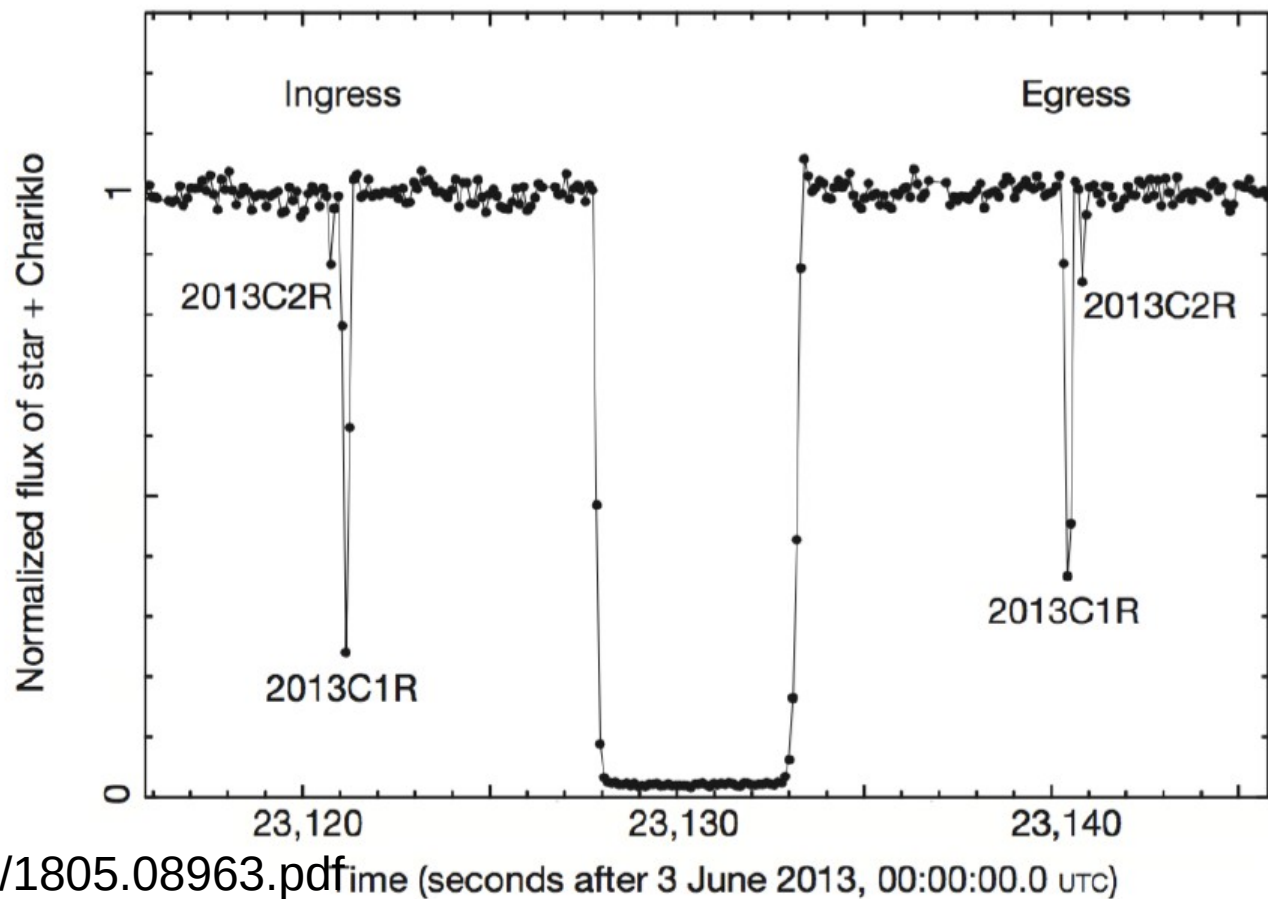
Rings of giant planets

- All gas planets have rings
- Jupiter – dust particles 0.1-30micron
- The rings are tied to the moons and vice versa



Images from: <https://arxiv.org/pdf/1805.08963.pdf>
(Excellent review by the way)

Chariklo dwarf planet



Images from:

<https://arxiv.org/pdf/1805.08963.pdf>

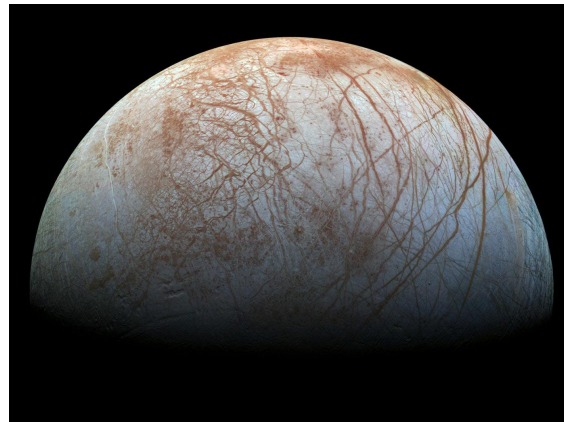
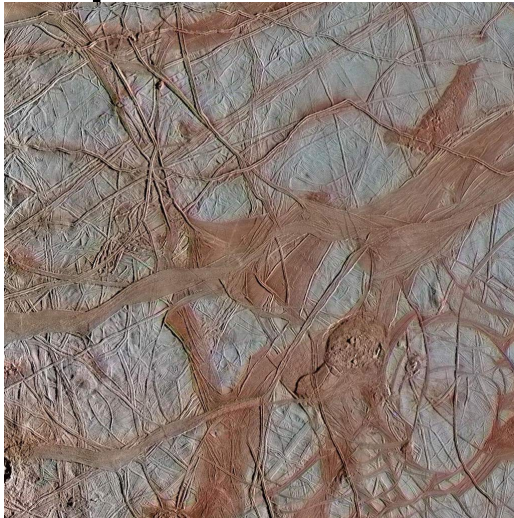
Galilean moons



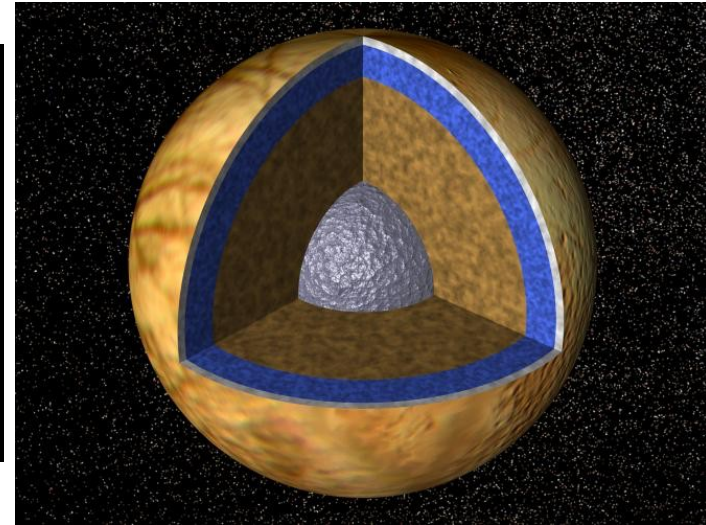
Credit: NASA

Europa

- Ice covered Jupiter's moon
- Radius $R=1565\text{km}$
- Liquid water expected below ice



Images credit: NASA JpL

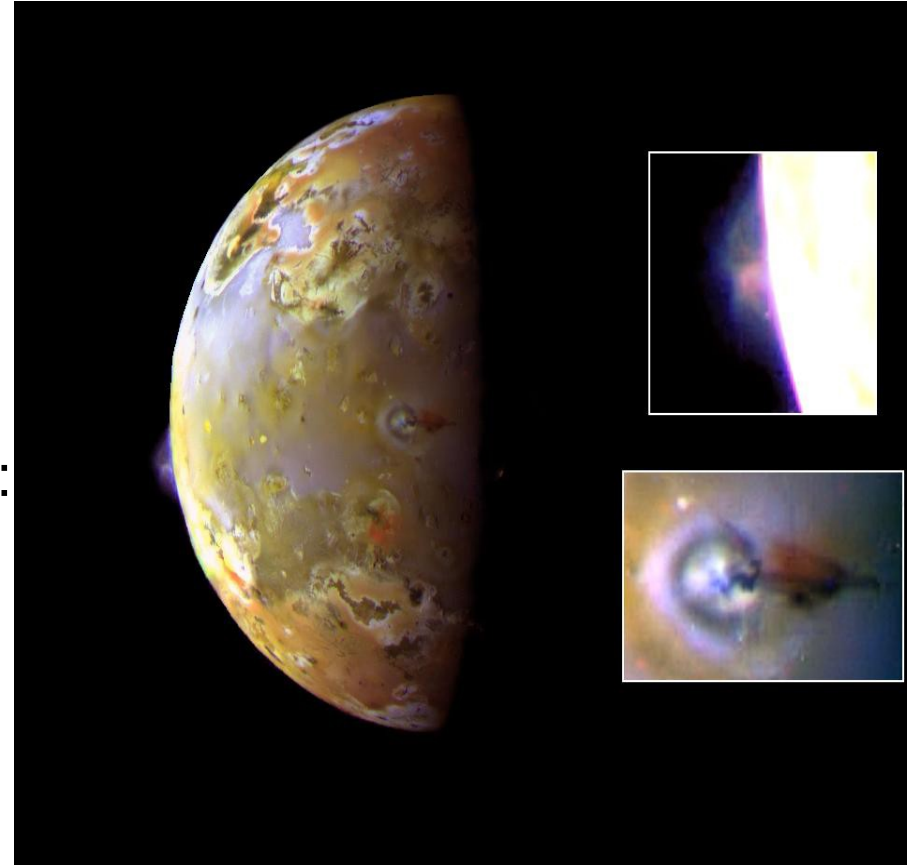


Ganymede

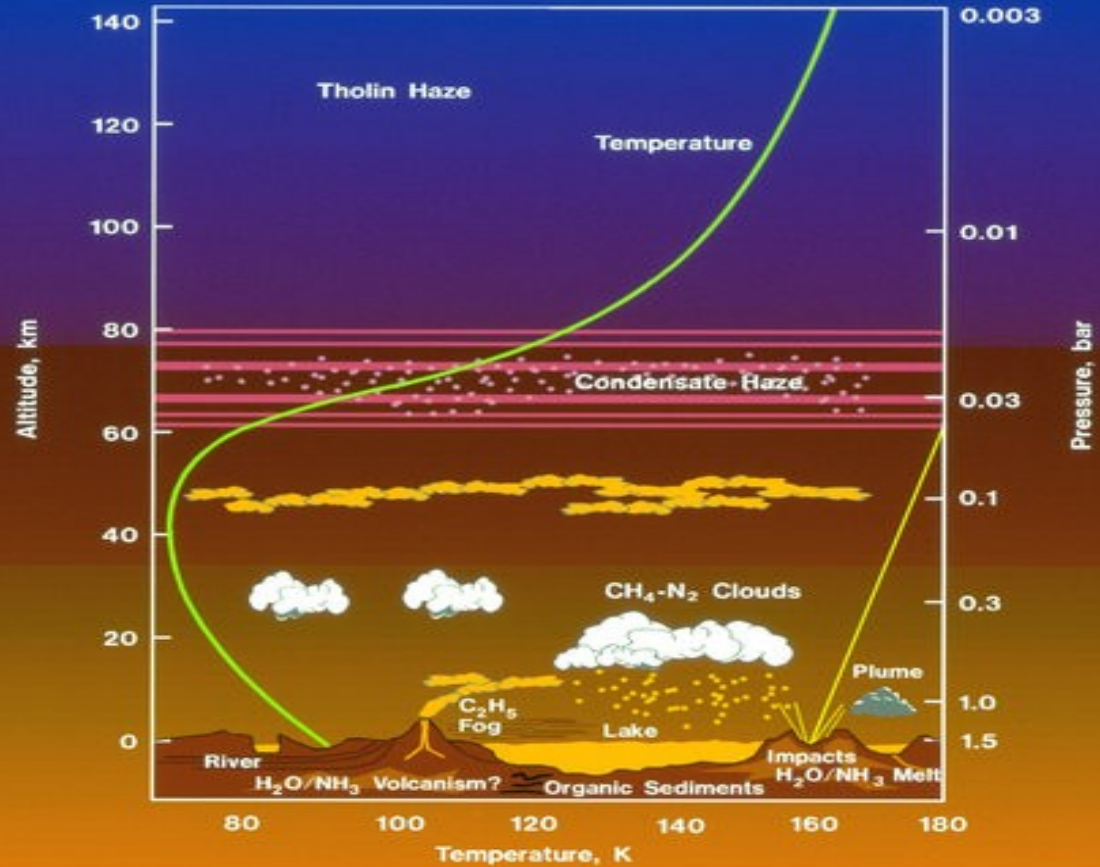
- Large Jupiter moon
- Undersurface water?
- Icy surface
- <https://arxiv.org/pdf/1910.07445.pdf>
- McCord, et al. 2001, Science 292, 5521, 1523

Io

- Small moon of Jupiter
- Volcanic activity
- Extremely strong volcanos
- Review how the volcanism was discovered:
<https://arxiv.org/pdf/1211.2554.pdf>



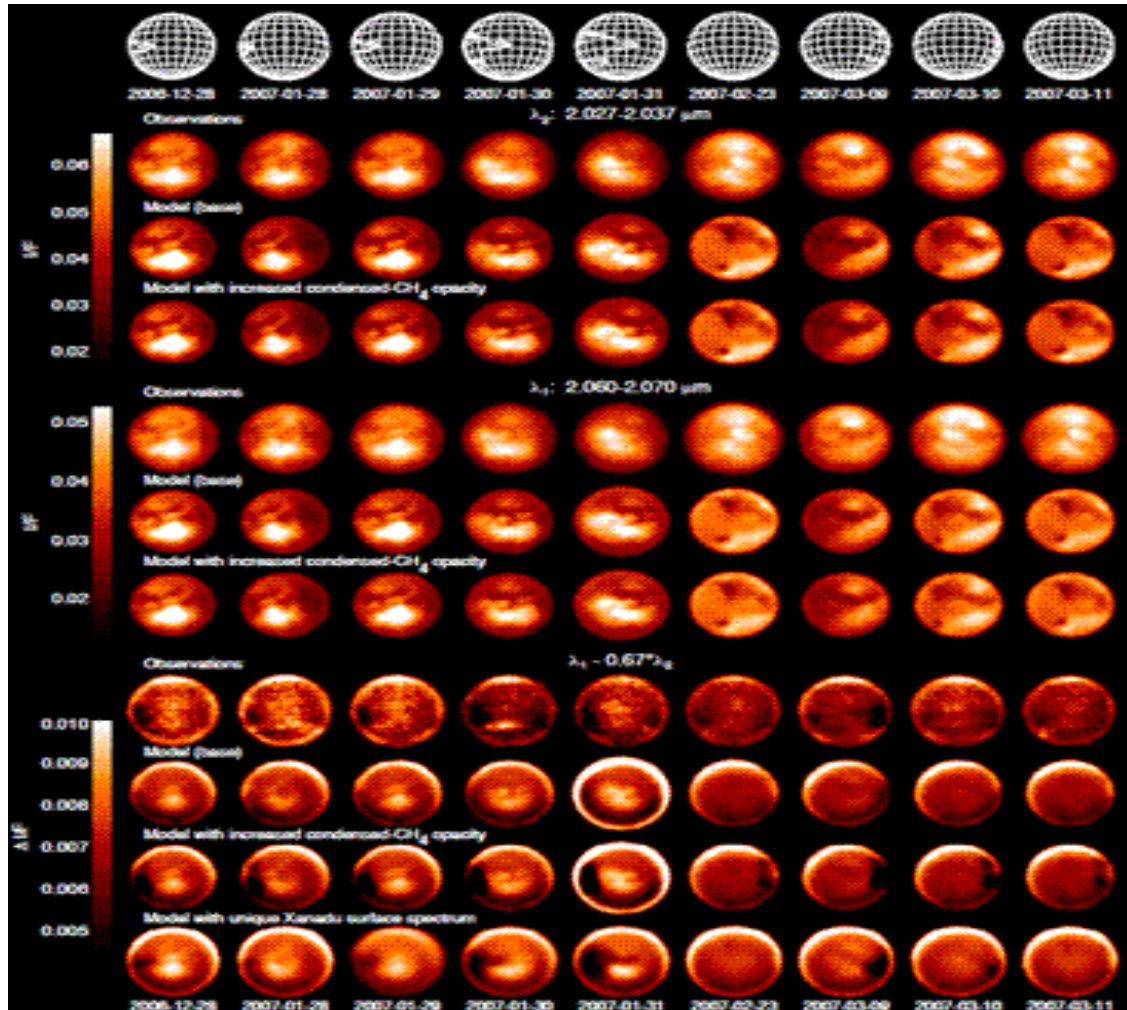
Titan



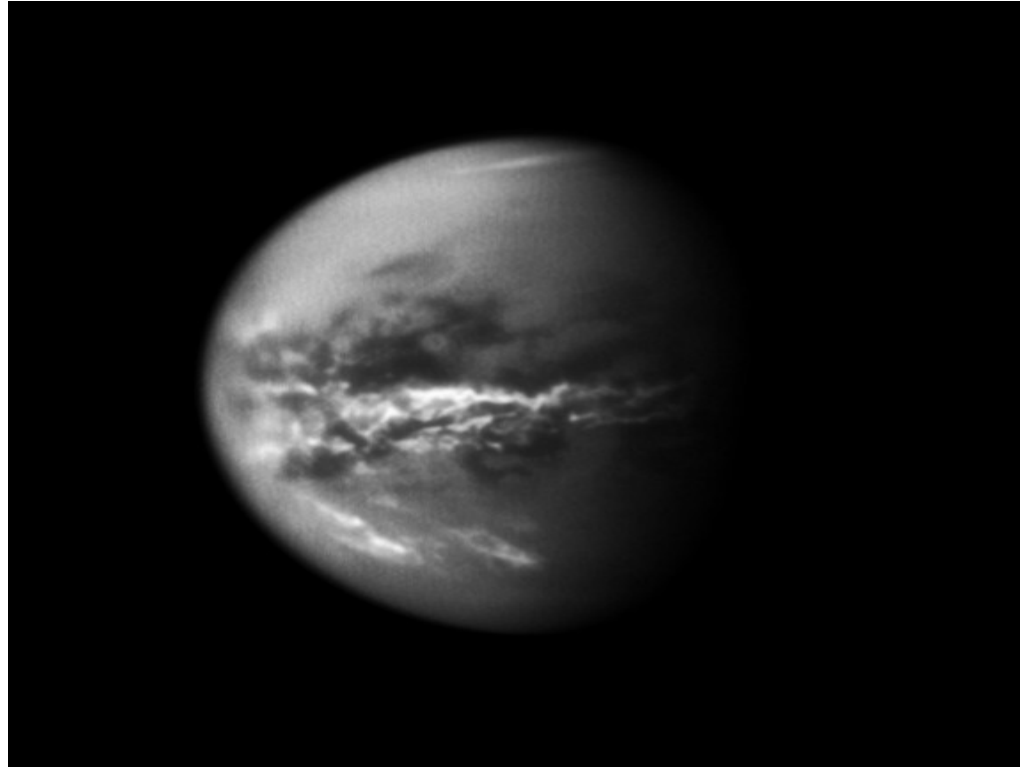
Credit: ESA

H. Thomas 98

Weather on Titan

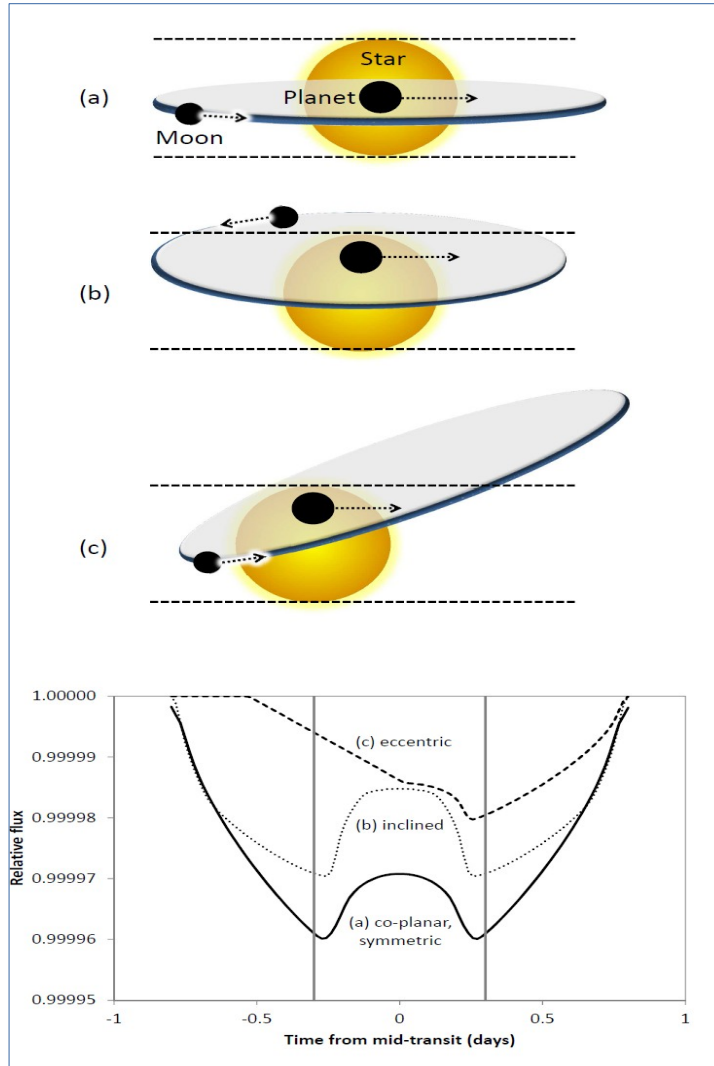


Methan rain on Titan

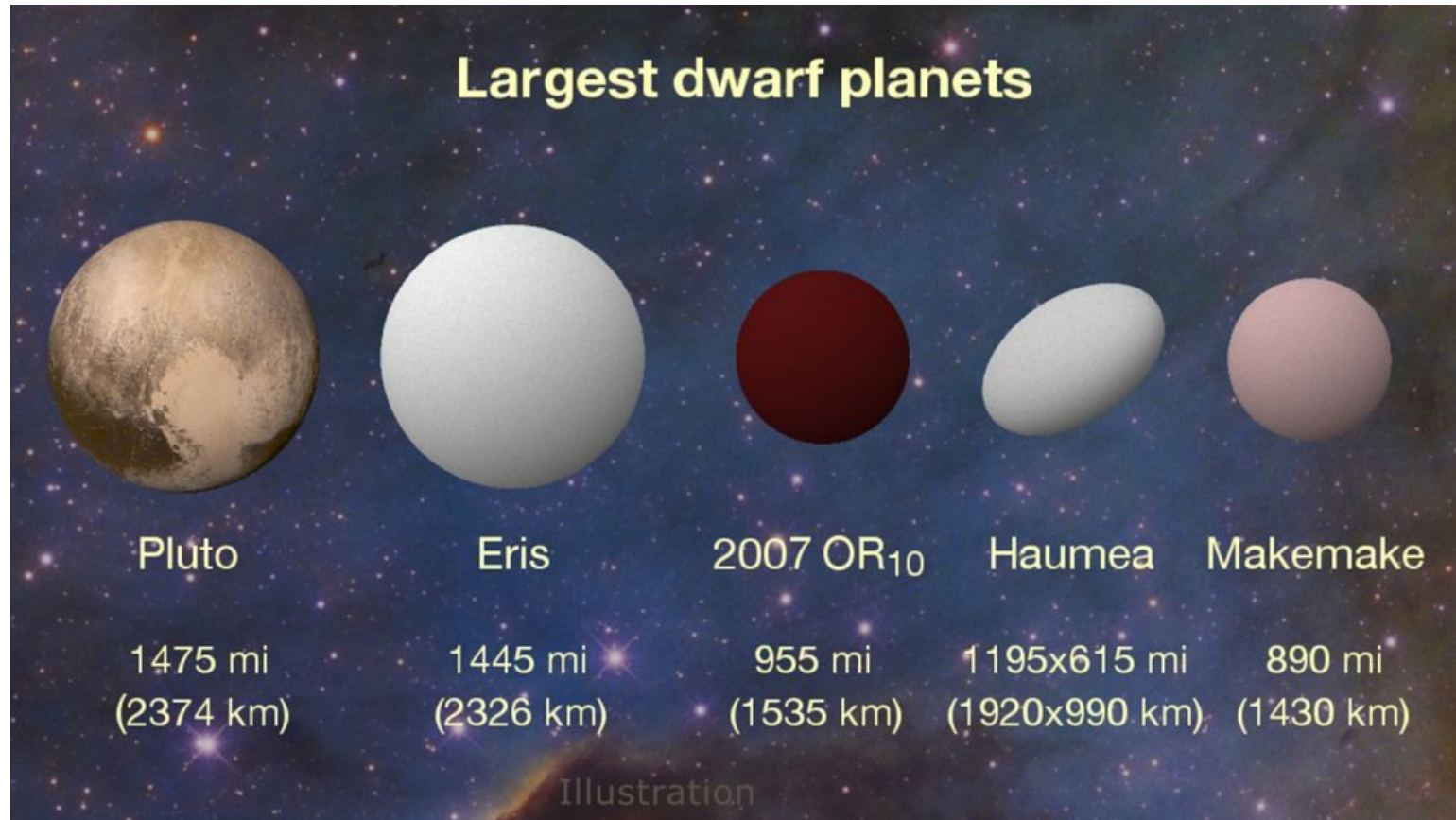


Credit: NASA

Detecting an exo-moon



Dwarf planets

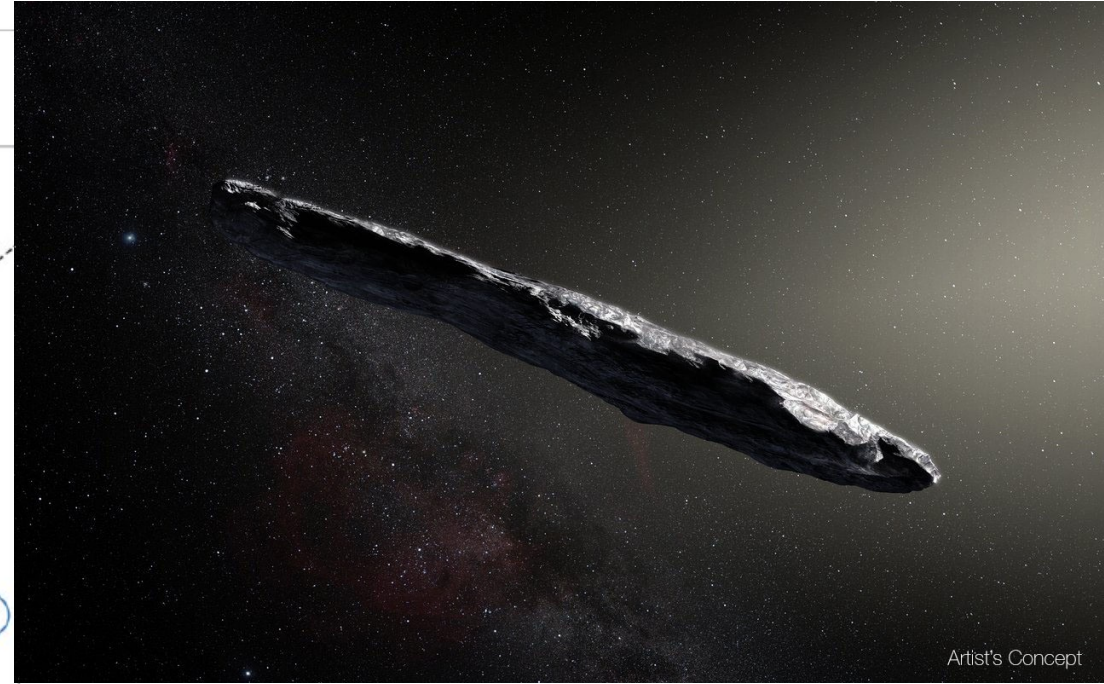
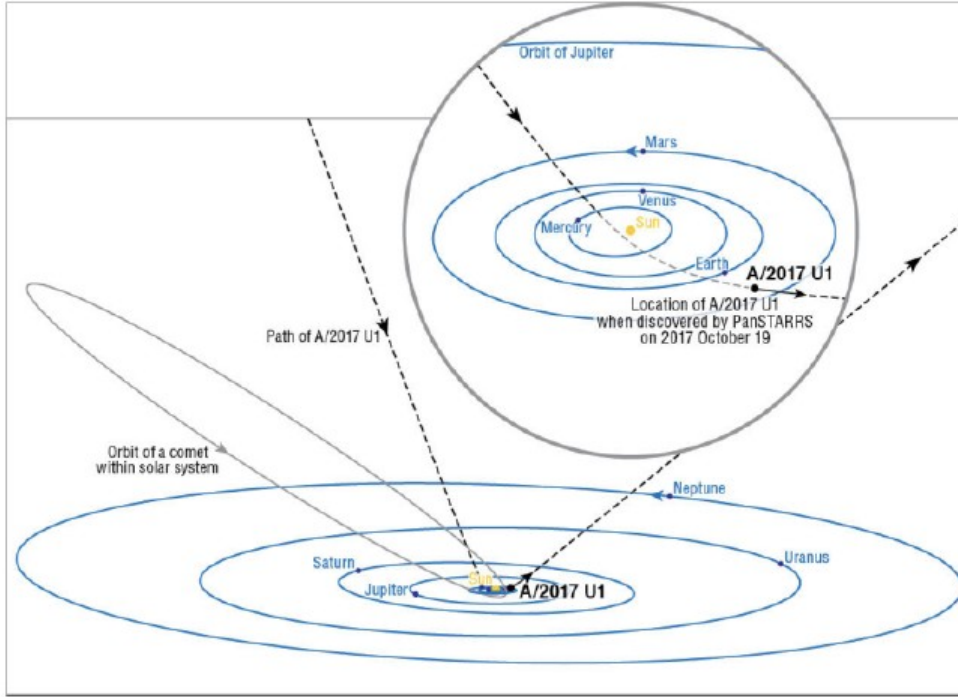


- Not moons but not cleared their neighborhood from similar bodies/Image András Pál

Interstellar traveller Oumuamua

- Size in hundreds of meters
- Asteroid or a comet?
- Came from direction of nowadays Lyra constellation
- Originated from a planetesimal from around a young star?
- <https://www.nature.com/articles/s41550-019-0816-x>
- <https://ui.adsabs.harvard.edu/abs/2017Natur.552..378M/abstract>
- <http://www.ifa.hawaii.edu/~meech/papers/2017/Meech2017-Nature552.pdf>

Oumuamua



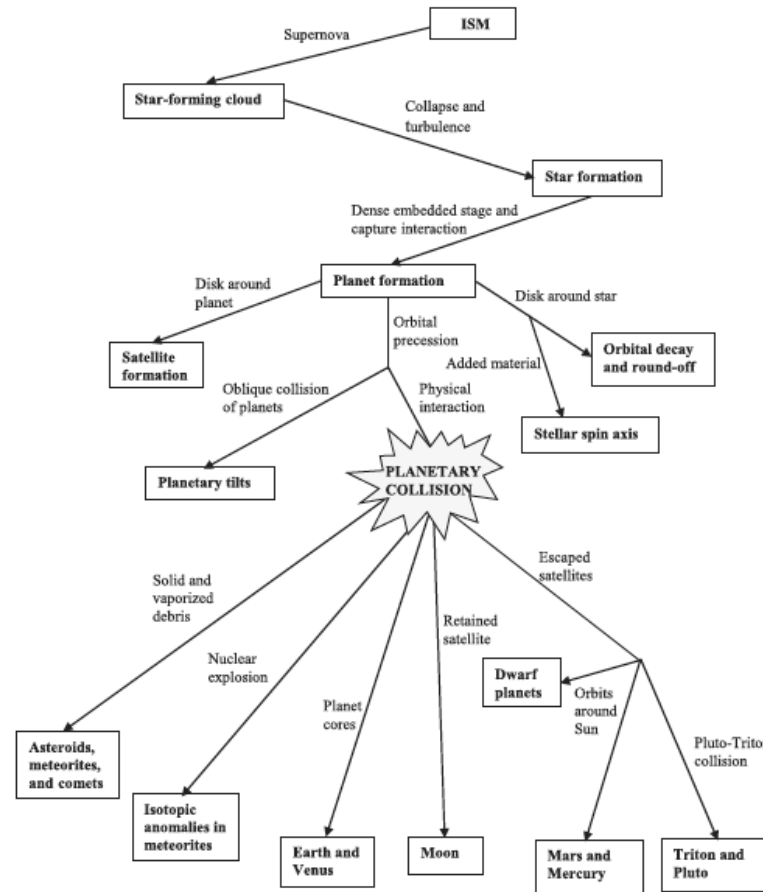
Credit: ESO

From Meech et al Nature, Volume 552, Issue 7685, pp. 378-381 (2017).

Evolution of Solar System

Phys. Scr. 94 (2019) 113001

Invited Comment



Next week

- Evolution of Solar system
- Evolution of exoplanetary systems
- Solar System and exoplanetary systems compared
- Interesting systems