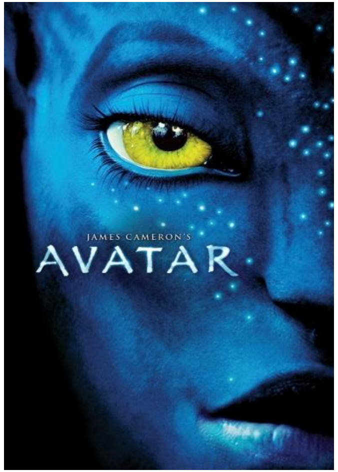
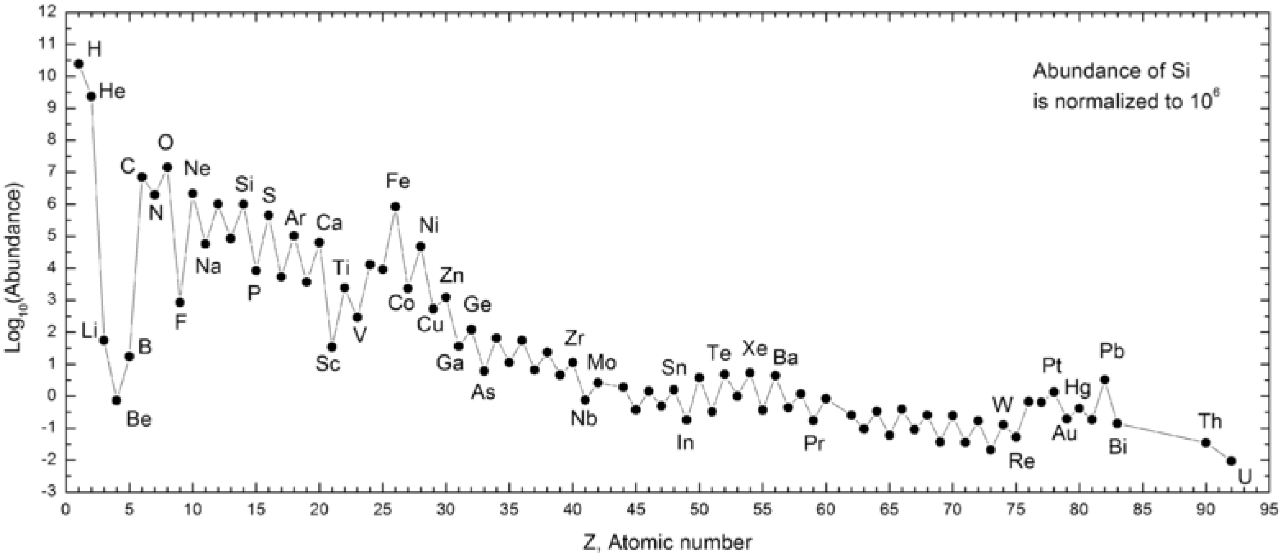
- Where should we look?
  - ✓ On **Earth**: Understand full range of "**right conditions**" for life on Earth [**extremophiles**]
  - ✓ On **planets** and moons in our own Solar System [**robot space probe technology**]
  - ✓ On **planets** orbiting other stars [**telescope technology**]
  - ✓ In the "**aether**"—signals (e.g., radio) broadcast by advanced civilizations [**SETI**]

- What are we looking for?
  - ✓ "I**ntelligent**", even humanoid life, like in Avatar?
  - ✓ "**Less intelligent**" life, akin to plants or fish?
  - ✓ **Microbes**, akin to archaea and bacteria?
  - ✓ **Something else** entirely, e.g., carbon/water → silicon/ammonia?
  - ✓ <u>**All of the above**</u>: **any** evidence of past/present "biological activity"!

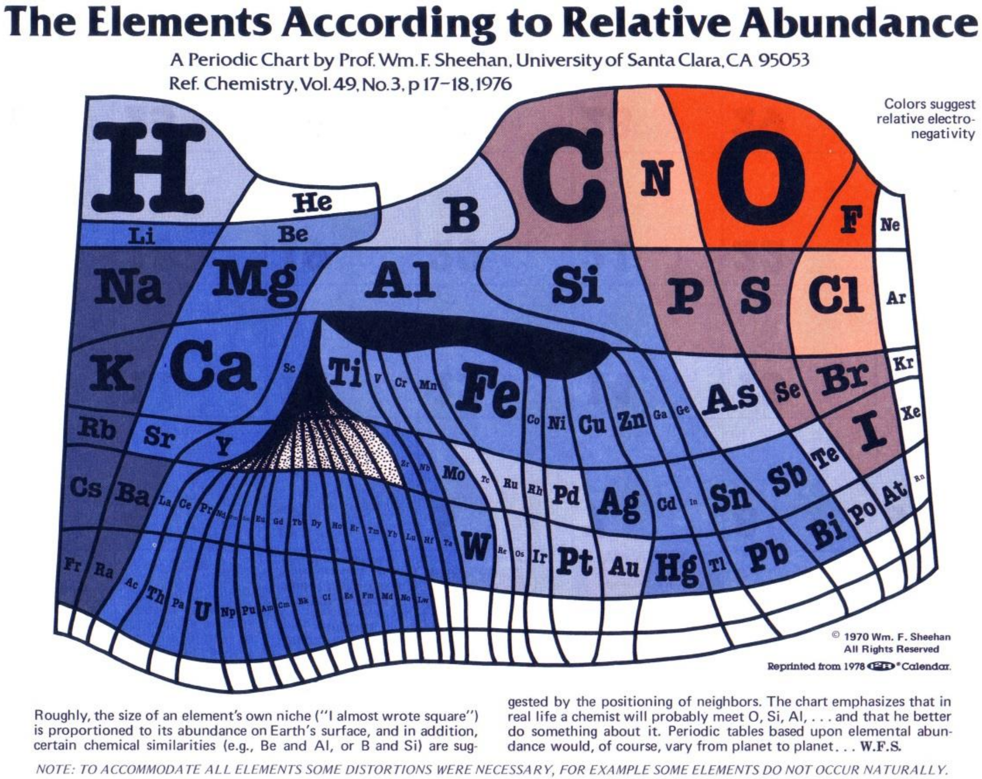


- **Chemical Elements** [needed to construct more complex biomolecules]:
    - ✓ Life on Earth uses about 25 of the 92 naturally occurring chemical elements
    - ✓ **Hydrogen, oxygen, carbon, nitrogen** make up ~ 96% of mass of living organisms
    - ✓ Ignoring He (chemically inert), **these are the most abundant elements in the universe**
    - ✓ **Big Bang** produced mostly H & He; **stars** produced the rest



“Right Conditions”

- **Chemical Elements** [needed to construct more complex biomolecules]:



Relative abundances of elements on **Earth’s surface**

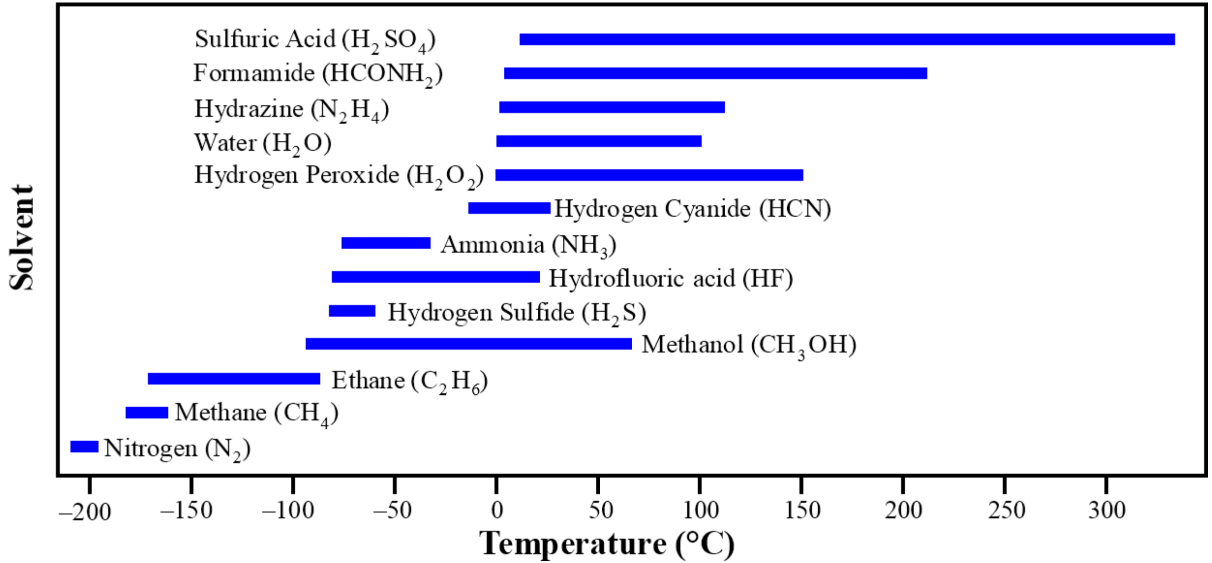
Recall: **H, O, C, N** make up 96% of the mass of living organisms

Mere coincidence that life uses the most abundant elements?

(From these are constructed amino acids, etc., as discussed before; the “chemical elements” right conditions are **widespread**)

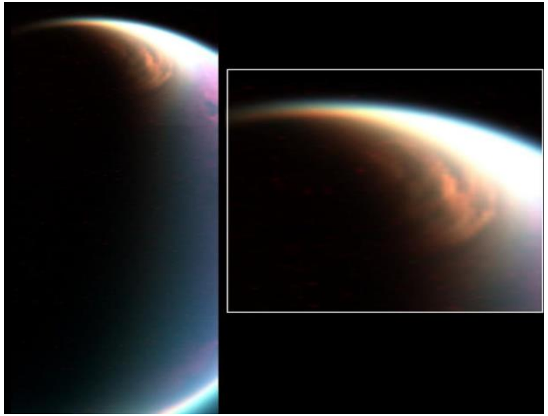
- **Solvent (liquid or gas)** [needed to facilitate chemical mixing and interactions]:
  - ✓ **Liquid**:
    - Apparently, **all** life on Earth **requires liquid water**, e.g., human = sack of seawater
    - Water needed to: (1) **dissolve** organic & inorganic molecules, making them available for chemical reactions; (2) **transport** chemicals into and out of cells; (3) is directly involved in many **metabolic reactions**
    - Water is special because:
      - ➢ It **remains liquid** over a relatively wide and high range of temperatures
      - ➢ **Ice floats** (usually, solidified liquid sinks, so oceans of it would freeze solid)
      - ➢ It is a **polar molecule**, so easily dissolves other polar molecules (e.g., salt); also makes possible **hydrogen bonds**, very important to life on Earth
      - ➢ It is made of the two most common elements in the universe (aside from He) → it is a very **common compound** in the universe

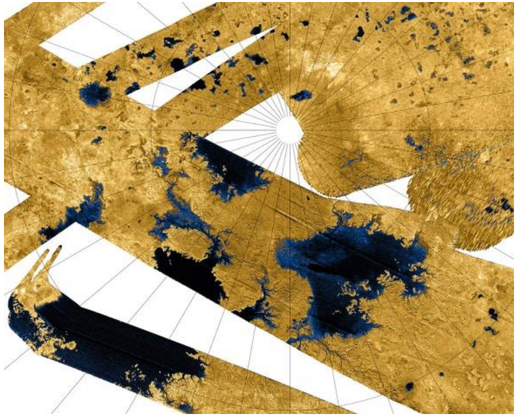
- **Solvent (liquid or gas)** [needed to facilitate chemical mixing and interactions]:
  - ✓ **Liquid**:



← Colder (slower metabolism) | Hotter (faster metabolism) →

- **Solvent (liquid or gas)** [needed to facilitate chemical mixing and interactions]:
  - ✓ **Gas**:
    - An atmosphere can also facilitate chemical mixing and interactions; it can also be part of an organism's **metabolism** (e.g., O_2 & CO_2 in Earth's atmosphere)
    - Atmospheres & oceans also **protect** organic molecules that tend to be broken down by a star's radiation (UV light) or high-energy particles from space (cosmic rays)





Titan (Saturn's largest moon) has a dense, **nitrogen-rich atmosphere** (like Earth), with methane clouds, and lakes of liquid ethane and methane. Could Titan support life?

"Right Conditions"

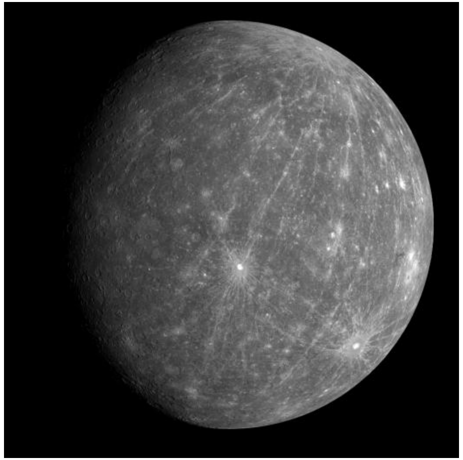
- **Free Energy** [needed to fuel metabolism and allow low entropy structures to form]:
  - ✓ **Light energy** for photosynthesis (e.g., from a nearby star; some deep-sea bacteria seem to get energy from the infrared and visible light emitted by molten volcanic rock!)
  - ✓ **Chemical energy** for chemosynthesis (e.g., deep-sea hydrothermal vents; bacteria or archaea that oxidize inorganic compounds of iron, sulfur, or hydrogen…may support life below the surface of Mars, Jupiter's moon Europa, and other planets)
  - ✓ **Thermal energy** (e.g., heat from gravitational tidal flexing)

<u>Europa</u> (one of Jupiter's moons) may have a 100 km thick outer layer of salty H_2O: **liquid** underneath due to heat from **gravitational tidal flexing**, with a tectonically active frozen upper crust. Could Europa support life?

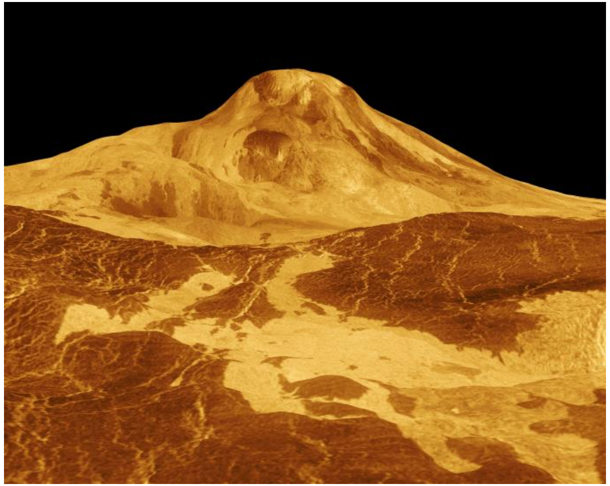
“Right Conditions”—Summary

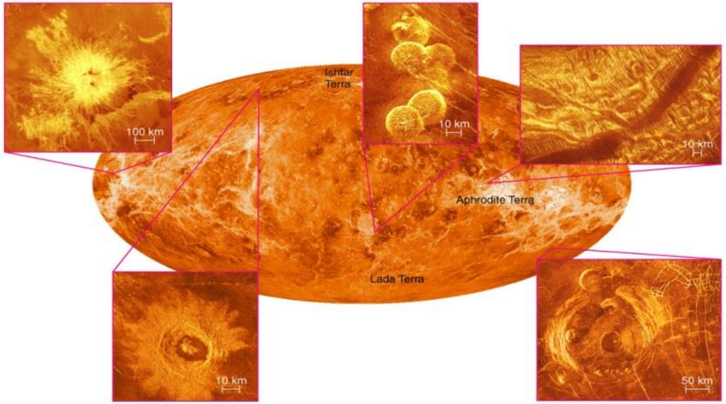
- “Right conditions”:
  - Source of molecules from which to build organisms
  - Source of free energy to fuel metabolism
  - Liquid medium—most likely water—for transporting the molecules of life
- **Liquid water** is probably the most stringent condition, and any world that satisfies it likely satisfies the other two. Hence NASA’s “follow the water” strategy.
- Might be too limiting, but must start somewhere…

- Moon? Mercury?
    - Small → core has cooled → no volcanism (or tectonics) → no fresh source of atmosphere (outgassing); gravity so weak that any past atmosphere has escaped into space → super hot in the Sun, super cold in the shade
    - Have some water ice at bottoms of polar craters (and the Moon has water molecules mixed in the soil), but **no liquid water**.
    - Life? Highly unlikely…



- Venus?
  - **Atmosphere:** 96% CO_2; Pressure 90 times that on Earth's surface (equivalent to pressure 1 km under Earth's oceans); Completely enshrouded in thick, sulfuric acid clouds
  - **Surface**: Temperature 470 ℃, planet-wide, day and night (hot enough to melt lead); Some continents, planet wide volcanic/tectonic resurfacing 1 BYA; still active volcanos?





- Venus?

Runaway **greenhouse effect**: Venus started like Earth ("sister planet") with similar volcanic outgassing of CO_2 and H_2O in atmosphere, but…

Earth: a bit further from Sun → *cooler*

H_2O gas cools, condenses, falls as rain, makes oceans, and evaporates again; H_2O liquid/gas cycle.

CO_2 dissolves in rain → stored in oceans → carbonate rocks → tectonic subduction → volcanos. Photosynthesis: CO_2 → O_2.

Left with almost no CO_2, a little O_2, and H_2O in a cycle (and original "inert" N_2).

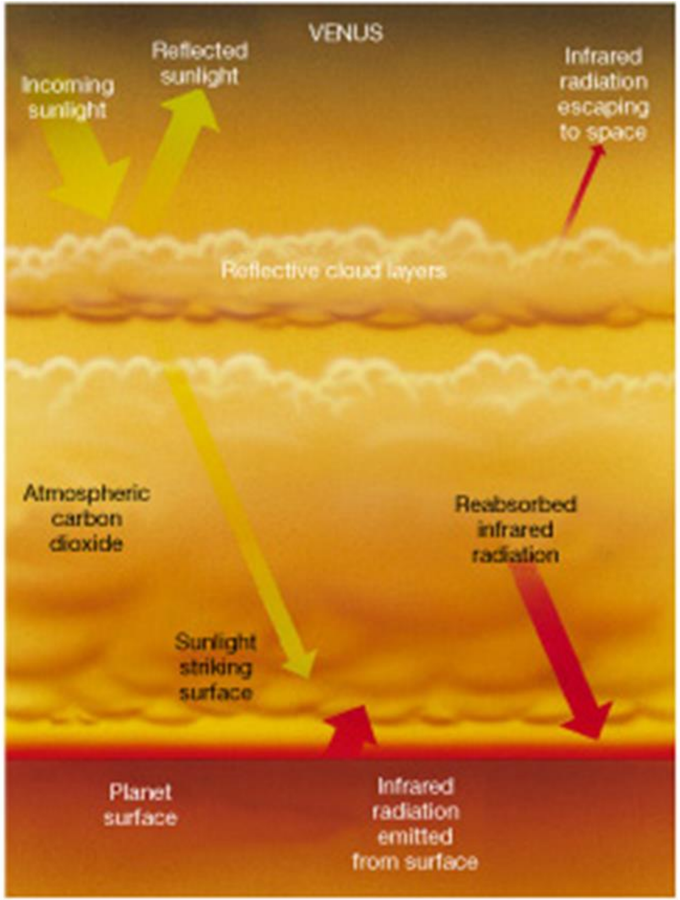
Venus: a bit further from Sun → *warmer*

Even if it started with oceans: warmer → more evaporation & air can hold more H_2O → more H_2O greenhouse gas → warmer. *Positive feedback*.

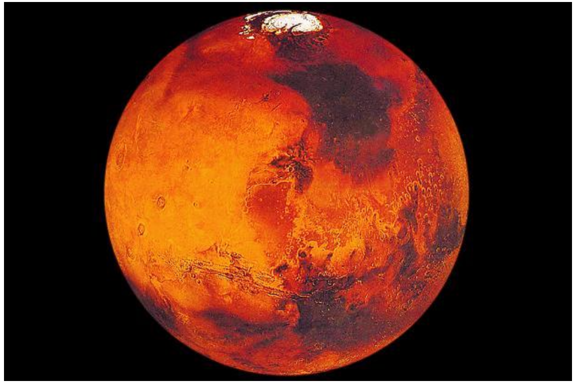
Oceans evaporate, H_2O photo-dissociates. H → space; O → chemically bound up in rocks.

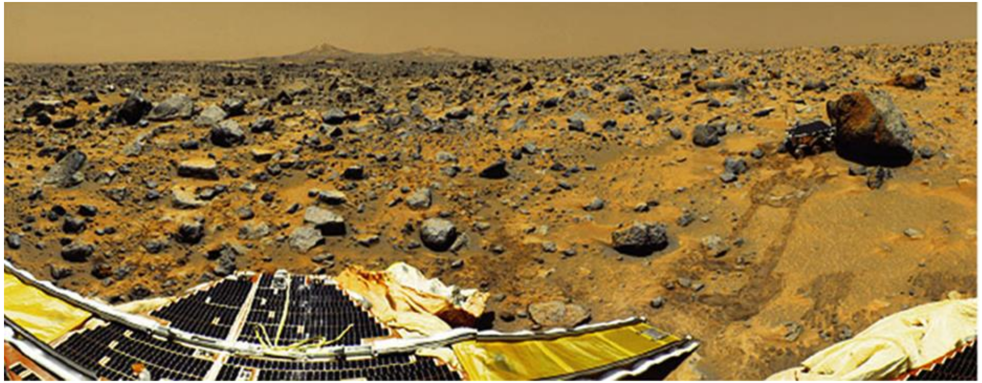
Left with lots of CO_2, no H_2O. Runaway greenhouse effect!

- Life on Venus?
    - Venus ***may*** have had an ocean, and ***maybe*** even life up to 4 BYA, but volcanic/tectonic resurfacing up to 1 BYA would have erased all fossil evidence
    - Microbes may still survive in the upper atmosphere: cooler 50 km up; liquid water droplets; sulfuric acid could provide chemical energy for extremophiles



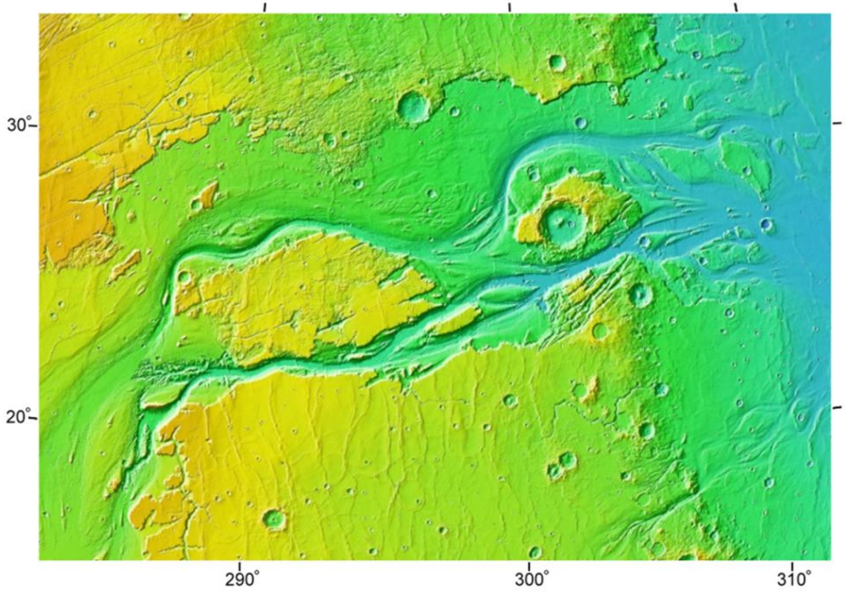
- Mars?
  - Went in opposite direction as Venus:
    - ✓ Evidently **started warm and wet**, with a fairly thick atmosphere (> 2-3 BYA). Volcanic outgassing estimates suggest early atmosphere denser than Earth's today, and enough water to fill planet-wide oceans 10s to 100s of meters deep
    - ✓ …but is **now cold and dry**, with atmospheric pressure so low (< 1% Earth & 95% CO_2) that **liquid water cannot exist on the surface**.

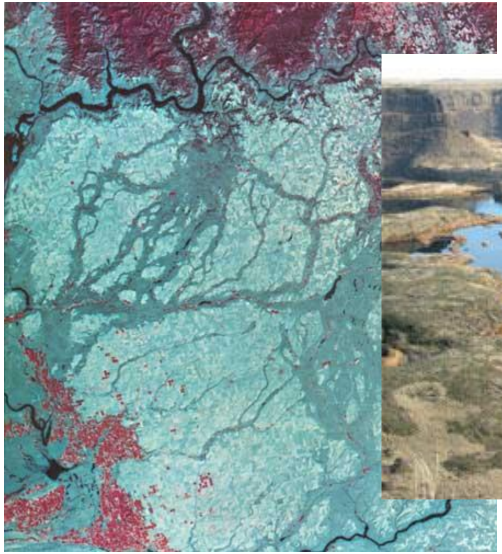




- Mars?
  - **Why?** Basic physics: Mars is half the diameter of Earth → **one-quarter** the surface area, but only **one-eighth** the volume → **twice** the surface-to-volume ratio:
    - ✓ **Lost its internal heat** energy quickly → lost further volcanic outgassing AND lost protective magnetic field. Coupled with weaker gravity, solar wind then likely stripped away the atmosphere (and some of the water vapor)
    - ✓ Also, Mars has/had **no ozone layer**, so UV rays can split H_2O into hydrogen gas (that escapes into space) and oxygen gas (that reacts with the surface → rust)
    - ✓ **Greenhouse effect** (that must have been important in having a warm and wet early period, at least intermittently) diminished, and Mars froze over. Surface temperature is now $-143\ ℃$ to $+35\ ℃$, average $-63\ ℃$.

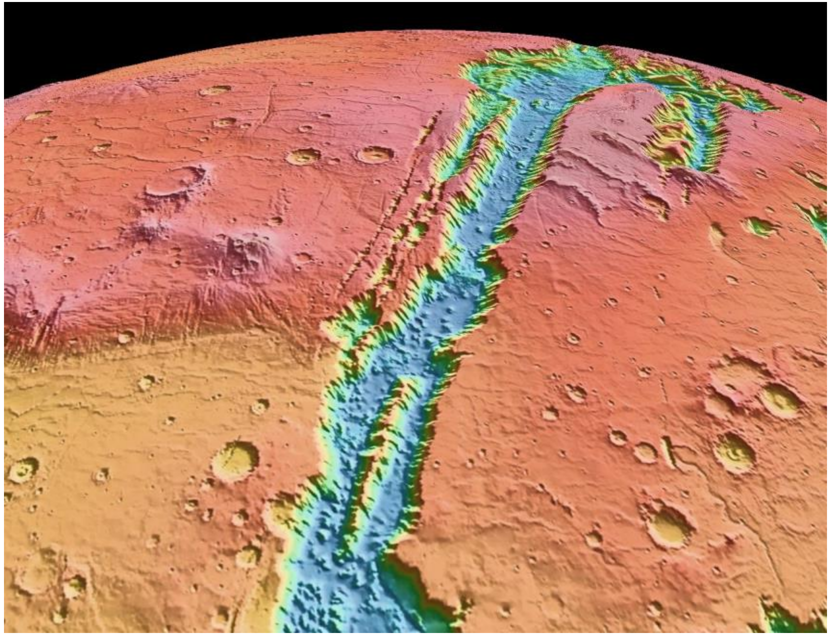
- Evidence of past water on Mars:





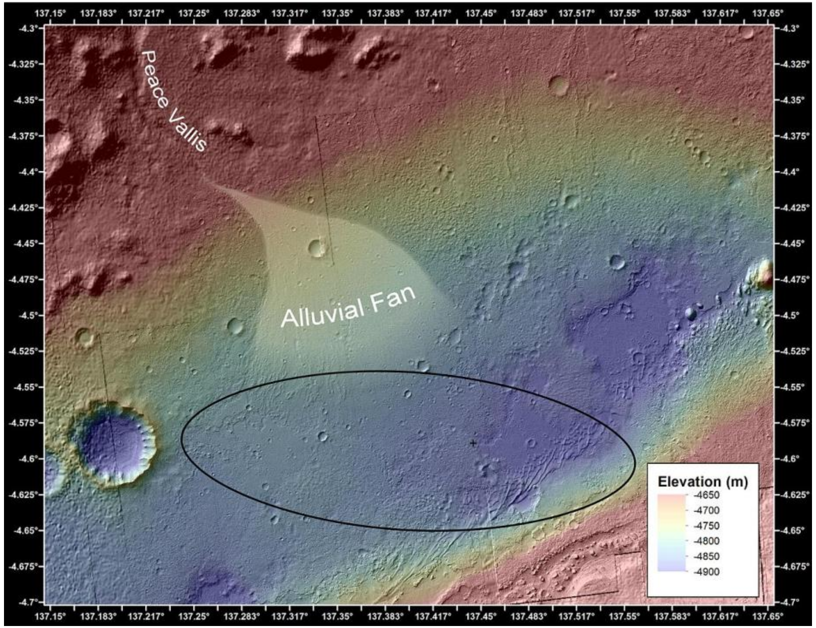
Kasei Valles outflow channel → catastrophic flooding ~ 3 BYA, comparable to largest ever floods on Earth ("scablands"). Some outflow channels on Mars are as recent as 10s MYA (!)

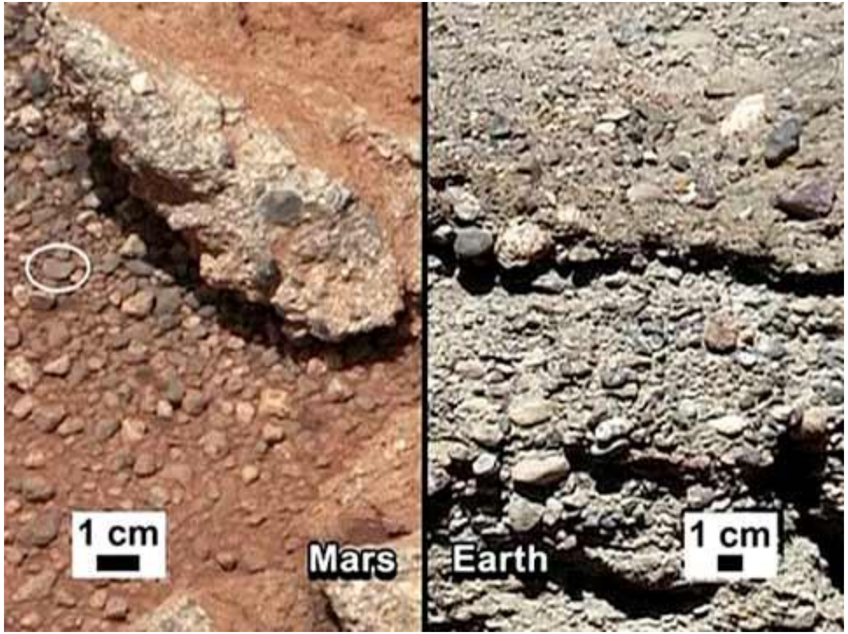
- Evidence of past water on Mars:



Valles Marineris is long and deep: Large tectonic crack? Widened by erosion? Flow channels?

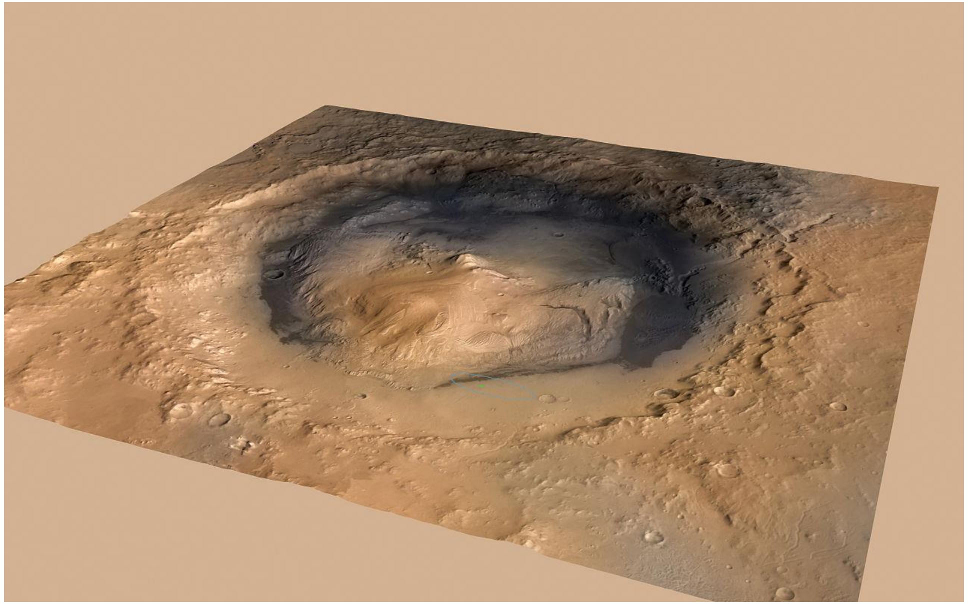
- Evidence of past water on Mars:

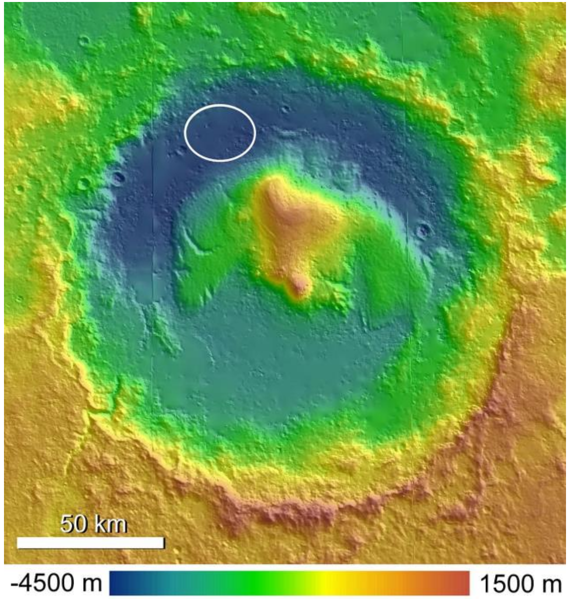




Curiosity rover found ancient river bed. Analysis showed the pebbles were formed in a stream that flowed at walking pace and was ankle to hip-deep

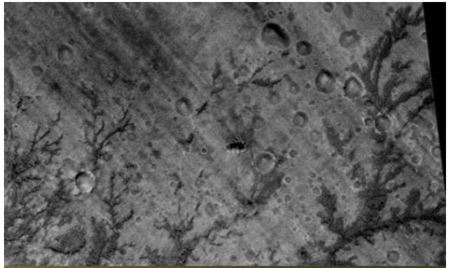
- Evidence of past water on Mars:

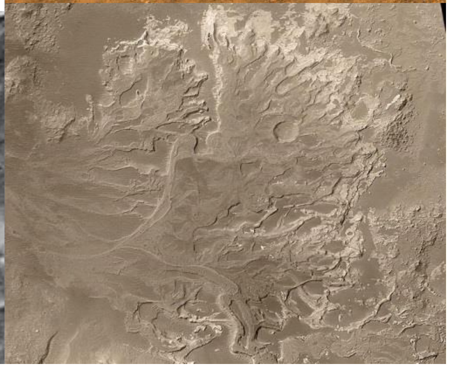


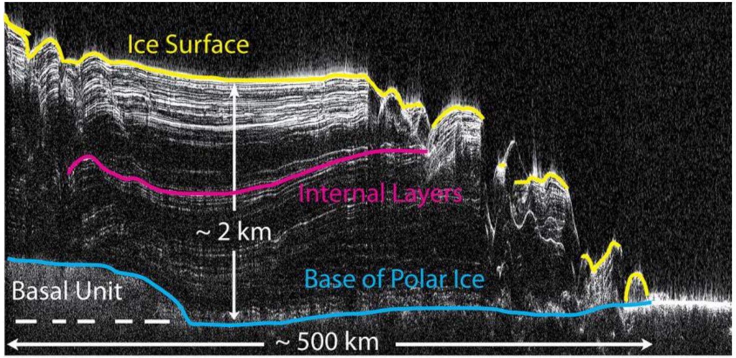


Curiosity rover found that Gale Crater contained an ancient (3.3-3.8 BYA) freshwater lake that could have been a hospitable environment for microbial life.

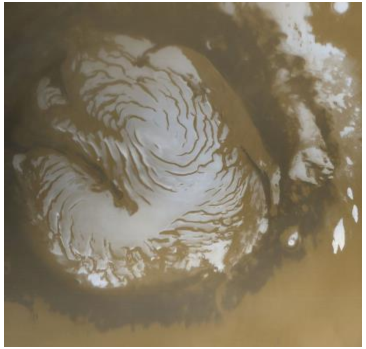
- Past water:
  - **Sensing technology**: Orbital imaging & remote sensing (spectroscopic, radar, etc.), and surface landers and rovers.
  - **Evidence for:** Enormous outflow channels, ancient river valley networks, deltas, and lake beds; and the detection of surface rocks and minerals that could only have formed in liquid water. Possibly a large ocean that covered one-third of the planet?

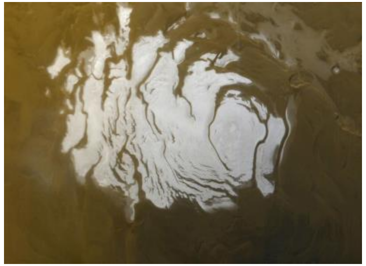






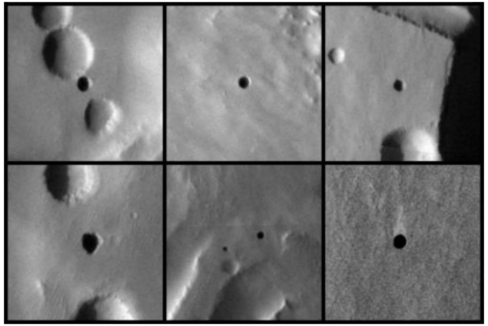
- Present water:
    - **Known:** Almost entirely in the form of ice in the shallow subsurface, and in the polar ice caps. South cap is permanently covered by about 8 m of CO_2 ice, North cap is covered by 1 m of CO_2 ice in the Northern winter only. If the known water ice were melted, it would be enough for a 35 meter deep planet-wide ocean.
    - Even more ice is likely locked away in the deep subsurface. Pockets of liquid water may exist underground, where it is warmer and higher pressure.
    - 2015: Mars Reconnaissance Orbiter confirmed summer flows of liquid salt water flowing down crater slopes, then evaporating. Curiosity finds nightly films of liquid salt water in subsurface.

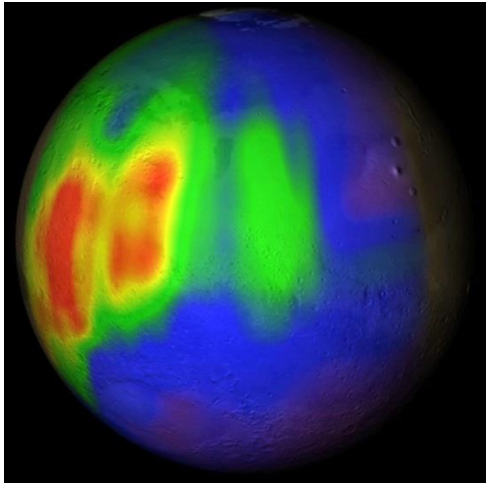




- Life on Mars?
  - **Past:**
    - ✓ Curiosity soil analysis reveals that ancient Mars had the **right chemistry to support living microbes**: S, N, O, C, Phosphorus (recall ADP, ATP), and clay minerals.
    - ✓ Curiosity also revealed evidence for **organic molecules** (e.g., C & H) (complicated by the presence of perchlorate minerals; when heated, the perchlorates alter the organic compound structure, making identifications uncertain).
    - ✓ Mars almost certainly had the "**right conditions**" for life during its warm and wet periods > 2-3 BYA.

- Life on Mars?
    - **Present:**
        - ✓ The most likely place to find present life is **below the ground**, safe from intense UV & cosmic rays, and warm enough for possible liquid water. Image: cave skylights (scientists really want a sample-return from here!)
        - ✓ Curiosity *seems* to have found fluctuating concentrations of **methane** (CH_4) in the atmosphere. Also found earlier; debated for 50 years. If present, could be biological OR geological in origin. Either way, Mars may be more alive than we think…

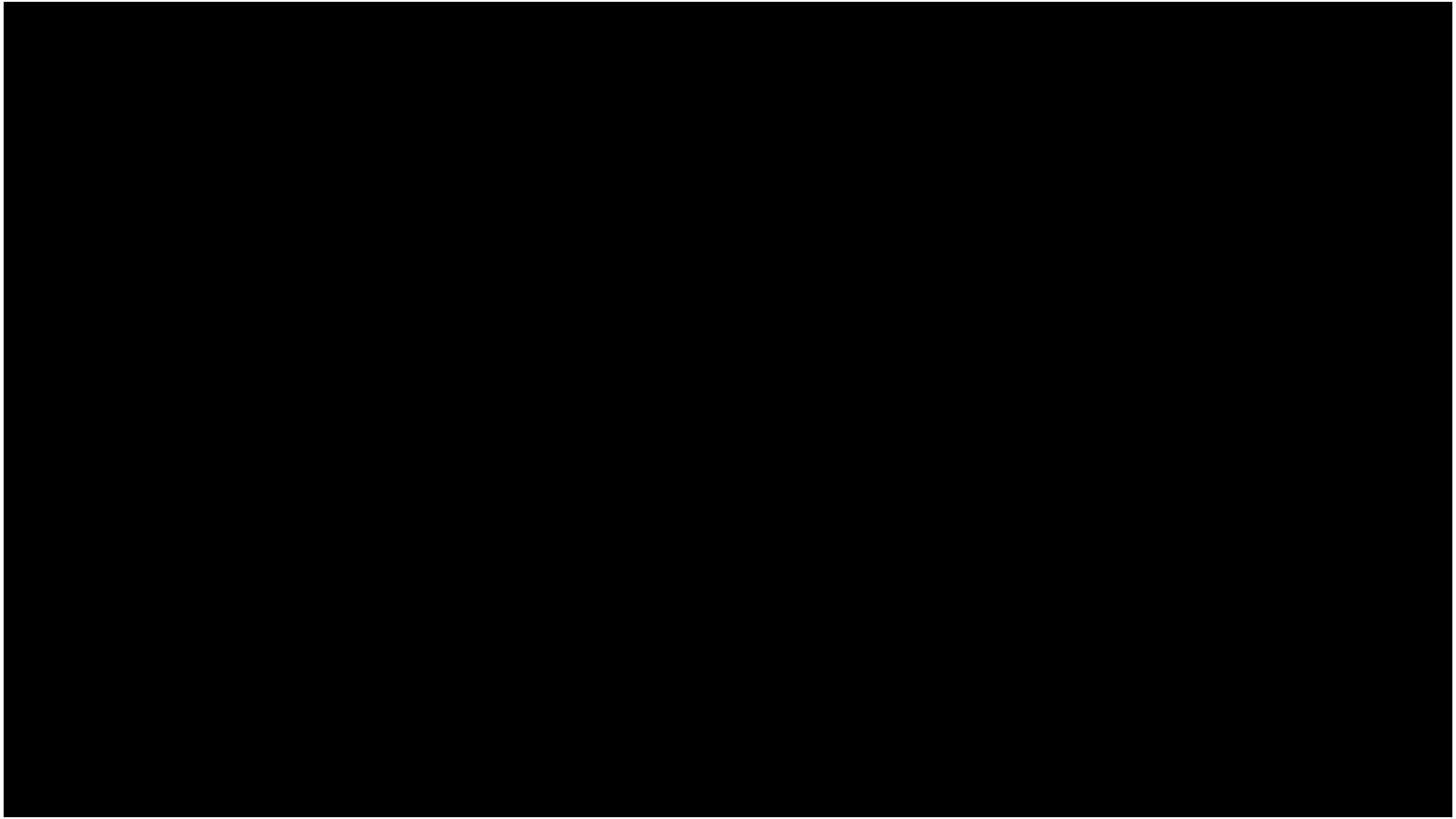




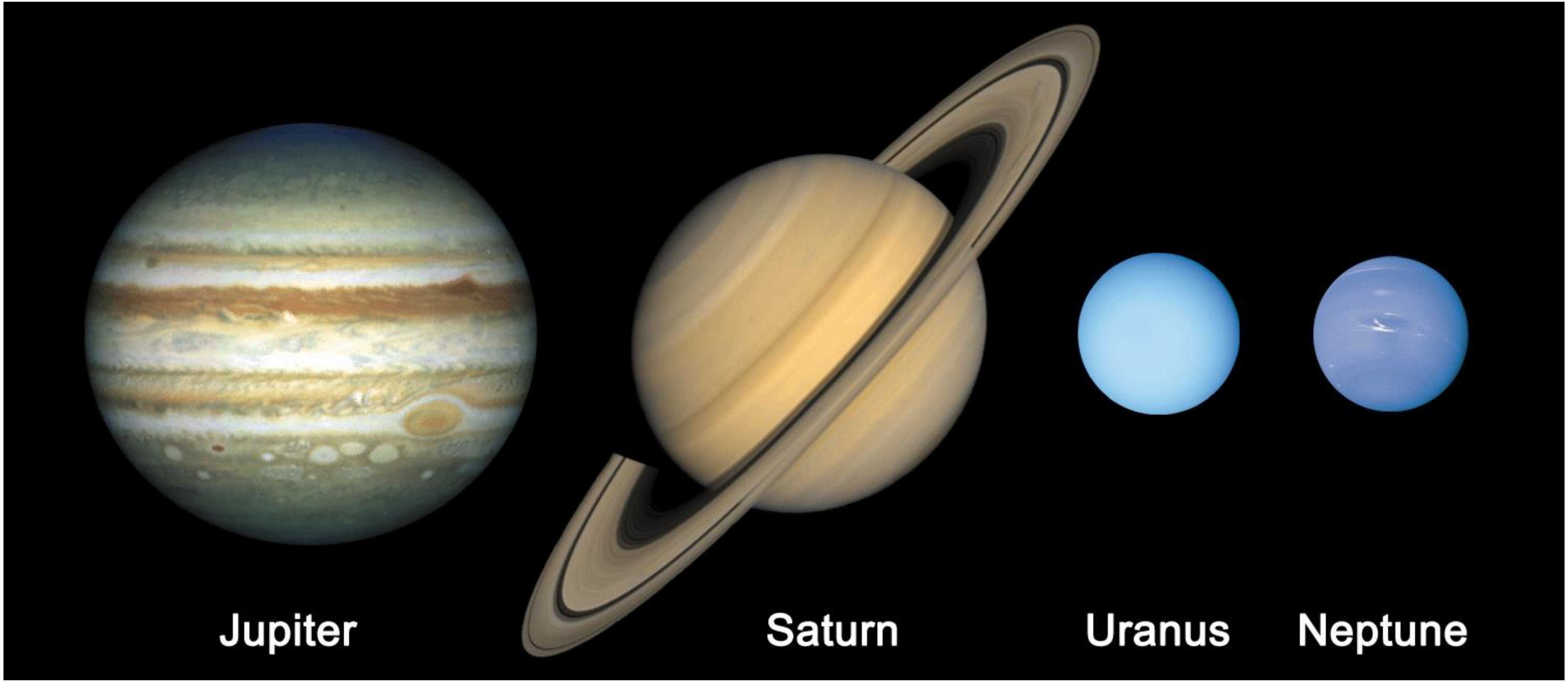
- Life on Mars?

    - **Future plans:** More rovers, drilling down, sample return? The **technology** is amazing, but it’s not easy!

Life in the Solar System?



- Gas Giants?



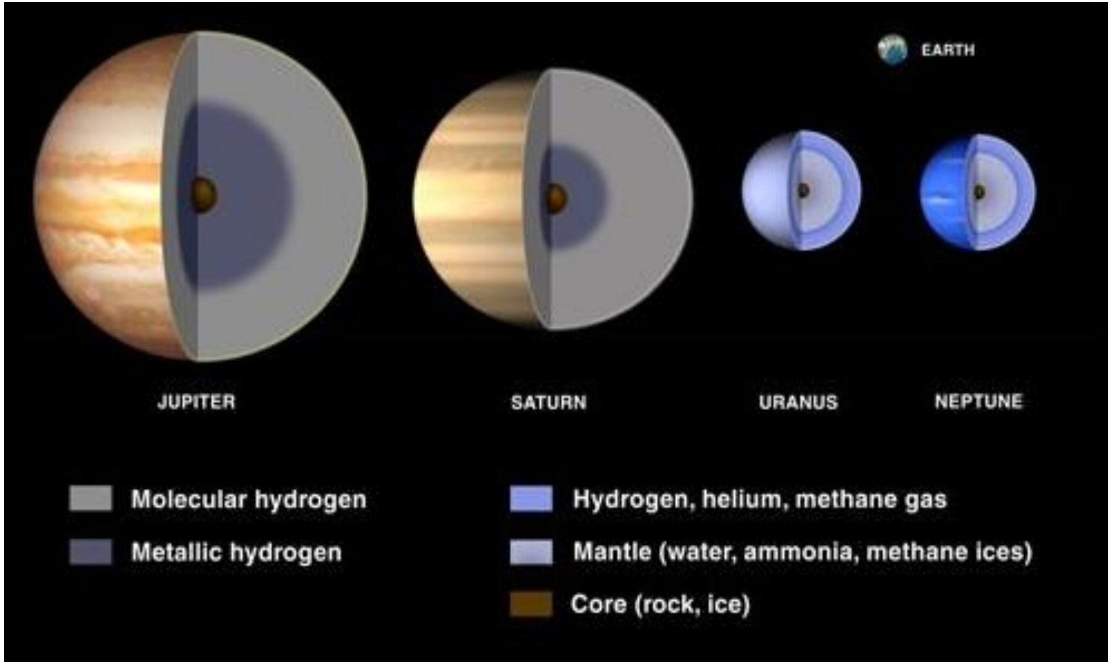
- Gas Giants?
  - Made of hydrogen, helium, and hydrocarbons like water, methane, ammonia

<u>Jupiter & Saturn</u>:

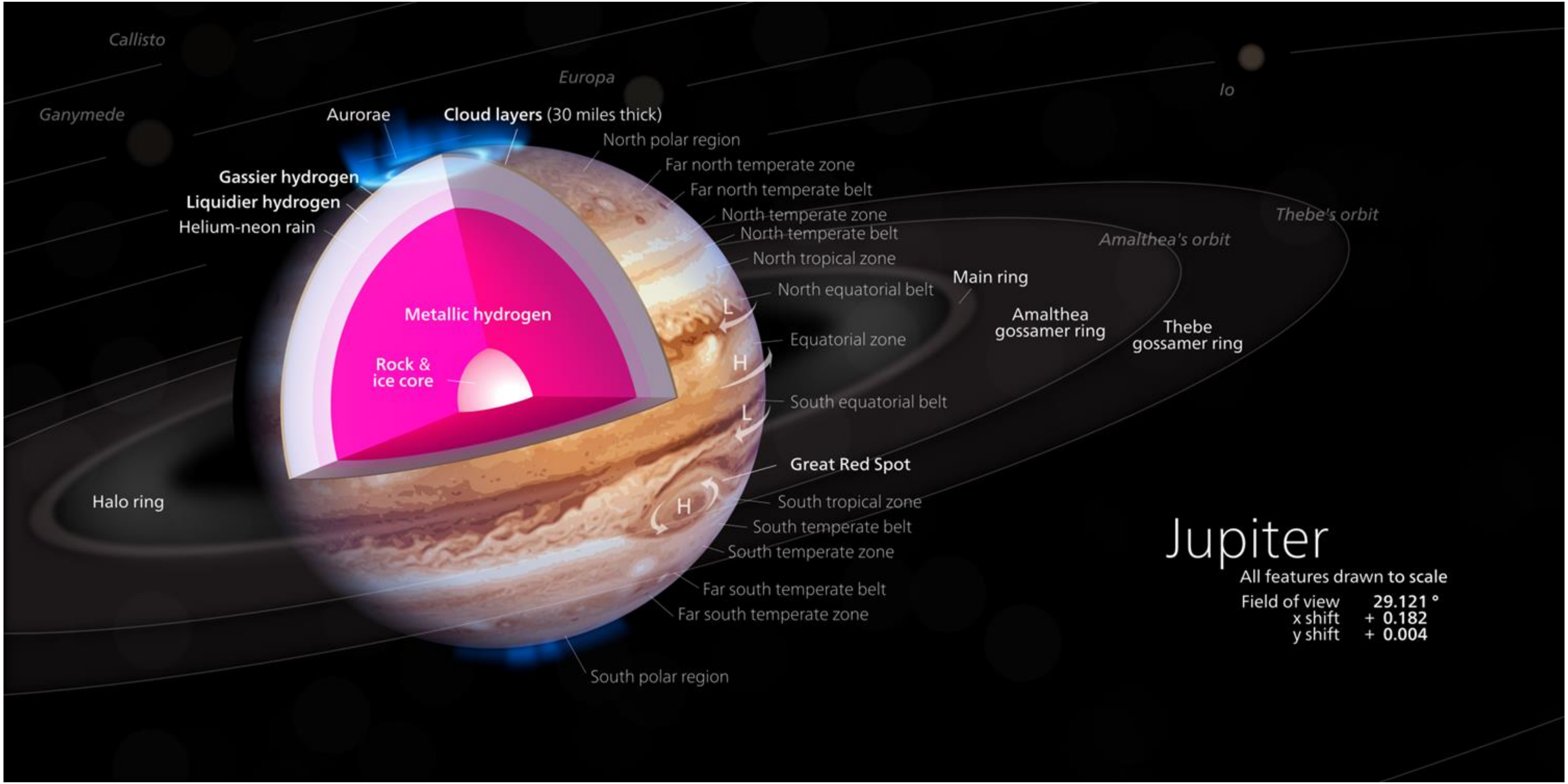
- Gas → liquid → metallic hydrogen (extreme pressure and temperature) → core of rock/metal/ hydrocarbons

<u>Uranus & Neptune</u>:

- Gas → hydrocarbons → core of rock/metal

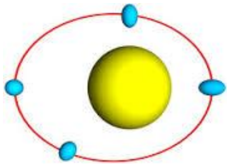


Life in the Solar System?

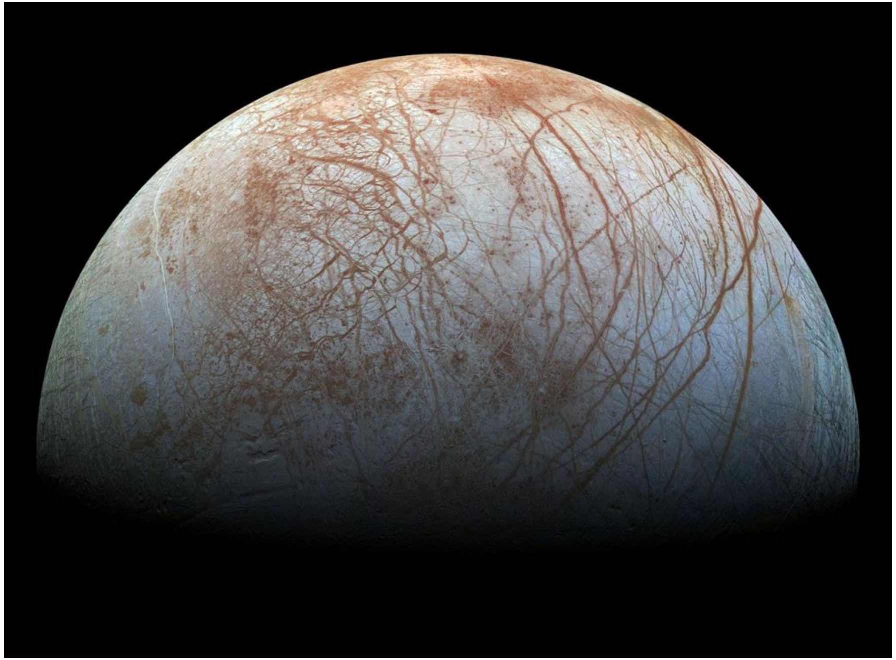


- Gas Giants?
  - **Life?** Not likely.
  - **No solid surface:** If you fell in, you would continue downward till crushed by intense pressure; your remains would sink into a hot liquid in a very strange phase.
  - **Jupiter/Saturn:** About 100 km below the cloud tops, the “right conditions” (water, temperature, and energy—lightning) can exist, but there are strong vertical convection currents that would sweep organisms to higher/lower regions that are too cold/hot.
  - **Uranus/Neptune:** Similar story, but maybe life could exist in the high pressure liquid water/methane/ammonia ocean near the core? Problem: Energy source?

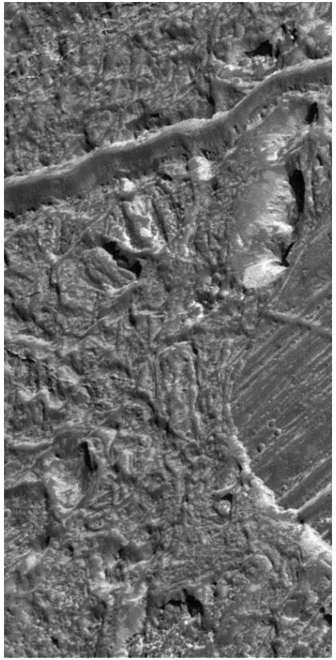
- Moons of Jupiter (e.g., Europa)?



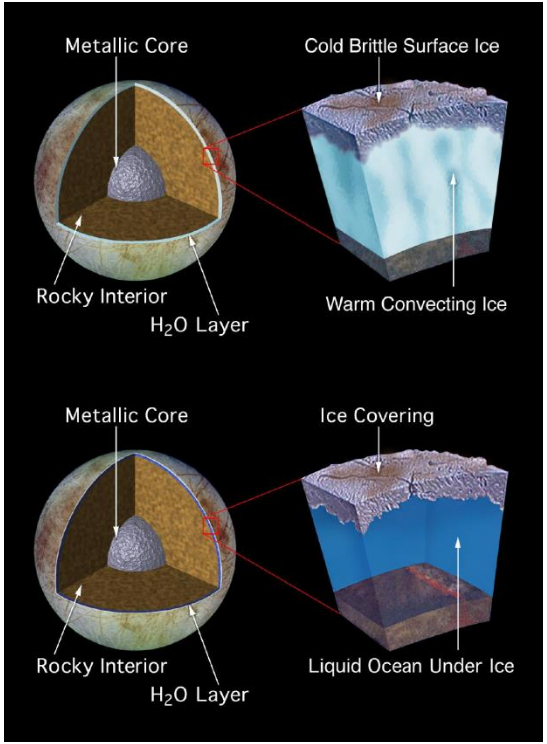
  - **Energy source:** Gravitational tidal flexing (or tidal waves) → Heating



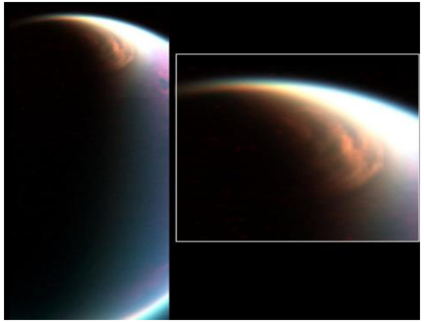
Cracked, icy surface; craggy, 250 m high peaks and smooth plates jumbled together

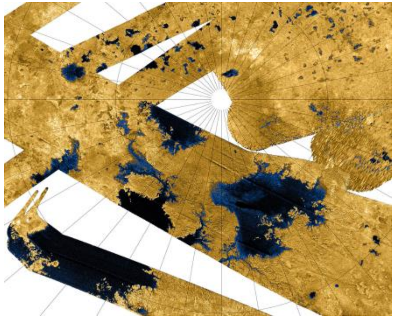


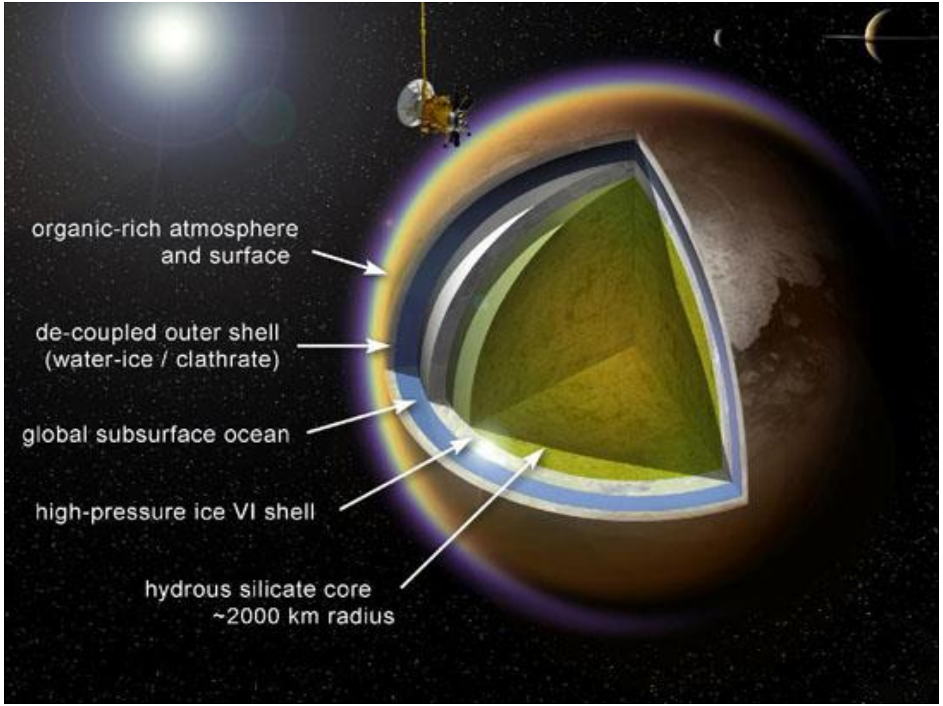
- Moons of Jupiter (e.g., Europa)?
    - Average surface temperature at equator = $-160\ ℃$ → water ice is hard a granite. But (relative) smoothness and youth, plus magnetic field → **salt water ocean underneath**. Different models being debated, but note that a 100 km thick ocean would be twice the volume of Earth's oceans.
    - Volcanic vents in the ocean floor (like on Earth) could provide enough energy for a **small amount of simple life**.
    - 2015: NASA laboratory expts suggest the yellowish-brown streaks near younger surface areas are likely **sea salt from a subsurface ocean**, discolored by exposure to particle radiation due to Jupiter's magnetic field; suggests the ocean surface is **interacting** with its rocky seafloor, important for the moon's ability to support life.



- Moons of Saturn (e.g., Titan)?

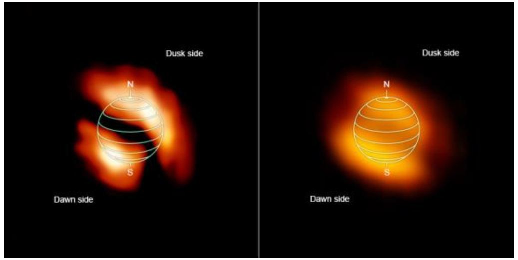




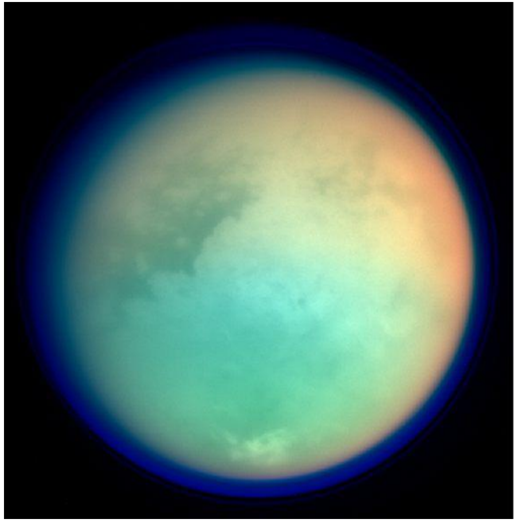


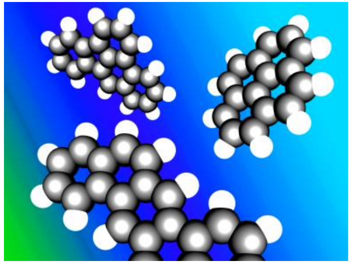
Possible model of Titan's internal structure that incorporates data from NASA's **Cassini spacecraft**. The mantle, in this image, is made of icy layers, one that is a layer of high-pressure ice closer to the core and an outer ice shell on top of the sub-surface ocean.

- Moons of Saturn (e.g., Titan)?
    - Life on Titan?
        - ✓ **Atmosphere:** Thick, chemically active, rich in organic compounds → chemical precursors of life?
        - ✓ 2013 NASA simulations of Titan's atmosphere suggest complex organic chemicals could arise. Two months later, NASA **detected** *polycyclic aromatic hydrocarbons* (PAHs) in the upper atmosphere.

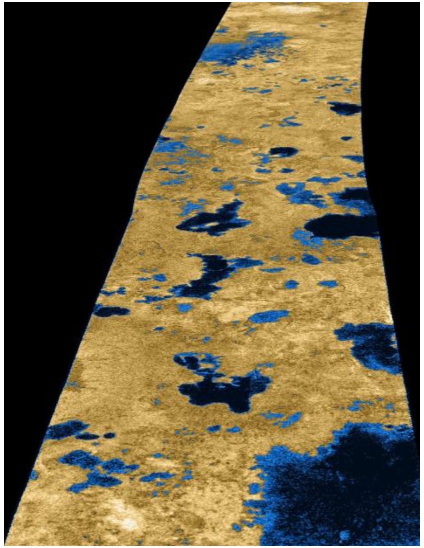


Trace HNC & HC_3N

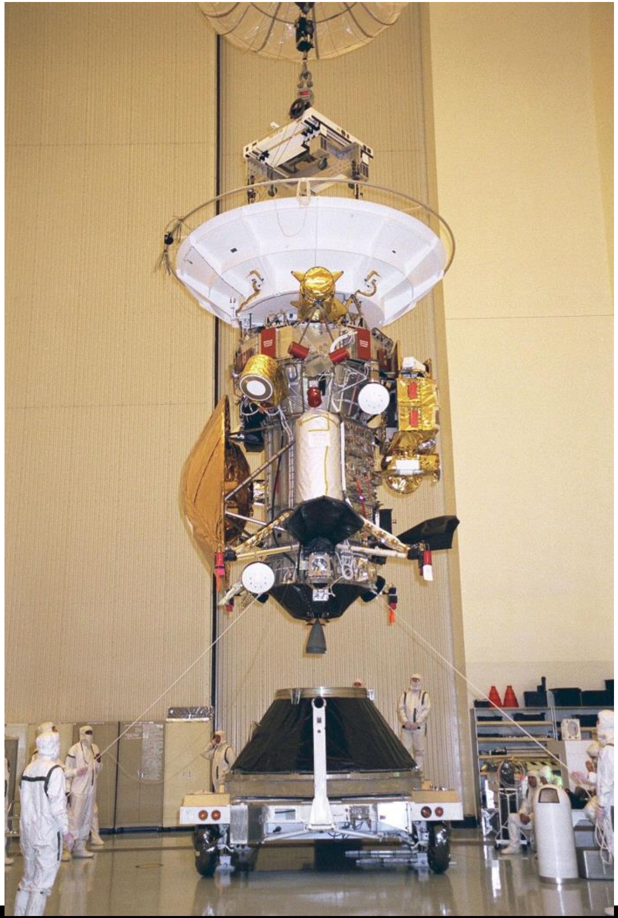




- Moons of Saturn (e.g., Titan)?
  - Life on Titan?
    - ✓ **Surface:** bodies of liquid ethane and methane; solvent for a different kind of life? Instead of glucose + oxygen → carbon dioxide, maybe acetylene + hydrogen → methane?
    - ✓ Evidence *suggesting* this has been detected, but **non-life explanations are more likely (and have yet to be ruled out)**. Note: Extremely cold temperature → any life would have **very slow metabolism**!
    - ✓ Future missions? Land in a lake?

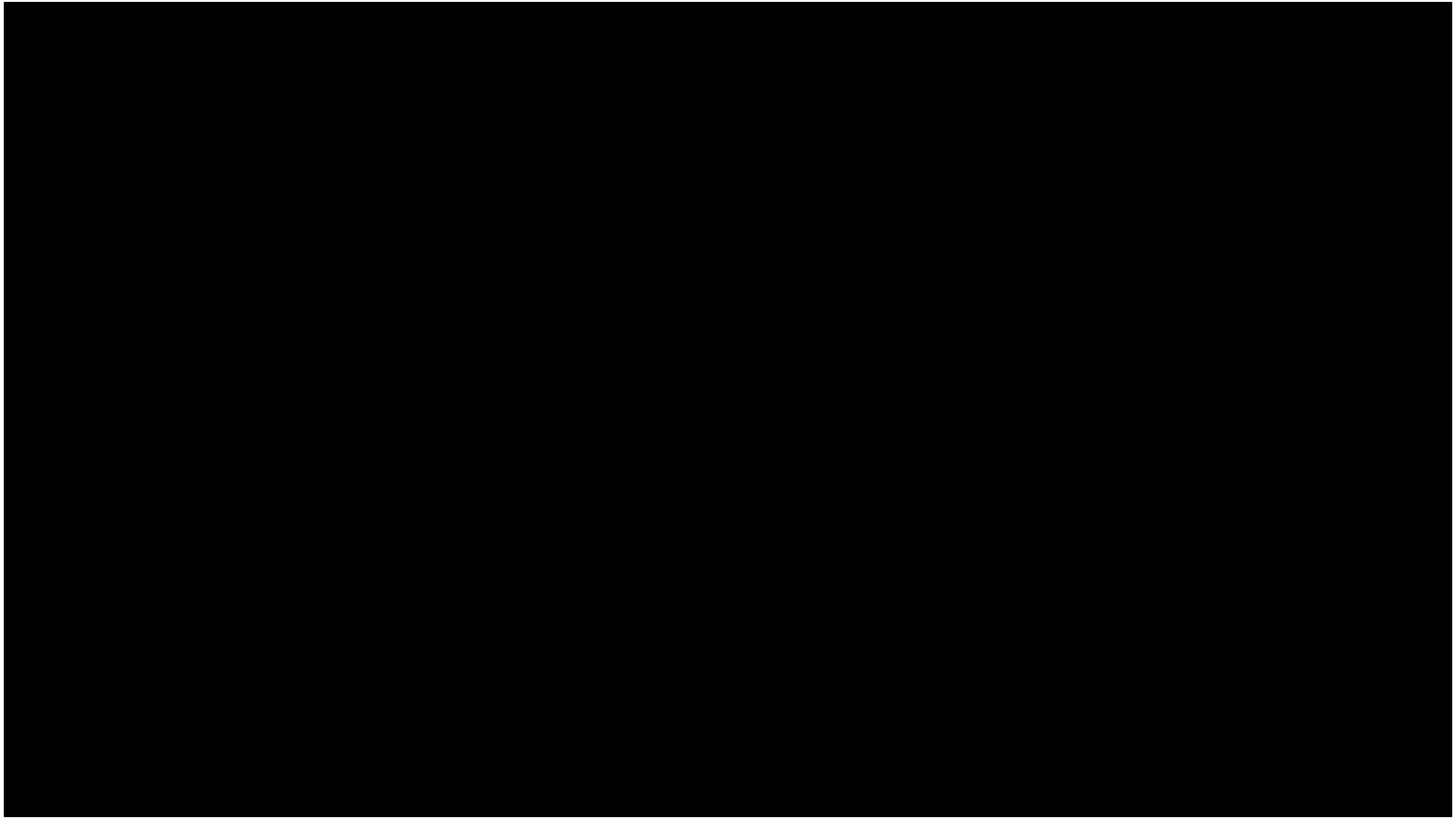


- **Technology** of Cassini-Huygens mission—amazing!

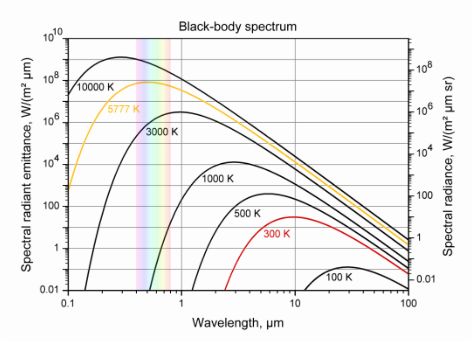


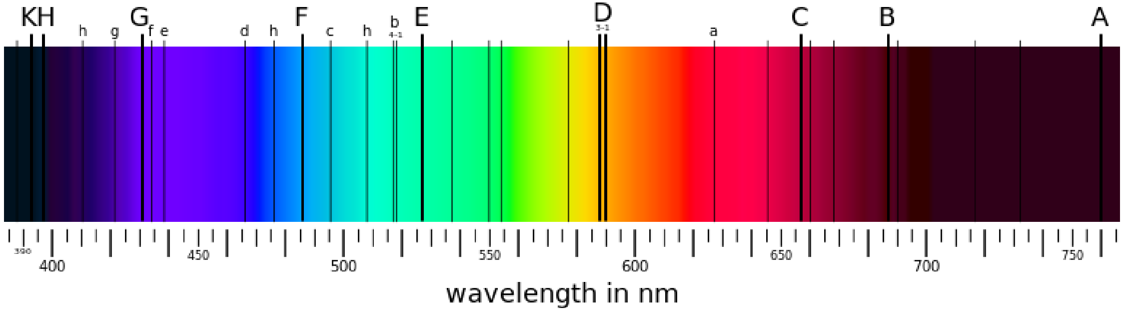
Huygens' landing on Titan (next slide)

Life in the Solar System?



- **Basic idea**: Measure the **light** (visible and IR) coming from an exoplanet…
  - **Brightness**: Overall brightness gives crude information about **ratio of water to land** (water darker than land), daily cloud cover, seasonal snow or ice, etc.
  - **Spectrum**: Even a crude spectrum reveals the average **surface temperature**; a better spectrum can reveal **chemical fingerprints** of gases in the atmosphere (CO_2, O_2, O_3, CH_4, H_2O, etc.), **types of minerals or ices on the surface**, etc. Precise abundances and ratios can provide strong evidence of the presence (or not) of life on the planet.

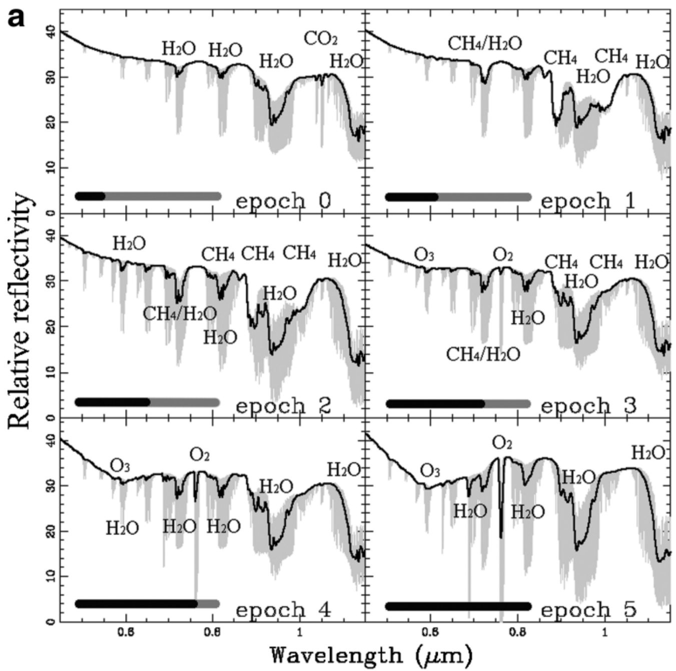




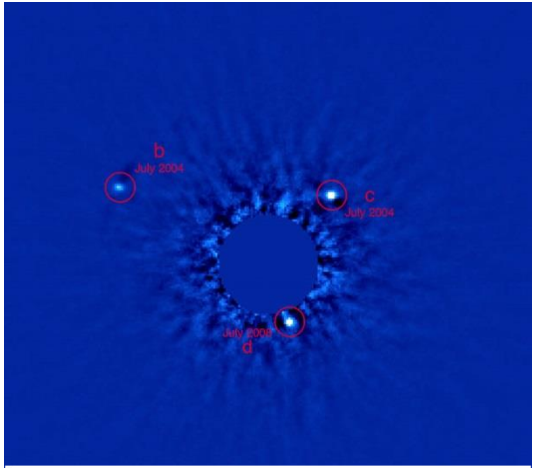
- **Basic idea**: Measure the light (visible and IR) coming from an exoplanet…

  - Figure shows how the chemical fingerprint of **Earth's atmosphere** would have changed due to the presence of life; notice O_2 and O_3 arising due to photosynthesis; also biological CH_4.

  - Volatile gasses like oxygen and methane must be continually replenished, **suggesting life** (but not necessarily conclusively—could have non-biological origin)

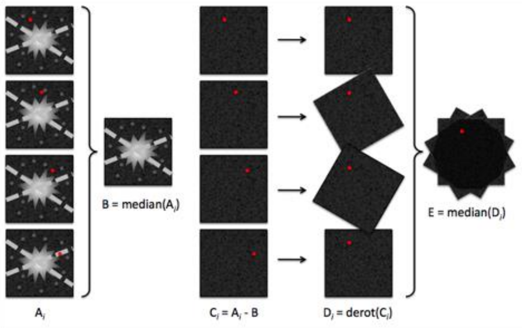


- **Problem:** It’s hard to detect light from an exoplanet due to **million-fold glare of parent star**

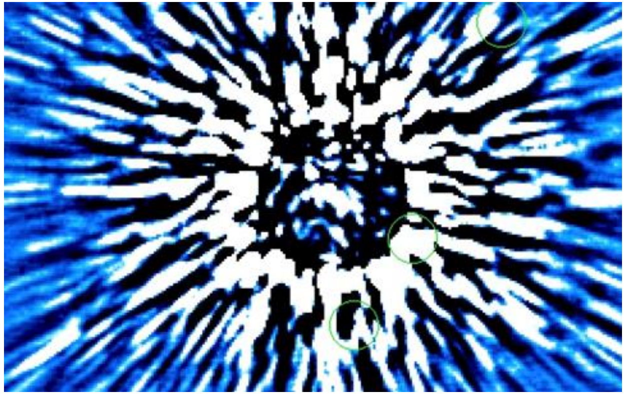


  - 2008: team led by C. Marois of Canada’s NRC announced first direct image of 3 exoplanets at 24, 38, and 68 AU around star HR8799 (1.5x mass of Sun, 5x luminosity of Sun).

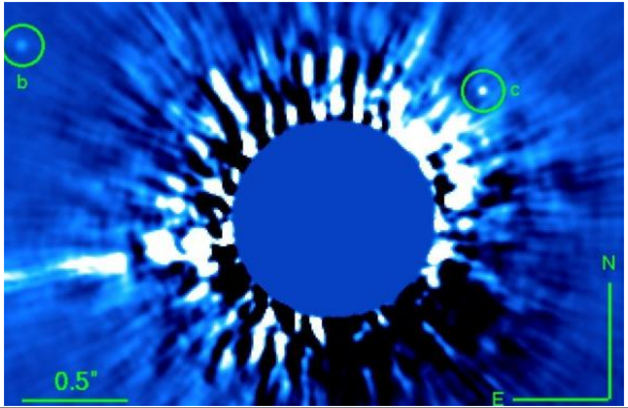
  - They invented “Angular Differential Imaging (ADI)”: Find pixel-wise median of many rotated images (B); subtract from original images (Ci); de-rotate and median-average…



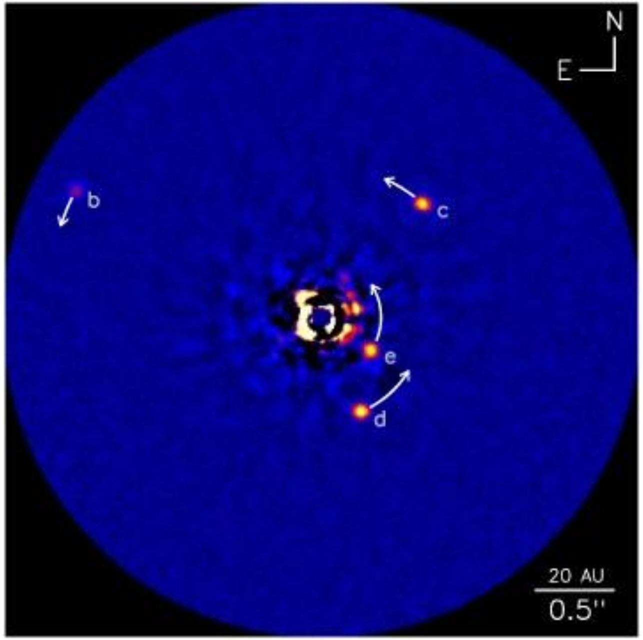
- **Problem:** It's hard to detect light from an exoplanet's due to **million-fold glare of parent star**



Without ADI



With ADI

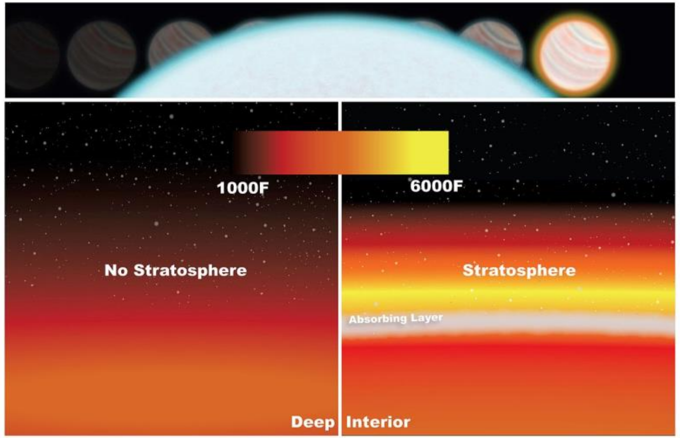


Works best for young planets (hotter in IR), and far from star

Life on Exoplanets?

- Steady progress since then (…more than shown here; cool recent example):
  - 2001: **Sodium** detected in atmosphere of HD 209458 b.
  - 2008: **Water, carbon monoxide, carbon dioxide, methane** detected in HD 189733 b.
  - 2013: **Water** detected in atmospheres of 5 other exoplanets.
  - 2015: **Stratosphere** detected on HD 15082.

  A stratosphere is a **temperature inversion**. Monitor **drop** in total IR light as planet passes behind star (top). Greater drop → hotter upper atmosphere, in this case caused by titanium oxide in lower atmosphere absorbing light and heating up.



Life on Exoplanets?—Summary

- This is a very hot topic in science. Lots of **ultra high technology** coming down the pipe:
    - **James Webb Space Telescope** (launch 2018?): Successor to Hubble Space Telescope. Operates in IR. Very broad science mission, including **direct imaging** of exoplanets and **spectroscopic examination** of planetary transits.
    - The TMT (Thirty Meter Telescope)—nine times the area of Keck (2024?):

Dark energy, dark matter and tests of the Standard Model of particle physics
Characterization of first stars and galaxies in Universe
Characterization of the epoch of reionization
Galaxy assembly and evolution over 13 billion years
Connections between supermassive black holes & galaxies
Star-by-star dissection of galaxies out to 10 M parsecs
Physics of planet and star formation
Kuiper belt object surface chemistry
Solar system planetary atmosphere chemistry and meteorology
Exoplanet discovery and characterization
The search for life on planets outside the Solar System

Life on Exoplanets?—Summary

If life is common in the universe (even just microbial life), we may know “soon”