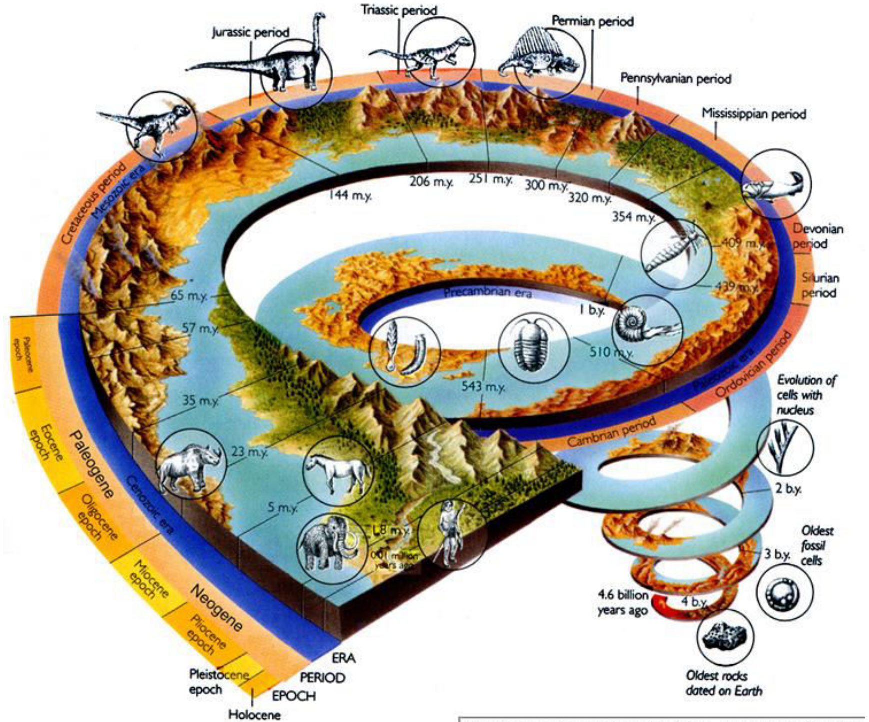
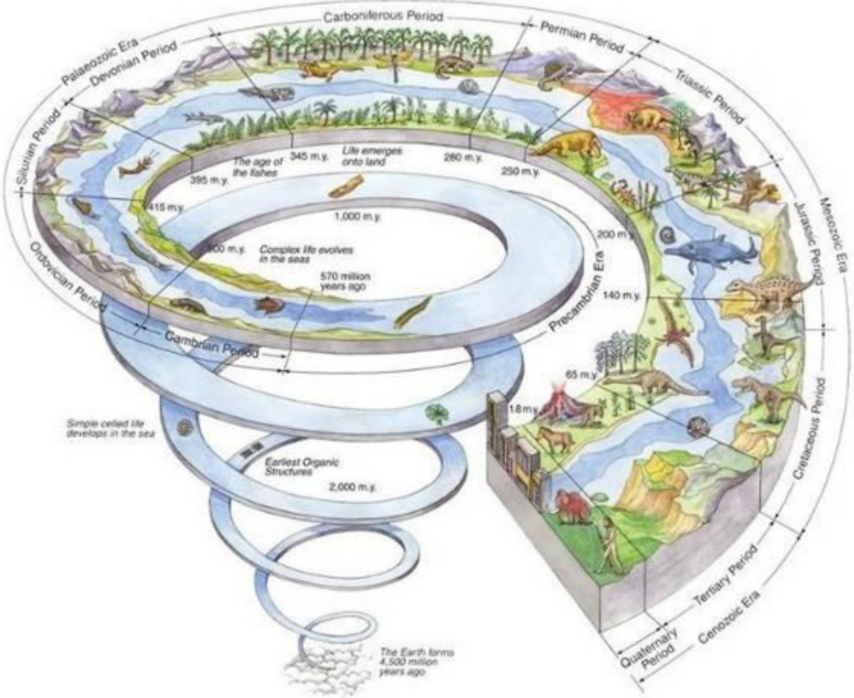
- The origin of life on Earth is still **deeply mysterious**.



Adapted from Press & Siever, 2000, Understanding Earth



Introduction

- The origin of life on Earth is still **deeply mysterious**.

- However:

  - ✓ The answer seems to be **within the reach of science**, at least *generally*.

  - ✓ **Right conditions** (chemical/solar free energy, organic molecules, liquid water) + increasingly **plausible origin models** ⇒ at least *simple* life is **probable**.

  - ✓ Indeed, if an idea like “dissipation-driven adaptation” turns out to be correct, then under the **right conditions**, life may be an **inevitable consequence** of physics.

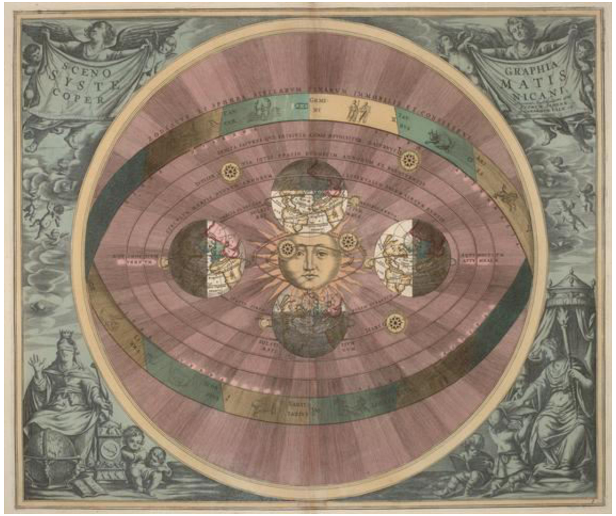
  - ✓ If so, and since the laws of physics appear to be the same everywhere, then life should be **common** in those places that have the **right conditions**.

Introduction

- The question “**Are We Alone**” is of ever increasing interest to scientists.

  ✓ **Why?** The discovery of life of *any* kind (or *not*) beyond the Earth would deeply and forever **change our perspective** of who we are, and what our place in the universe is. This is what science ***does***, e.g.:

  - Discovery of **heliocentrism** (Copernicus, and Newton’s “unification of heavens & Earth”);
  - Discovery of **deep time** and **deep space**;
  - Discovery of **evolution** and **genetics**;
  - Discovery of the **Big Bang** (beginning?);
  - Discovery of the **quantum nature** of the universe (freewill?), etc.



Introduction

- The question "**Are We Alone**" is of ever increasing interest to scientists.

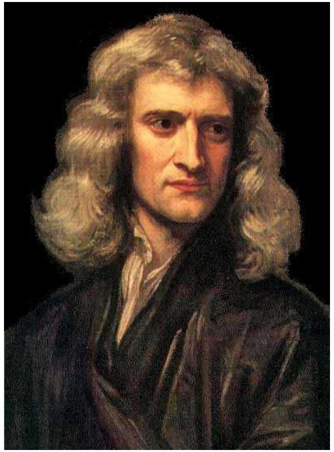
  ✓ **Why Now?** Scientists have *always* been interested in this question, but in the last few decades this interest has **dramatically intensified**:

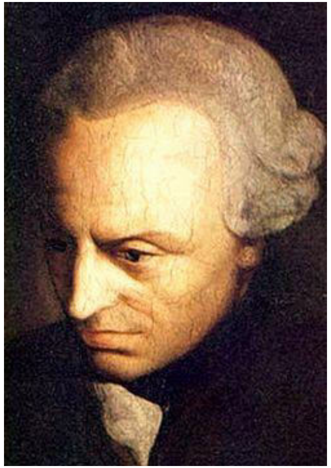
    - We now **know** **there are planets out there**. (Without them, ET life is unlikely.)
    - We now have much better reasons to think that **biology might be universal**.
    - We now have sufficient **technology** to begin **looking for ET life**.

  ✓ "…the study of life in the universe [astrobiology] is one of the most rapidly growing fields of active scientific research…"—Bennett & Shostak (2012).

- With his discovery of a universal laws of **motion** ($F = ma$) and **gravitation**, Newton “unified the heavens and the Earth”. However, he thought the order in our Solar System was initially imposed by God:

  > “Gravity explains the motions of the planets, but it cannot explain who set the planets in motion. God governs all things and knows all that is or can be done.”—Newton





- In his 1755 book, *General History of Nature and Theory of the Heavens*, the philosopher Immanuel Kant introduced his **nebular hypothesis**, attempting to explain the **origin of the order** in the Solar System.

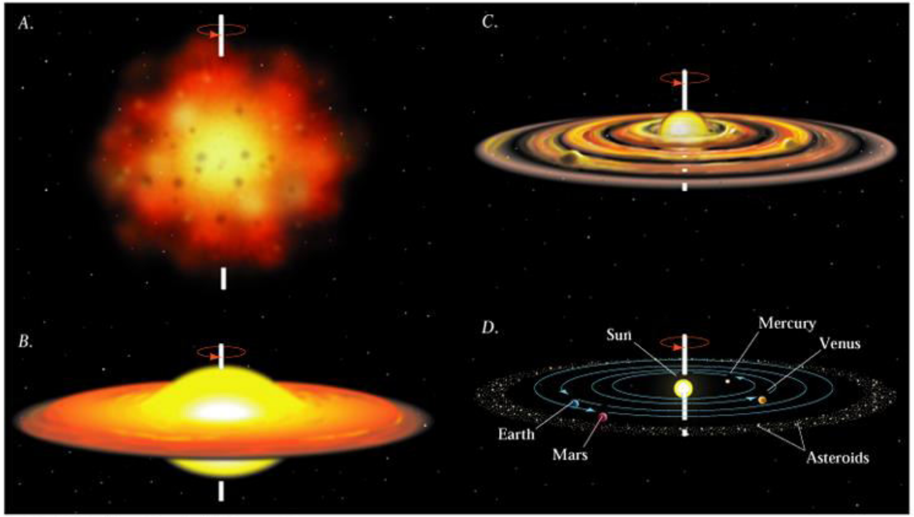
- Since then, the nebular hypothesis has been significantly developed, and provides a simple, **natural** explanation for the formation of stars and planets, not just the Solar System, but **throughout the universe**.

A. Large, relatively dense interstellar cloud of gas and dust, with small random overall rotation, begins gravitational collapse

B. Gravitational energy → thermal energy → sparks fusion in protostar. Rotation speeds up & cloud flattens into protoplanetary disk

C. Electrostatic then gravitational clumping in the disk → planetesimals → planets. We now have sophisticated computer models

D. Rocky planets form in warm region near star (like Earth); icy & gaseous planets form in cold region far from star (like Jupiter).



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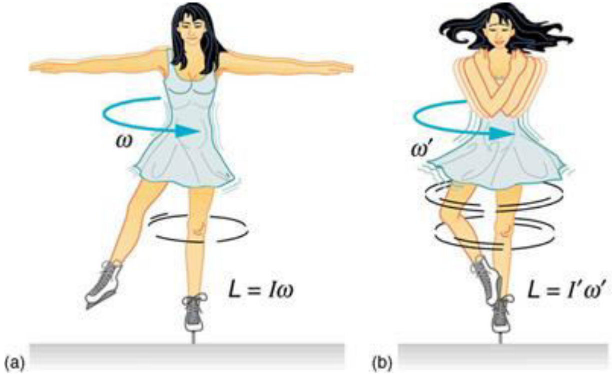
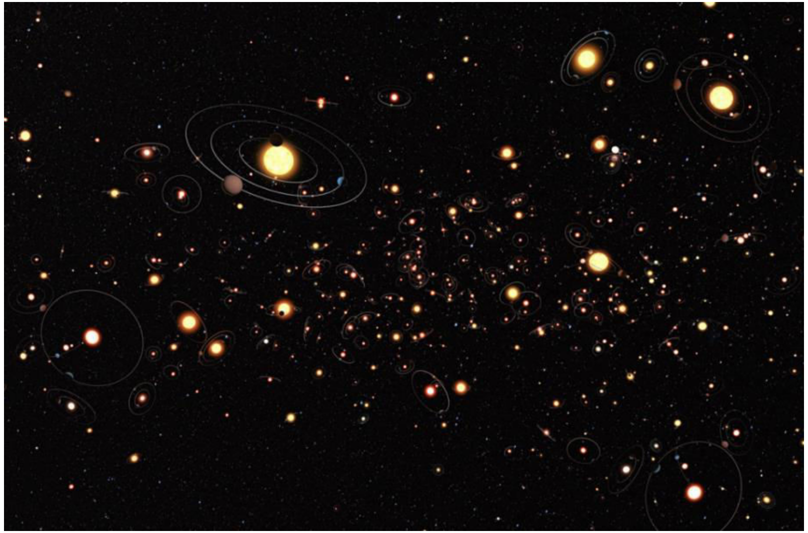
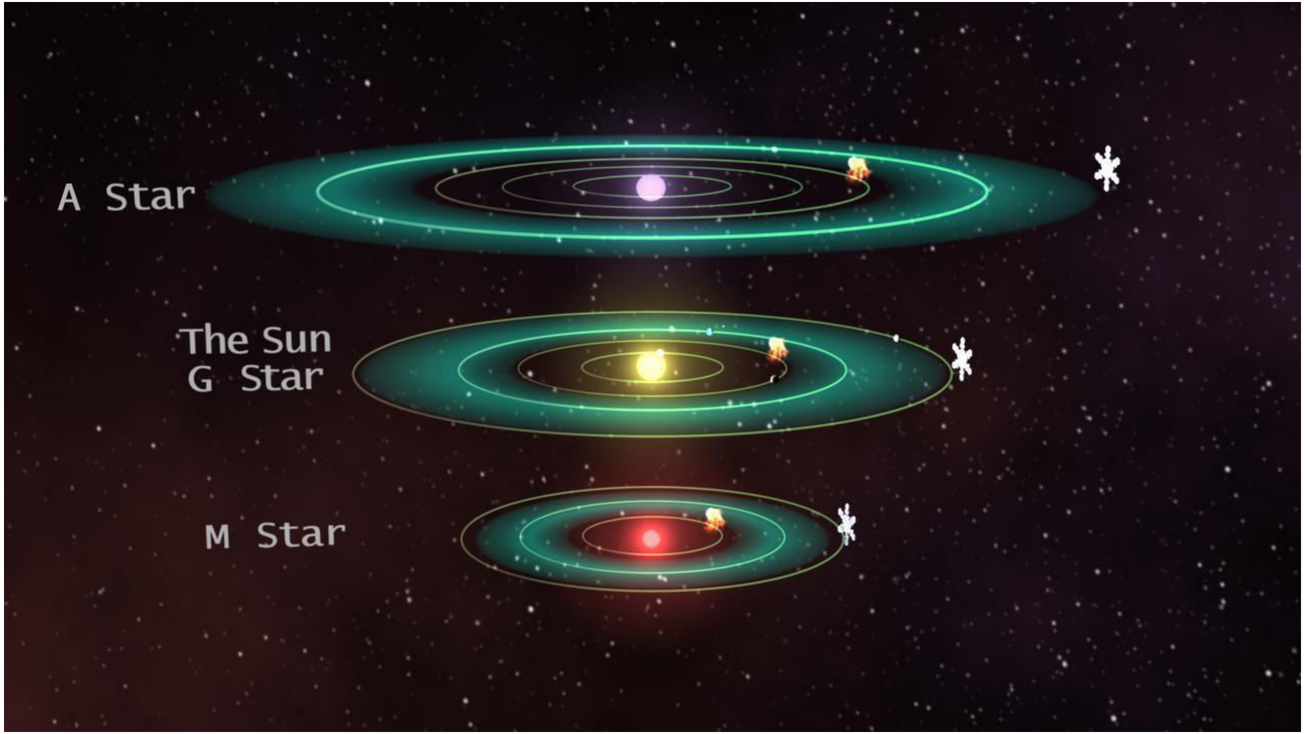


Exoplanets

- So scientists expected **virtually all** stars to have planets, but before 1988 the number of **known** *exoplanets* (planets orbiting other stars) was **zero**.
- Since 1988 the number of **known** exoplanets has risen to **more than 2000**. Extrapolating the numbers, **our galaxy contains over 10 billion Earth-like planets orbiting Sun-like stars in the "habitable zone" (i.e., would support liquid water)**!

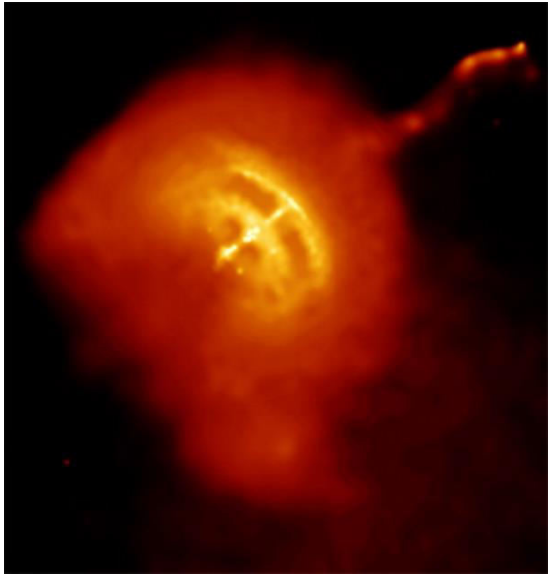




“habitable zone” (not too hot, not too cold → liquid water)

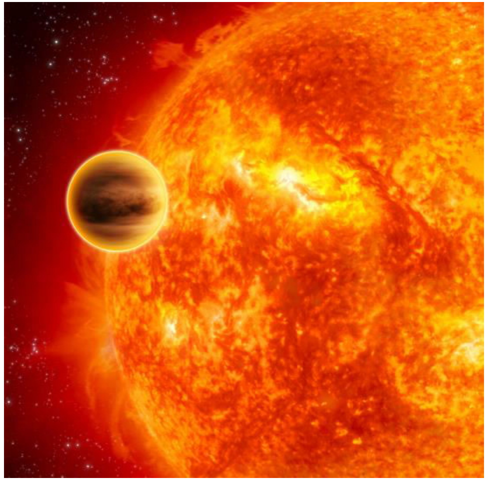
- First discoveries:
    - 1988: Canadian Bruce Campbell & team tentatively discovered a planet in the Gamma Cephei **binary star** system (like Luke Skywalker's planet Tatooine in Star Wars)

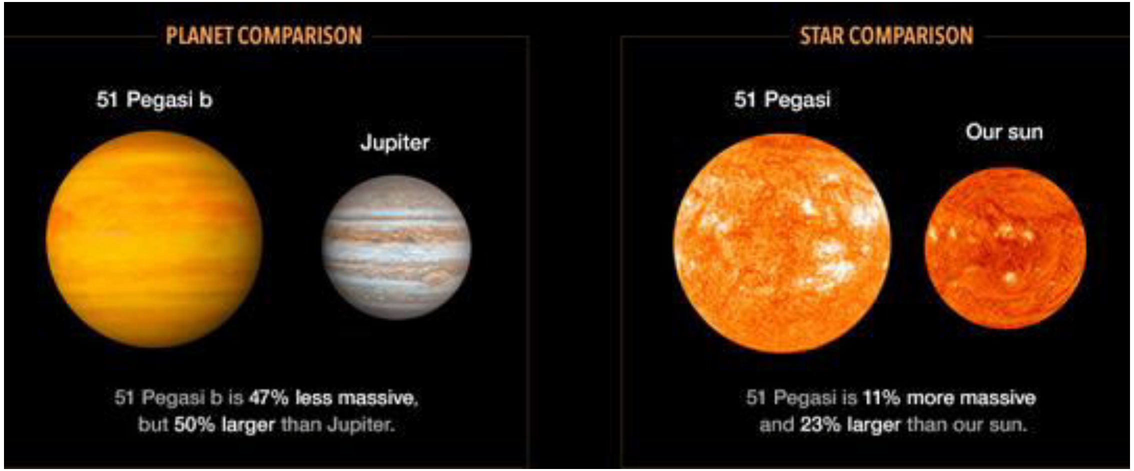
- First discoveries:
  - 1992: Aleksander Wolszczan and Canadian Dale Frail discovered two planets around **pulsar** PSR1257+12 (rapidly spinning, magnetized neutron star—life not likely!)



- First discoveries:

  - 1995: First exoplanet orbiting a ***main-sequence* star**, 51 Pegasi b (a Sun-like star 51 light years from Earth). Named “Bellerophon” from Greek mythology. At least half the mass of Jupiter, and orbits very close to the star → temperature around 1000 °C. Such “hot Jupiters” challenged existing theories of planet formation → “migration theory”





Main-sequence stars: Stably fusing H to He.

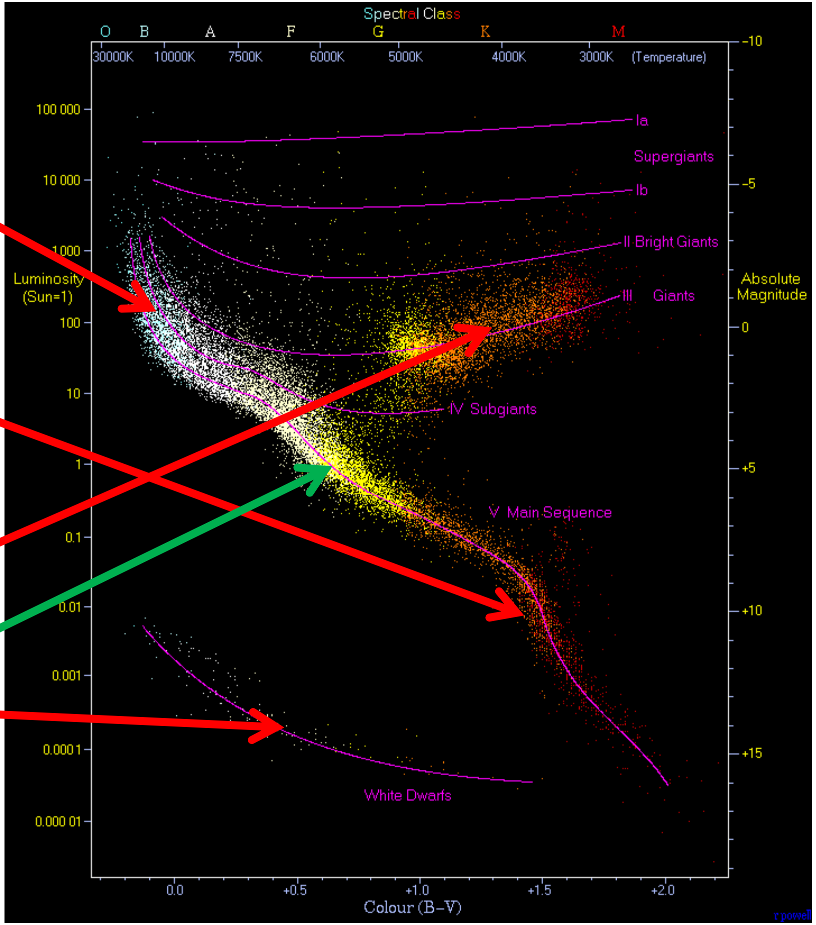
Blue giants: Bright & high mass → supernova. Least abundant, and too short-lived for life to likely evolve.

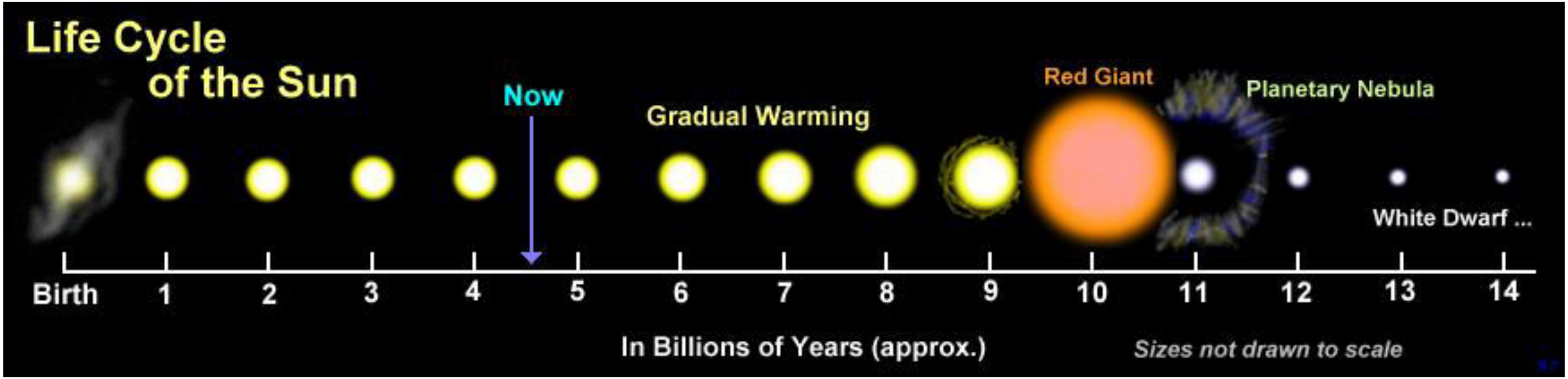
Red dwarfs: Dim & low mass → longest-lived and most abundant, but brightness variable & planet must be close → tidal heating and tidal locking. Feasibility for life is currently being debated…

Giants: Stars in transition state or death throes.

White dwarfs: End state of 97% of stars (including Sun); heavier stars end as **neutron star or black hole**

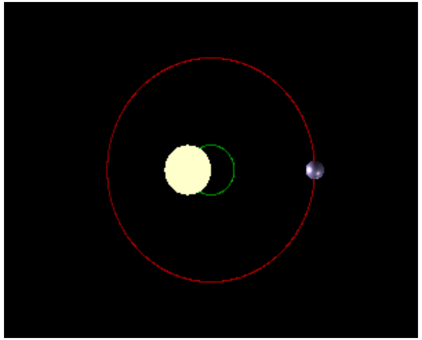
Sun-like stars are "just right"!

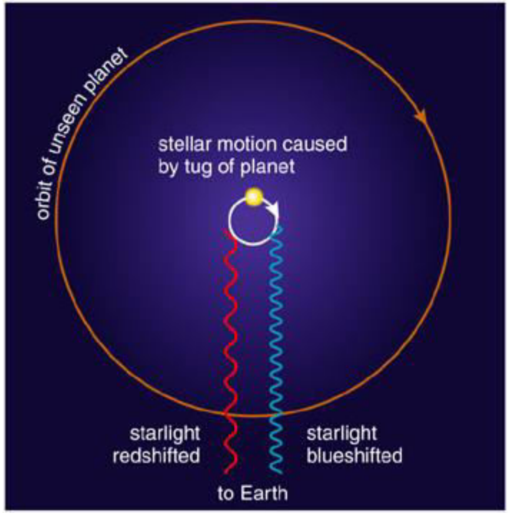


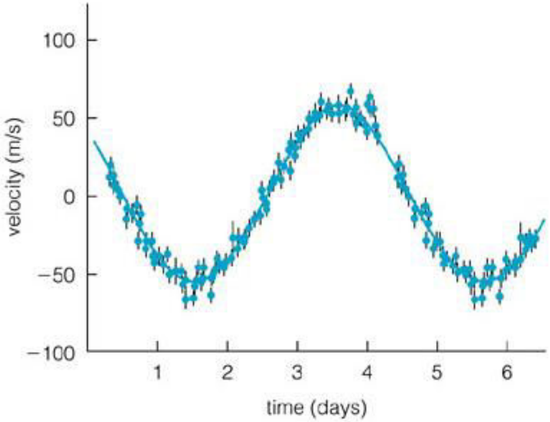

Life Cycle
of the Sun
Now
Gradual Warming
Red Giant
Planetary Nebula
White Dwarf ...
Birth
1
2
3
4
5
6
7
8
9
10
11
12
13
14
In Billions of Years (approx.)
Sizes not drawn to scale

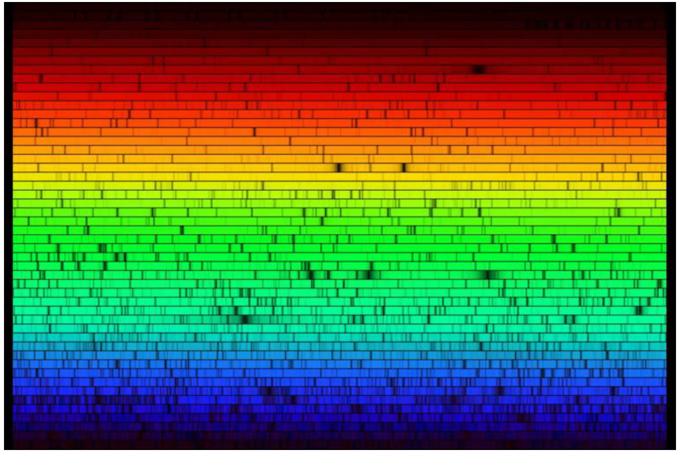
- Exoplanet **detection** methods:

  - **Doppler method**: Planet and star orbit **center of mass** → star *wobbles* → detect periodic shift in *spectrum* of starlight. Gives **mass** of planet (and period → orbital distance by Kepler's third law); best for **high mass planets close to their star**.

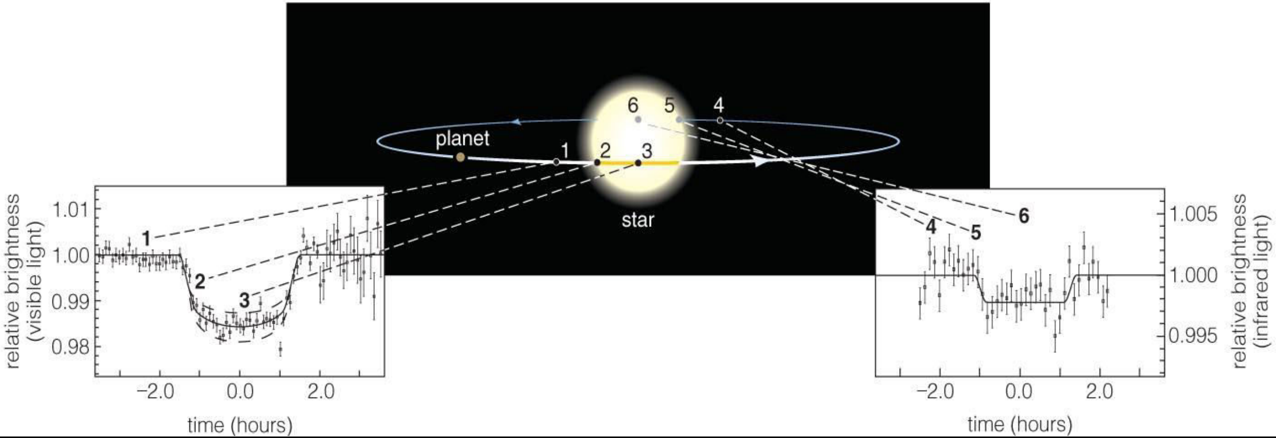




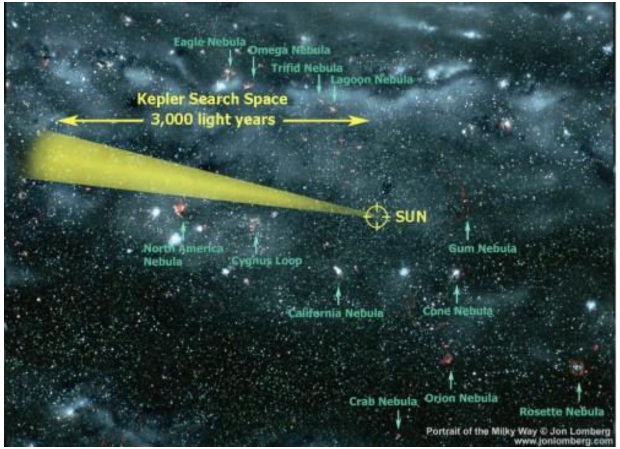


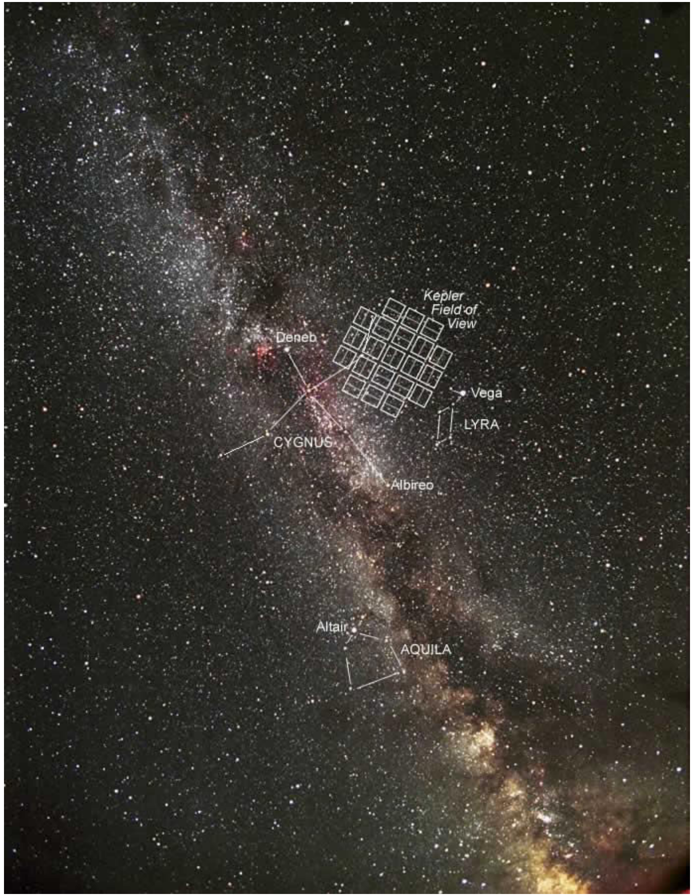


- Exoplanet **detection** methods:
  - **Transit method**: Requires **edge-on** view (probability about 1 in 200)
    - Planet in front of star → reduced visible light → planet **size**
    - (and period → orbital distance by Kepler's third law)
    - Planet behind star → reduced infrared light → planet **temperature**
    - Can also get some info about **chemicals in the atmosphere**!
    - Can detect also **small mass** (e.g., Earth-like) planets

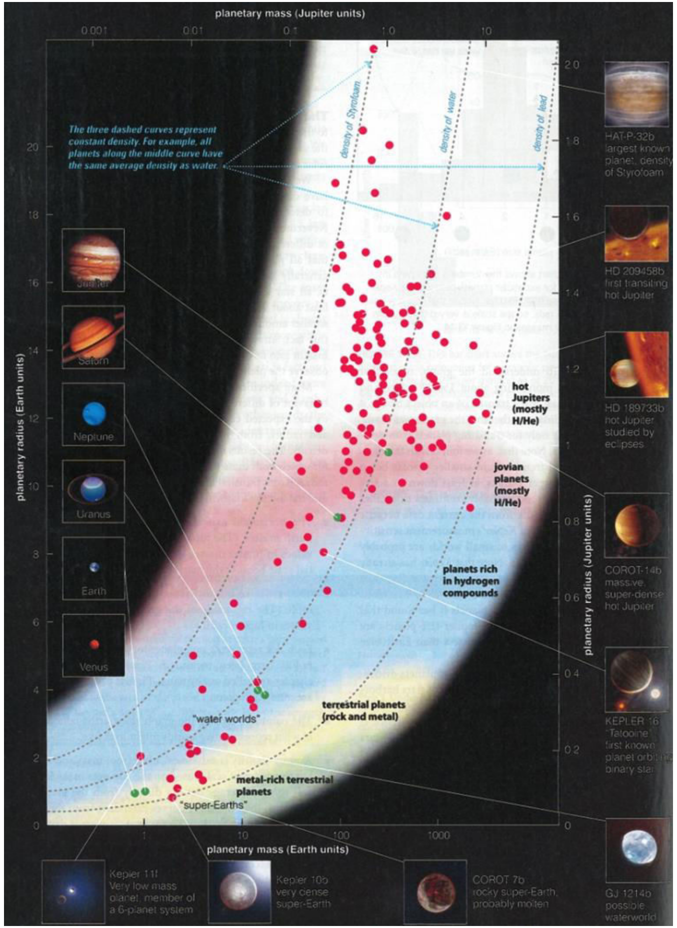


- Exoplanet **detection** methods:
  - **Kepler mission** (transit method): 145,000 main-sequence stars, imaged every 30 minutes to detect brightness changes. As of July 2015, candidate planets = 4,696; **confirmed planets = 1030**. (Added to ≈ 1000 from other planet searches.)

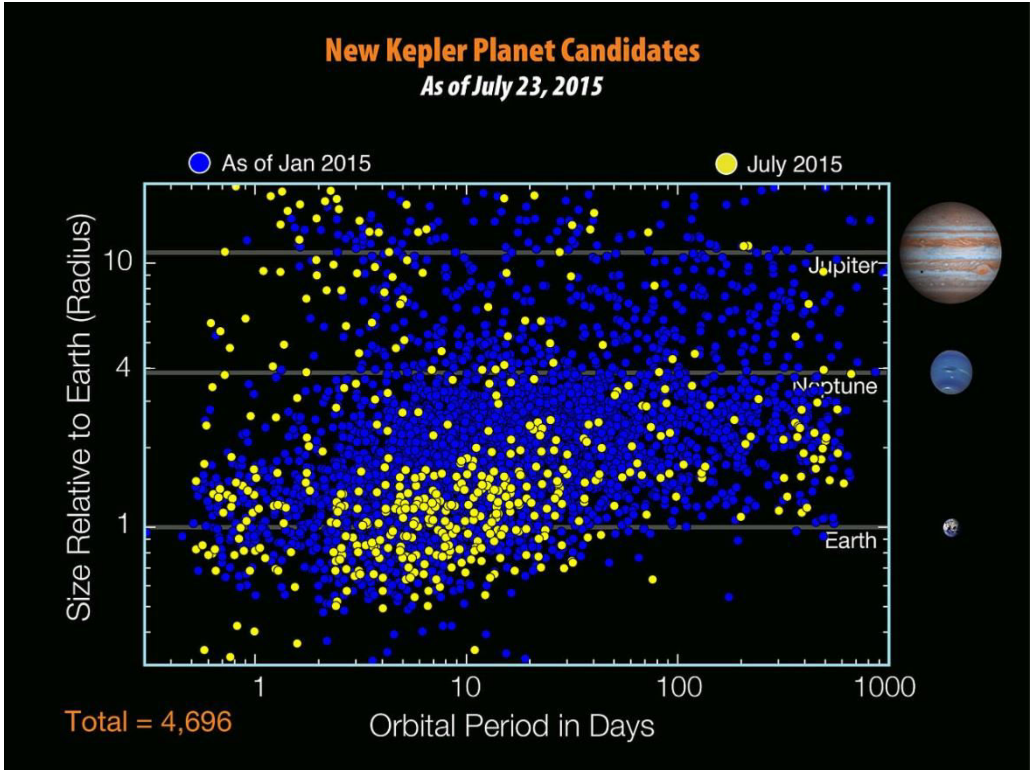




- Exoplanet **detection** methods:
  - Combine **both** methods:
    - ✓ Planet **mass** from Doppler
    - ✓ Planet **size** from transit
    - ✓ Gives planet average **density**:
      - **rocky?**
      - **gaseous?**
      - **other?**
  - Lots of **surprises** & **mysteries**!



- “Tons” of **data** (search for ET is now **real**!)



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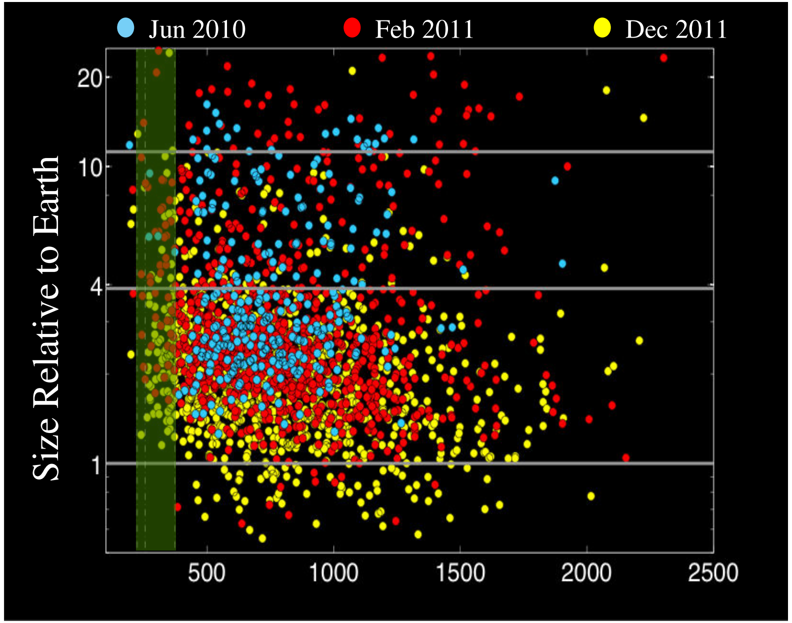
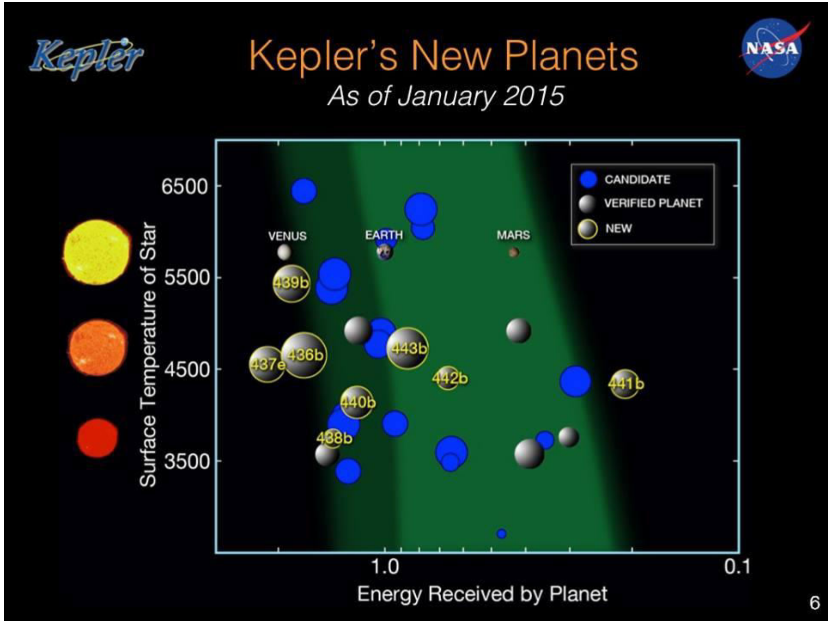


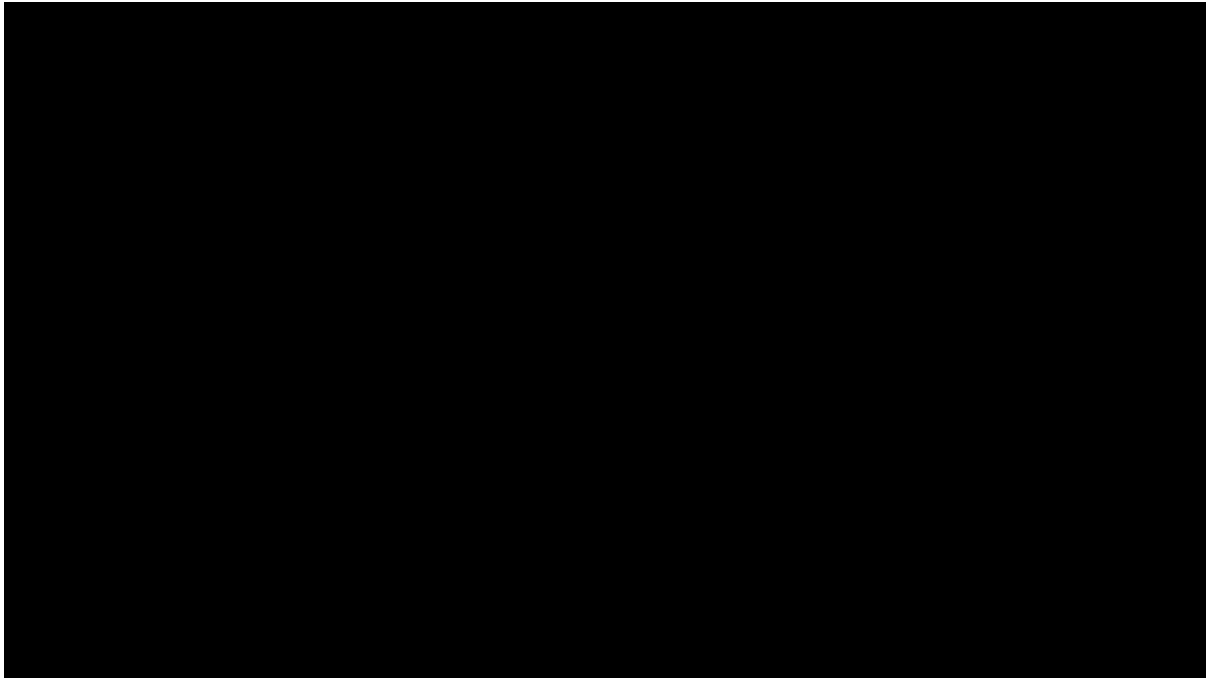
Equilibrium Temperature [K]

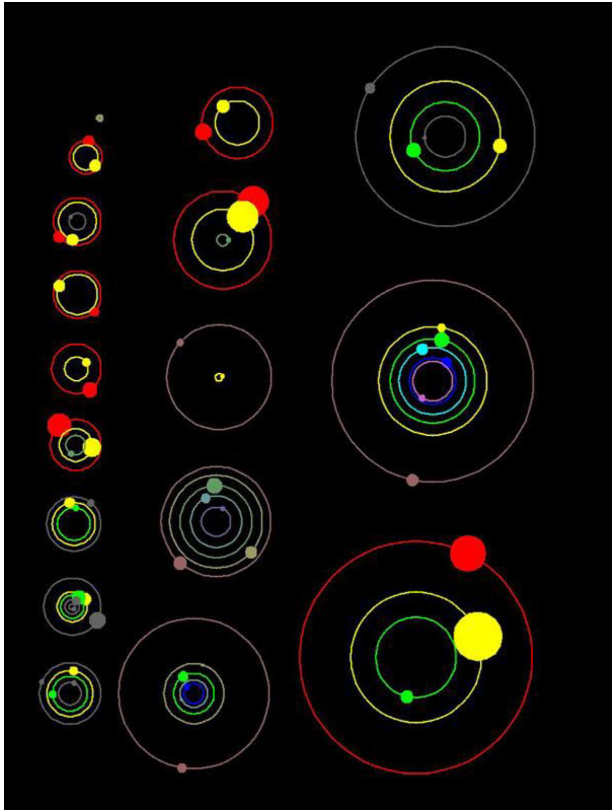


Planet Temperature (Green = “Habitable”)

Exoplanets

- “Tons” of **data** (search for ET is now **real**!)
- Amazing variety of planetary systems. Super cool link.

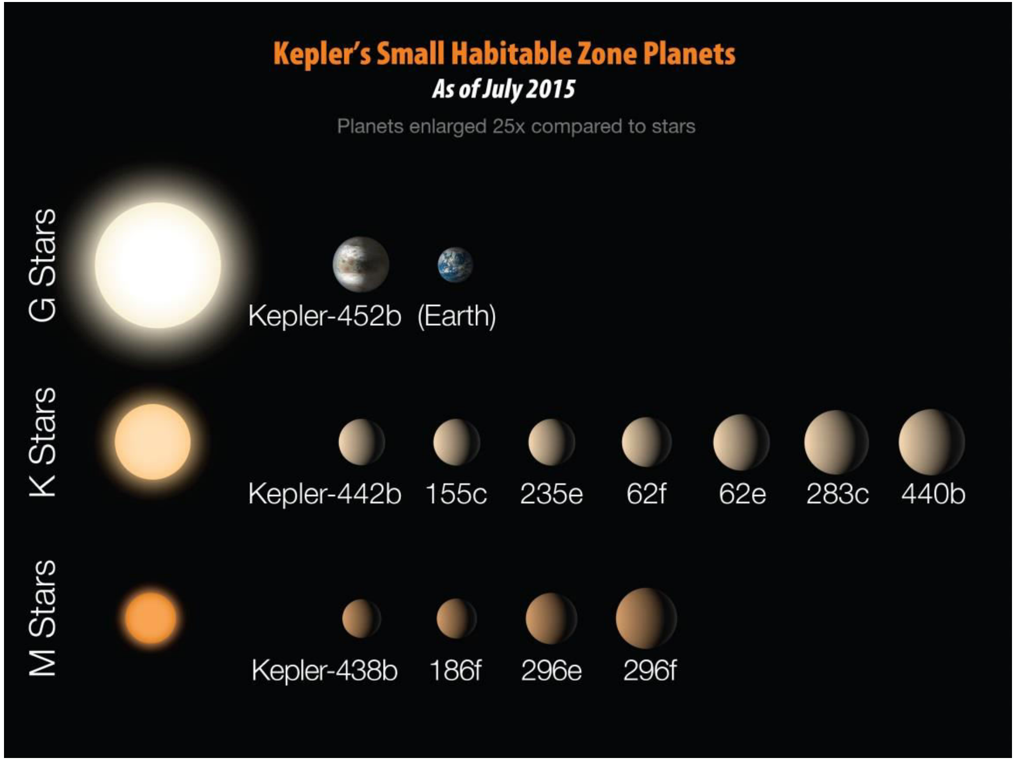




- Latest on search for **habitable** planets:

  - Twelve exoplanet discoveries from Kepler that are **less than twice the size of Earth** and reside in the **habitable zone** of their host star. G stars are **Sun-like**; K and M are smaller and cooler.

  - (The sizes of the planets are enlarged by 25X compared to the stars. The Earth is shown for reference.)



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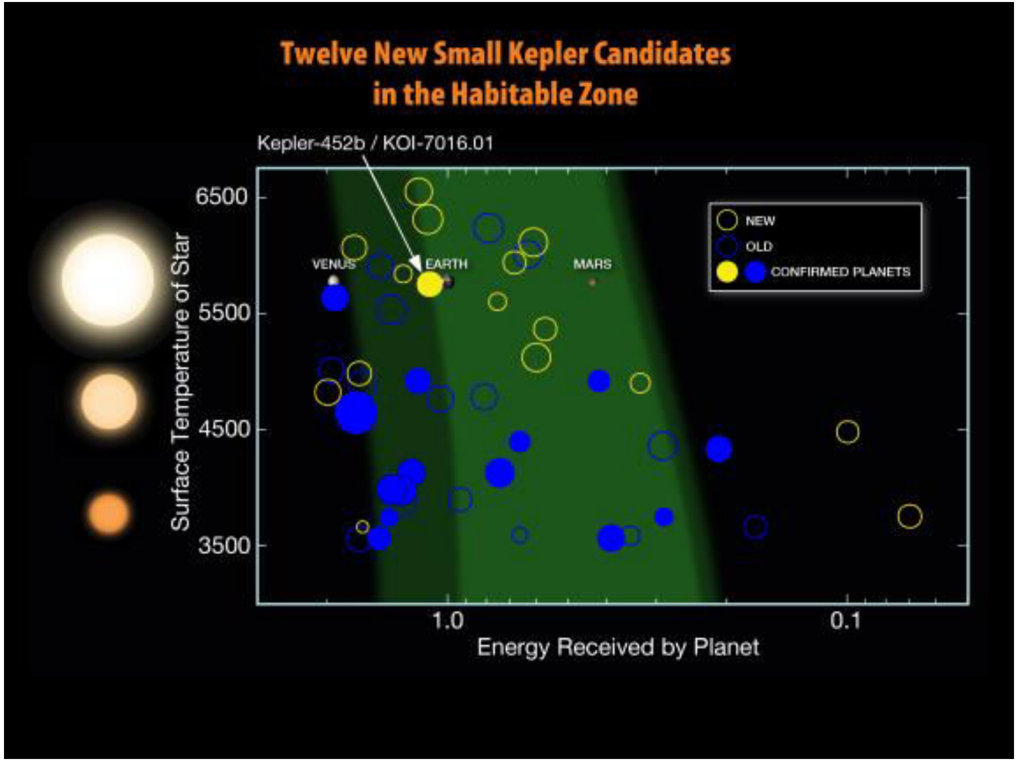
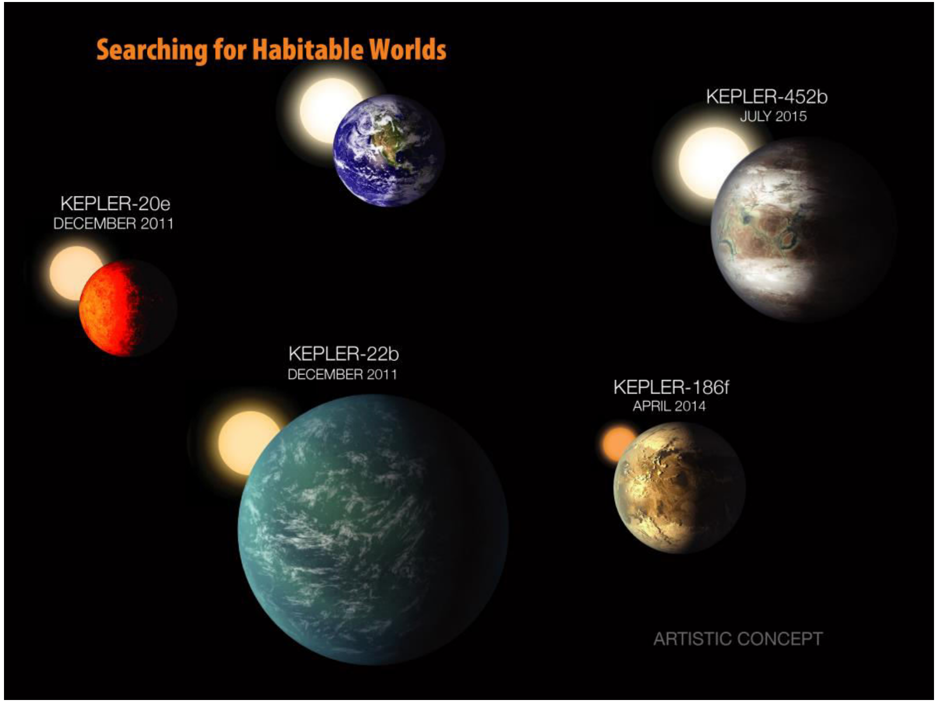


- Latest on search for **habitable** planets:

- Dec 2011: Kepler-20e, first planet **smaller than Earth**, orbits a star slightly cooler and smaller than our Sun every six days. But it is scorching hot and unable to maintain an atmosphere or a liquid water ocean.

- Dec 2011: Kepler-22b first planet in the **habitable zone** of a sun-like star, but is more than twice the size of Earth and unlikely to have a solid surface (“water world”?).

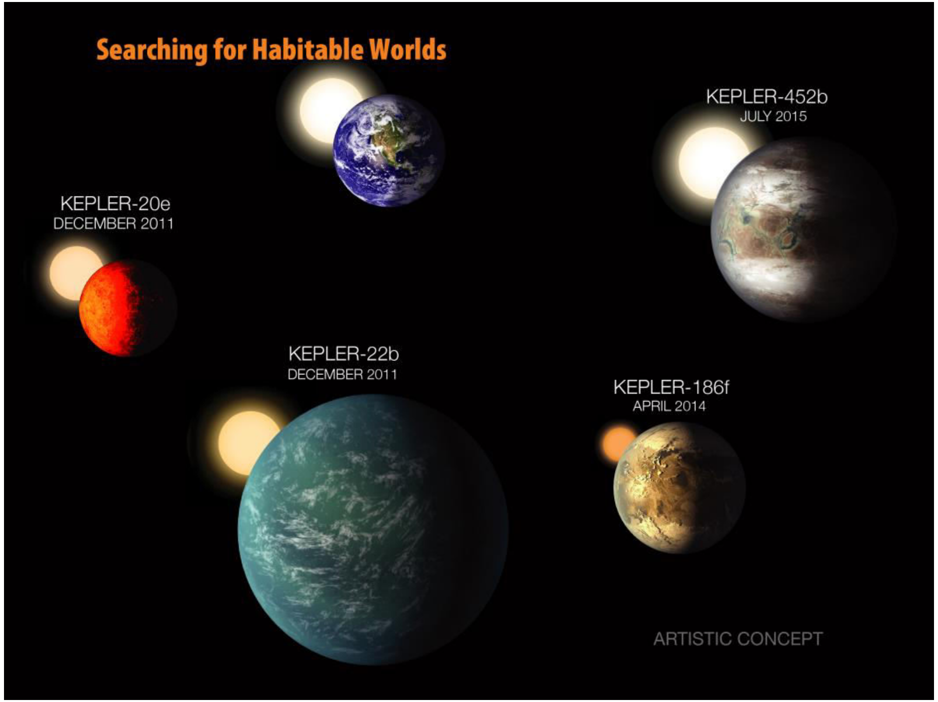


Exoplanets

- Latest on search for **habitable** planets:

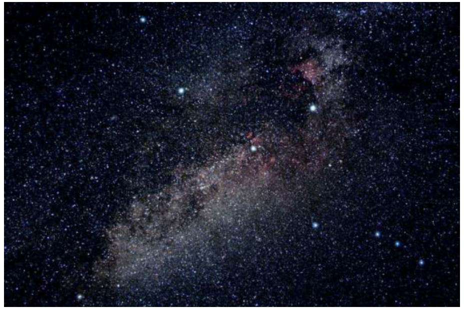
  - Apr 2014: Kepler-186f is the **first Earth-size planet** found in the **habitable zone** of a small, cool M dwarf (red dwarf star) about half the size and mass of our sun.

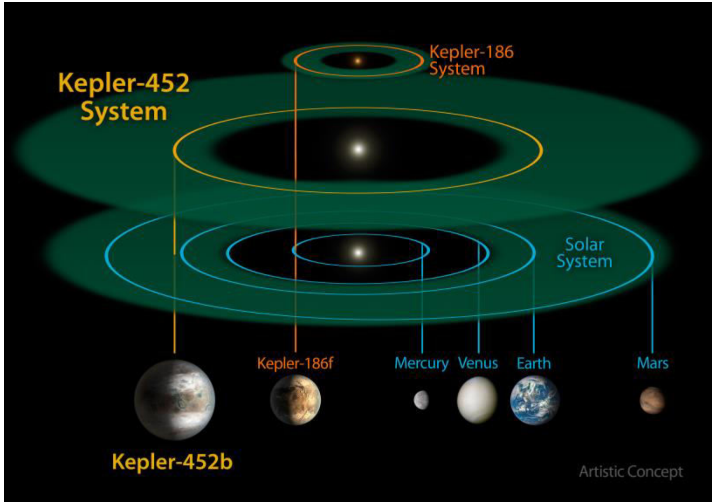
  - **July 2015**: Kepler-452b is the first **near-Earth-size world** to be found in the **habitable zone** of a star that is **similar to our Sun**. (All three!)

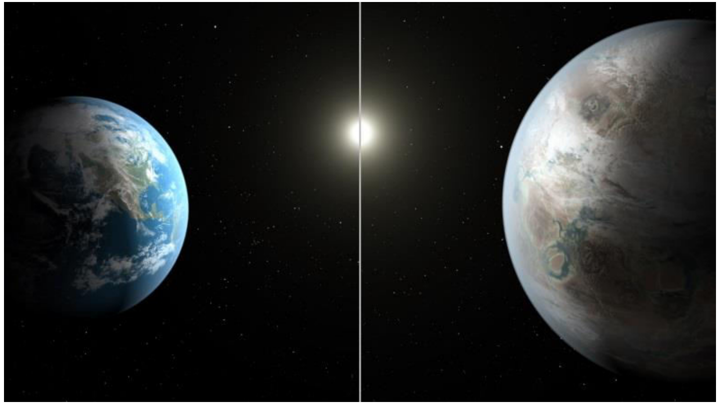


Kepler-452b:

- Found 1,400 light-years away in the constellation Cygnus, 452b is the first **near-Earth-size** planet in the **habitable zone** around a **Sun-like star**.
- 385-day orbit. Mass & composition not yet known, but small size suggests likely a **rocky** planet.
- 60% larger diameter than Earth ("**super-Earth**"), 6 billion years old → "bigger, older cousin" to Earth.



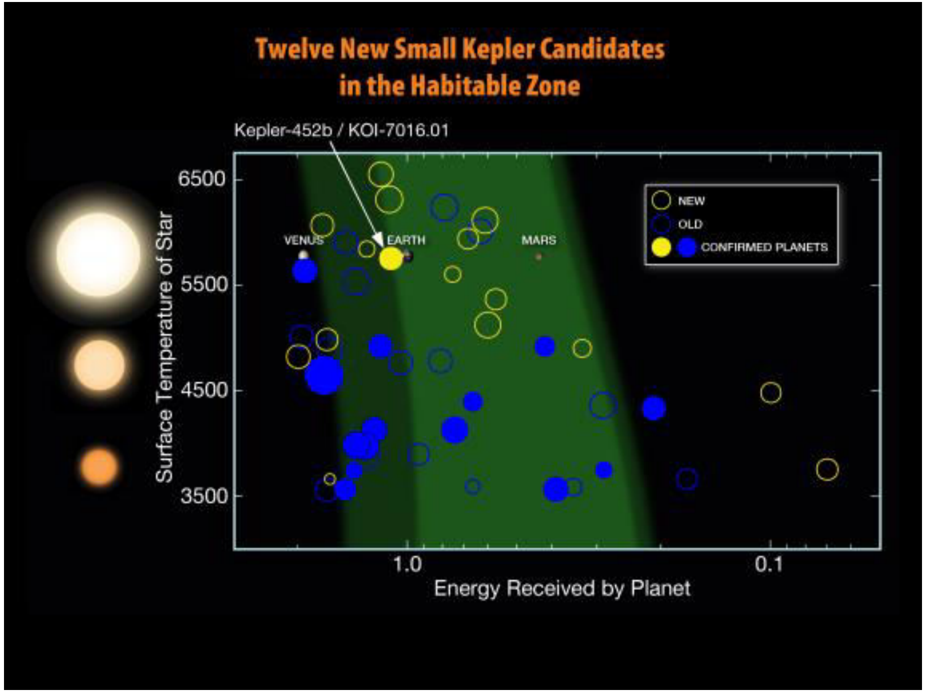




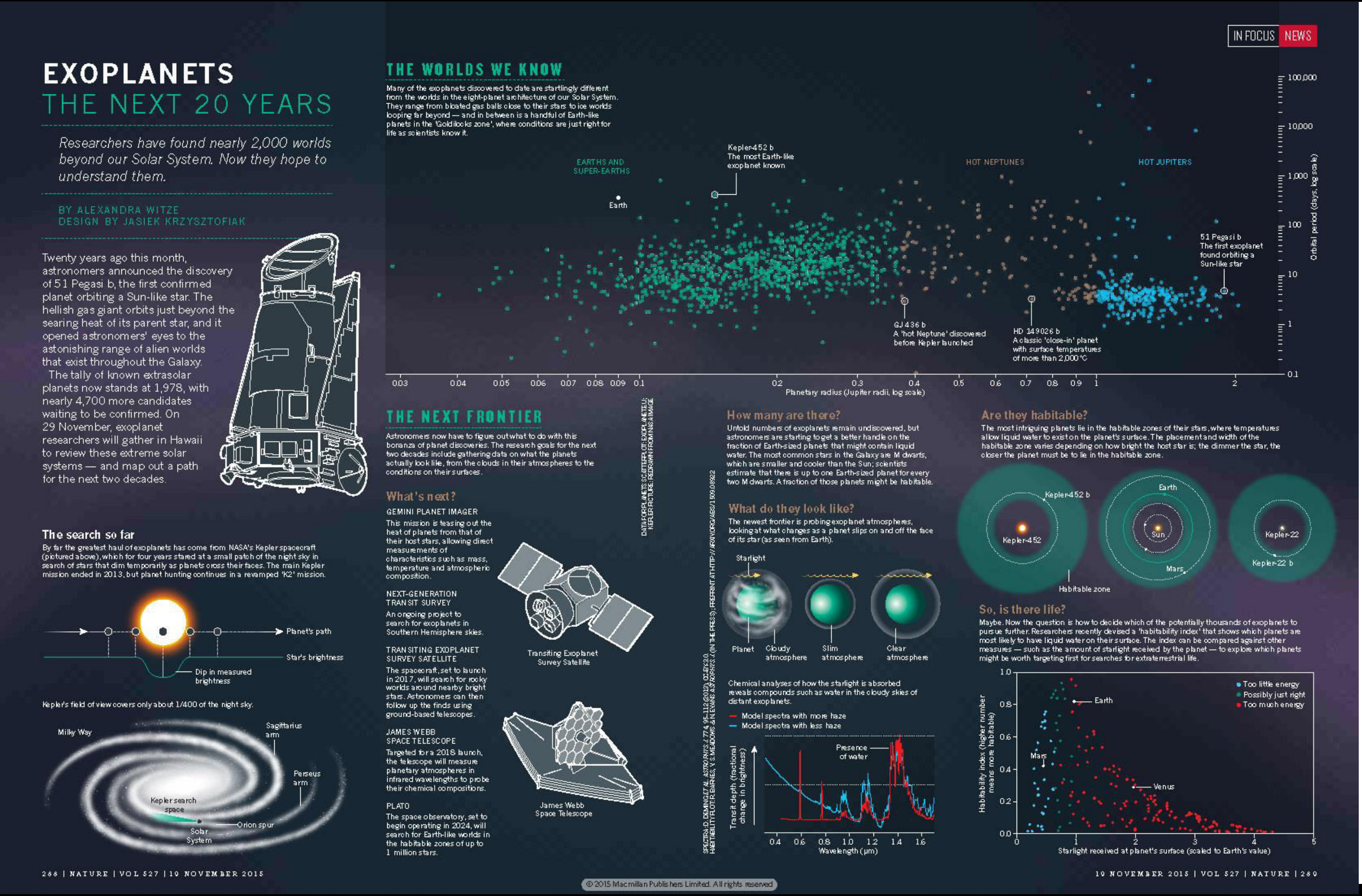
Kepler-452b:

"It's awe-inspiring to consider that this planet has spent 6 billion years in the habitable zone of its star; longer than Earth. That's substantial opportunity for life to arise, should all the necessary ingredients and conditions for life exist on this planet."

—Jon Jenkins, Kepler data analysis lead at NASA's Ames Research Center in Moffett Field, California, who led the team that discovered Kepler-452b.



Exoplanets—Summary



IN FOCUS NEWS

EXOPLANETS
THE NEXT 20 YEARS

Researchers have found nearly 2,000 worlds beyond our Solar System. Now they hope to understand them.

BY ALEXANDRA WITZE
DESIGN BY JASIEK KRZYSZTOFIAK

Twenty years ago this month, astronomers announced the discovery of 51 Pegasi b, the first confirmed planet orbiting a Sun-like star. The hellish gas giant orbits just beyond the searing heat of its parent star, and it opened astronomers' eyes to the astonishing range of alien worlds that exist throughout the Galaxy.

The tally of known extrasolar planets now stands at 1,978, with nearly 4,700 more candidates waiting to be confirmed. On 29 November, exoplanet researchers will gather in Hawaii to review these extreme solar systems — and map out a path for the next two decades.

The search so far

By far the greatest haul of exoplanets has come from NASA's Kepler spacecraft (pictured above), which for four years stared at a small patch of the night sky in search of stars that dim temporarily as planets cross their faces. The main Kepler mission ended in 2013, but planet hunting continues in a revamped 'K2' mission.

Kepler's field of view covers only about 1/400 of the night sky.

THE WORLDS WE KNOW

Many of the exoplanets discovered to date are startlingly different from the worlds in the eight-planet architecture of our Solar System. They range from bloated gas balls close to their stars to ice worlds looping far beyond — and in between is a handful of Earth-like planets in the 'Goldilocks zone', where conditions are just right for life as scientists know it.

THE NEXT FRONTIER

Astronomers now have to figure out what to do with this bonanza of planet discoveries. The research goals for the next two decades include gathering data on what the planets actually look like, from the clouds in their atmospheres to the conditions on their surfaces.

What's next?

GEMINI PLANET IMAGER
This mission is teasing out the heat of planets from that of their host stars, allowing direct measurements of characteristics such as mass, temperature and atmospheric composition.

NEXT-GENERATION TRANSIT SURVEY
An ongoing project to search for exoplanets in Southern Hemisphere skies.

TRANSITING EXOPLANET SURVEY SATELLITE
The spacecraft, set to launch in 2017, will search for rocky worlds around nearby bright stars. Astronomers can then follow up the finds using ground-based telescopes.

JAMES WEBB SPACE TELESCOPE
Targeted for a 2018 launch, the telescope will measure planetary atmospheres in infrared wavelengths to probe their chemical compositions.

PLATO
The space observatory, set to begin operating in 2024, will search for Earth-like worlds in the habitable zones of up to 1 million stars.

How many are there?

Untold numbers of exoplanets remain undiscovered, but astronomers are starting to get a better handle on the fraction of Earth-sized planets that might contain liquid water. The most common stars in the Galaxy are M dwarfs, which are smaller and cooler than the Sun; scientists estimate that there is up to one Earth-sized planet for every two M dwarfs. A fraction of those planets might be habitable.

What do they look like?

The newest frontier is probing exoplanet atmospheres, looking at what changes as a planet slips on and off the face of its star (as seen from Earth).

Chemical analyses of how the starlight is absorbed reveals compounds such as water in the cloudy skies of distant exoplanets.

Are they habitable?

The most intriguing planets lie in the habitable zones of their stars, where temperatures allow liquid water to exist on the planet's surface. The placement and width of the habitable zone varies depending on how bright the host star is; the dimmer the star, the closer the planet must be to lie in the habitable zone.

So, is there life?

Maybe. Now the question is how to decide which of the potentially thousands of exoplanets to pursue further. Researchers recently devised a 'habitability index' that shows which planets are most likely to have liquid water on their surface. The index can be compared against other measures — such as the amount of starlight received by the planet — to explore which planets might be worth targeting first for searches for extraterrestrial life.

DATA FOR PLANETS SCATTERPLOT: EXOPLANET.EU; KEPLER PICTURE: REDRAWN FROM NASA IMAGE

SPECTRA: D. DEMING ET AL. ASTROPHYS. J. 774, 95–112 (2013), CC-BY 3.0; HABITABILITY PLOT: R. BARNES, V. S. MEADOWS & N. EVANS ASTROPHYS. J. (IN THE PRESS); PREPRINT AT HTTP://ARXIV.ORG/ABS/1509.08922

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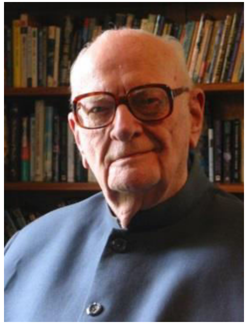
[Nature Infographic]

Exoplanet exploration is a **rapidly-developing field**.
See: intriguing exoplanets, latest news, future exoplanets, etc.

- **Brian Cox:** "Think about this:
  - There are **billions** of habitable Earth-like worlds out there in the galaxy, and yet **we are alone**.
  - There are **billions** of habitable Earth-like worlds out there in the galaxy, and **we are not alone**. There are others.
  - One of these statements is true…"

- **Arthur C. Clarke:**
  - "Sometimes I think we're alone in the universe, and sometimes I think we're not. In either case the idea is quite staggering."



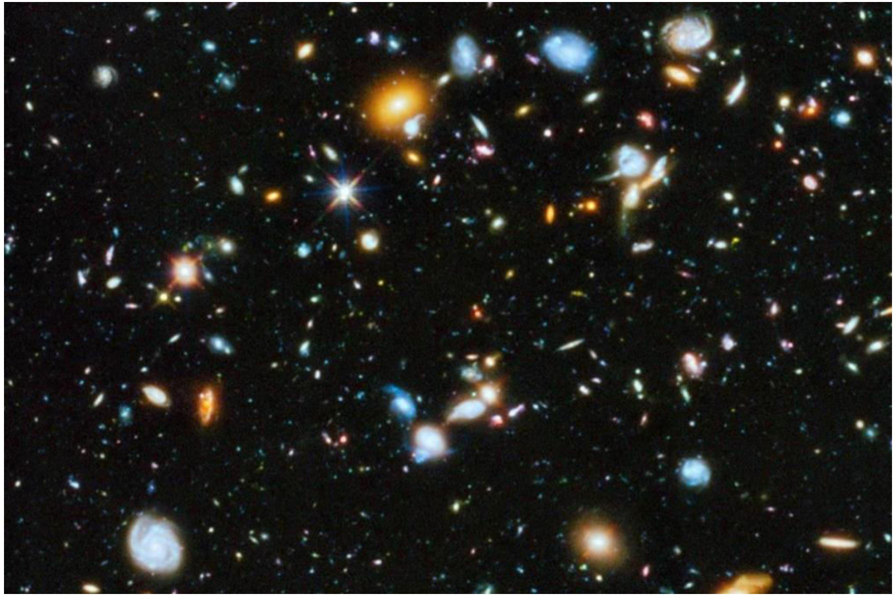
- The question "**Are We Alone**" is of ever increasing interest to scientists.

  ✓ **Why Now?** Scientists have *always* been interested in this question, but in the last few decades this interest has **dramatically intensified**:

    - We now <u>**know**</u> **there are planets out there**. (Without them, ET life is unlikely.)
    - We now have much better reasons to think that **biology might be universal**.
    - We now have sufficient **technology** to begin **looking for life**.

  ✓ "…the study of life in the universe [astrobiology] is one of the most rapidly growing fields of active scientific research…"—Bennett & Shostak (2012).

- Reason 1: Everywhere we have looked in the universe, the **laws of physics are the same**.
    - "Everywhere" means in both **space** and **time**: all across the vast space of the observable universe, and back to almost the beginning of time:



Similar galaxies sprinkled throughout space

Same chemicals in the stars, gas, and dust

Same stellar processes (e.g., supernovae)

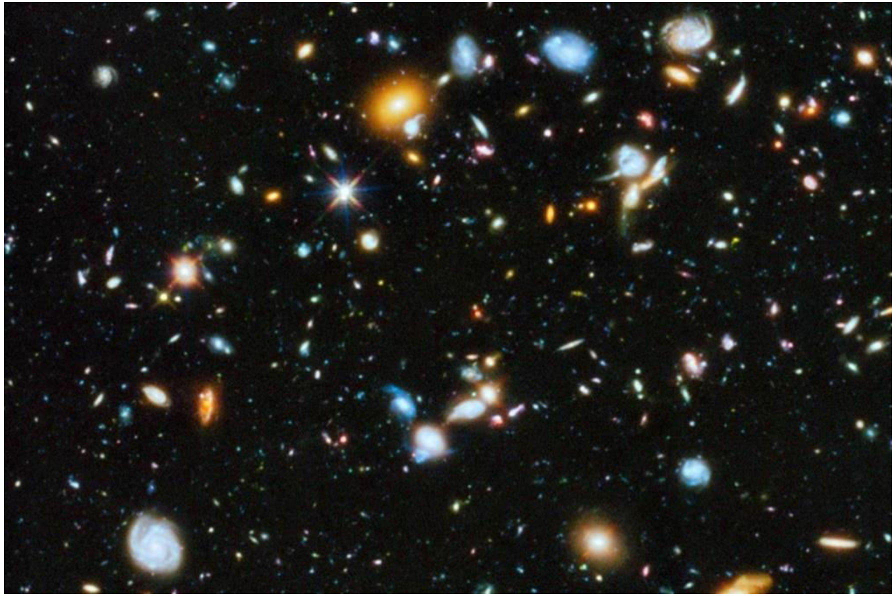
Same gravity (e.g., orbital motions)

Same electromagnetism (e.g., light)

Same thermodynamics (e.g., CMB)

Laws of physics are being tested at the LHC between 10^{-12}-10^{-6} seconds after Big Bang!

- Reason 1: Everywhere we have looked in the universe, the **laws of physics are the same**.
    - "Everywhere" means in both **space** and **time**: all across the vast space of the observable universe, and back to almost the beginning of time

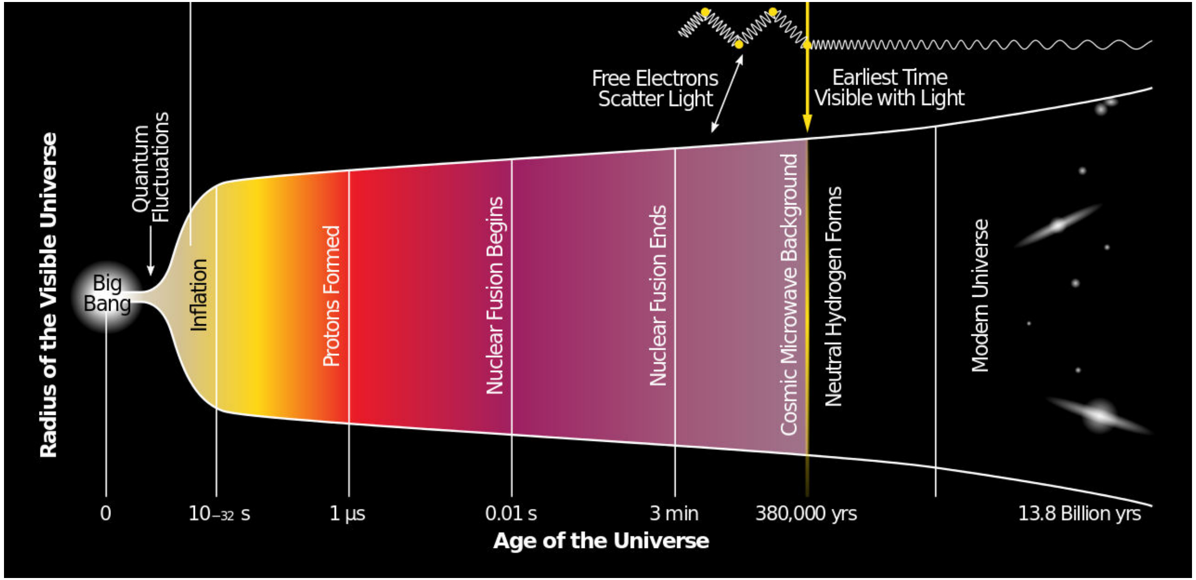


Newton's "unification of the heavens and the Earth" has been **vastly** extended:

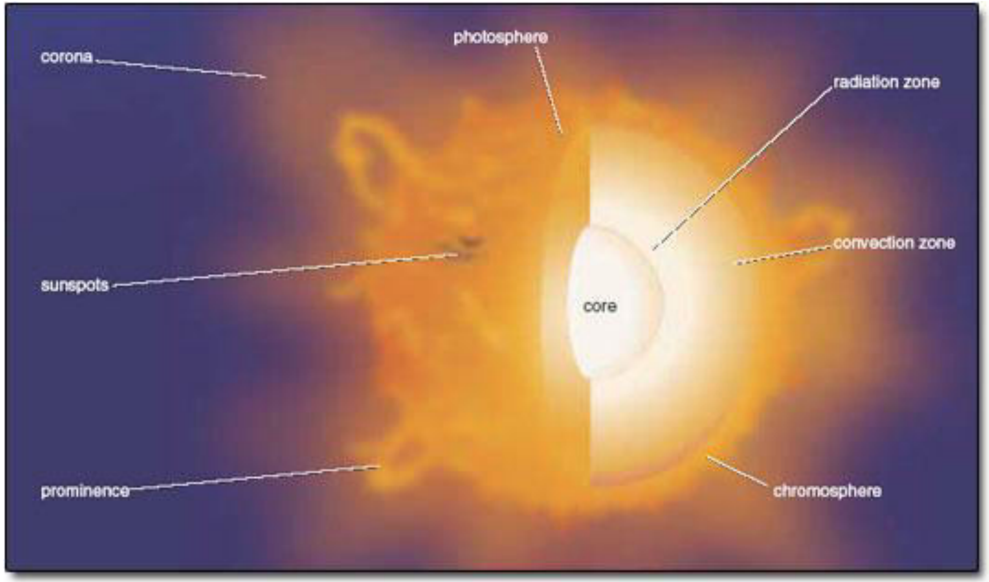
It appears that ***all*** the laws of physics we discover here on Earth (e.g., at the LHC) hold **throughout the universe** (not just the laws of motion and gravity in the Solar System)

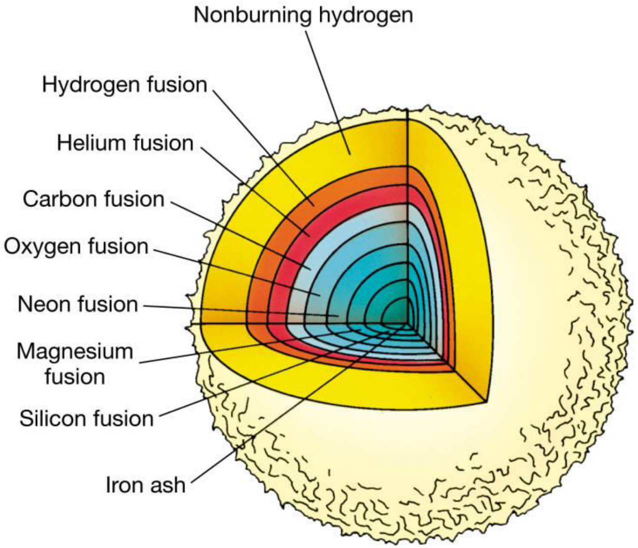
- Reason 1: Everywhere we have looked in the universe, the **laws of physics are the same**.
    - Biology is rooted in chemistry
    - Chemistry is rooted in physics
    - Thus, biology is ultimately rooted in physics. It is ultimately the laws of physics that allow (or disallow) life to emerge in a universe. (E.g.: Even **tiny** changes in certain particle masses or interaction strengths would result in **very** different universes, most of which **could not have life**. More later: "Fine Tuning" & "Anthropic Principle")
    - Thus, if the physics of our universe allowed life to emerge on the Earth, there is no reason to believe that, under similar conditions, life could not emerge on other Earth-like exoplanets orbiting Sun-like stars in their habitable zone.

- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.
    - The Big Bang created mainly **hydrogen** (75%) and **helium** (25%) through thermonuclear fusion, within the first three minutes:



- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.
  - The heavier elements up to **iron** (**carbon**, **oxygen**, **silicon**, etc., plus more helium) are forged by thermonuclear fusion in the cores of stars:





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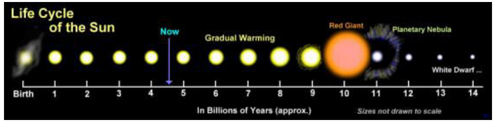
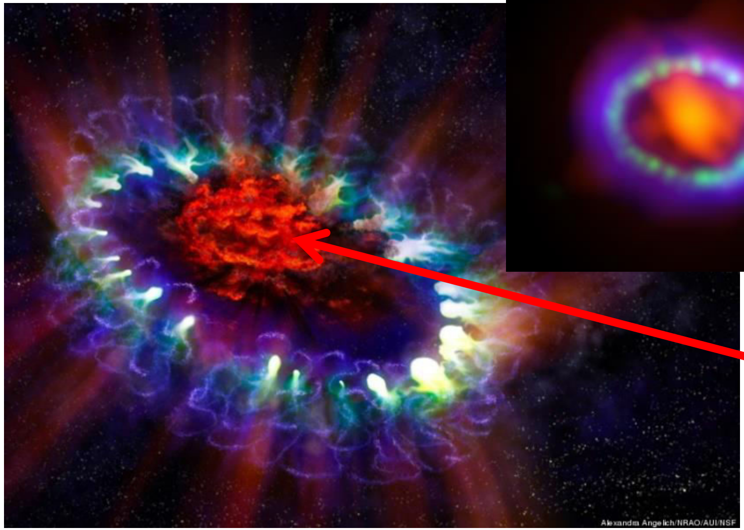
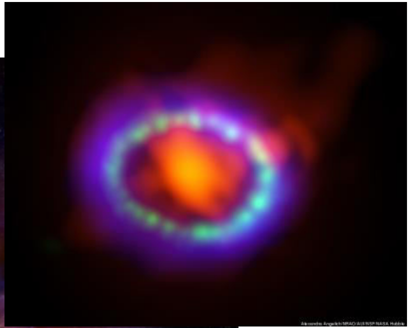


All low-to-medium mass stars (including the Sun) enter a **red giant** phase late in life. Strong stellar winds and "thermal pulses" dredge up the **carbon** and **oxygen** in the core, sloughing off 50-70% of the star's mass. About 1 in 6 are **carbon stars**, that are especially rich sources of sooty, **carbon compounds** (carbon-rich dust like graphite). [Article on Image](#).

This dust significantly enriches the mainly H & He interstellar medium, and becomes part of future generations of stars and planets.

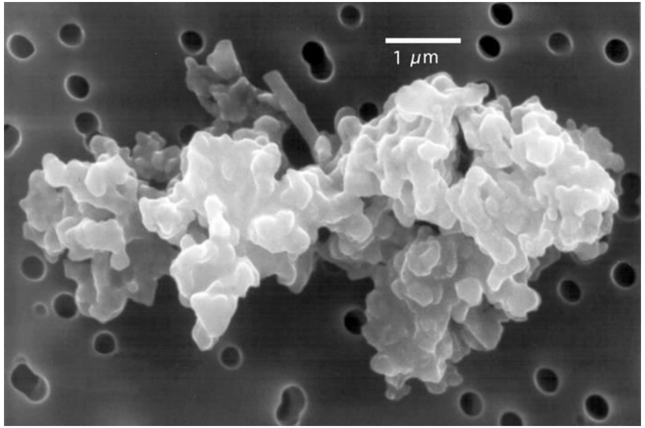
- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.
  - Elements heavier than **iron** (e.g., **uranium**) are formed in shockwave-induced nuclear fusion and rapid neutron capture in stellar supernovae:



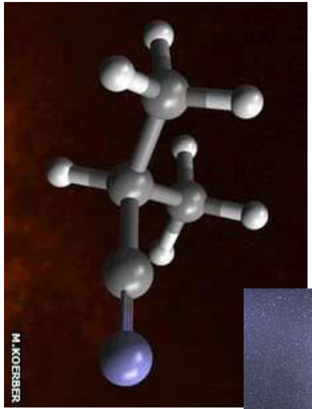


Supernova 1987A in the Large Magellanic Cloud: **First direct observation** of the long-held hypothesis that supernovas are a source of interstellar dust.

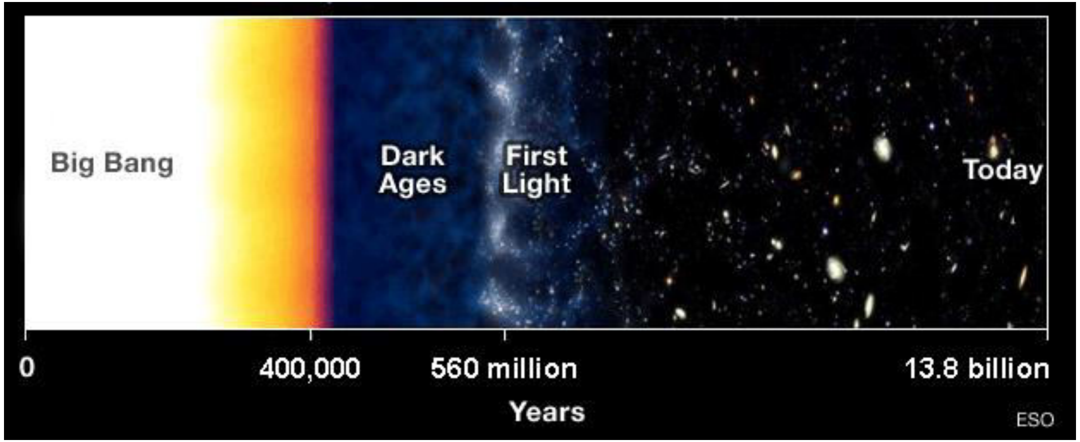
- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.
  - **Organic molecules** form in dusty interstellar clouds and rain down on planets
    - ✓ This was a **surprise**. No one expected chemical reactions in cold, diffuse gasses.
    - ✓ One idea: Nearby stars provide energy for chemical reactions on the surface of "**cosmic dust**" grains (tiny pieces of solid particles composed mainly of carbon, silicon and oxygen).
    - ✓ Another idea: Cosmic rays ionize atoms, and ions are electrostatically attracted to each other, forming more complex molecules.



- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.
    - **Organic molecules** form in dusty interstellar clouds and rain down on planets
        - ✓ **Early discoveries**: formaldehyde, methanol, and vinyl alcohol (discovered in 2001)
        - ✓ **Most complex to date** (2014): Iso-proply cyanide:
            - Branched carbon structure [like an amino acid] is closer to the complex organic molecules of life than any previous finding from interstellar space.
            - "So far we do not have the sensitivity to detect the signals from [amino acids] … **The interstellar chemistry seems to be able to form these amino acids but at the moment we lack the evidence**."



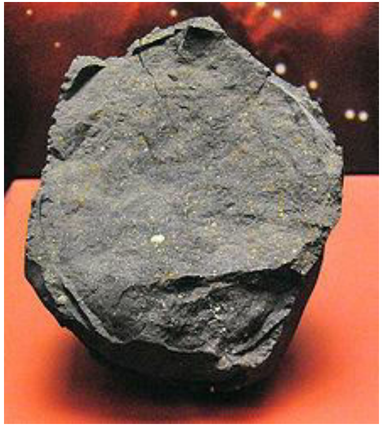
- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.
  - **Organic molecules** form in dusty interstellar clouds and rain down on planets
    - ✓ Avi Loeb (2014): has even suggested that the chemistry of life may have begun shortly after the Big Bang, during a "**habitable epoch**" when the universe was only 10-17 million years old (and there weren't any stars yet—a time called the *Dark Ages*).
    - ✓ News article.
    - ✓ Journal article.



- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.

  - **Organic molecules** form in dusty interstellar clouds and rain down on planets

    - ✓ The organic molecules (possibly including amino acids) make their way into **meteorites**, which rain down on planets.
    - ✓ Example: Murchison meteorite contains **common amino acids** such as glycine, alanine and glutamic acid as well as unusual ones like isovaline and pseudoleucine.
    - ✓ A 2010 analysis identified 14,000 molecular compounds including **70 amino acids**, with possibly **millions** of distinct organic compounds.
    - ✓ The quantity of organics from the Late Heavy Bombardment may be **comparable** to those produced by terrestrial sources.

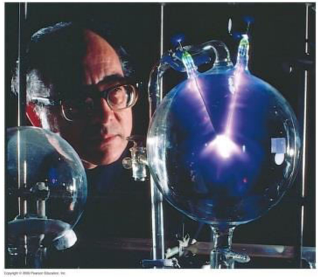


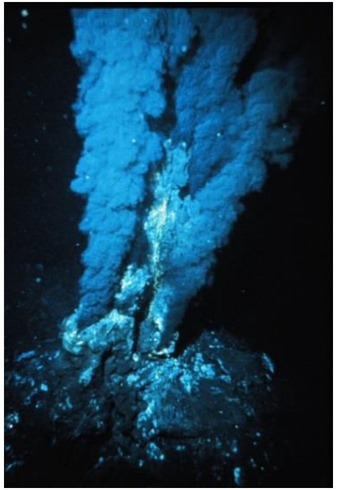
- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.

  - **Organic molecules** are created on Earth:

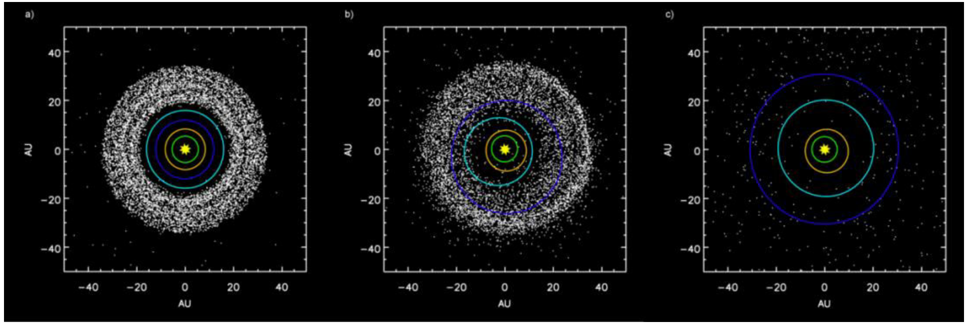
    ✓ **Energy sources**: Impact shocks, volcanic activity, UV light, lightning, etc. Recall famous Miller-Urey experiment.

    ✓ **In deep-sea hydrothermal vents**. Everett Shock (NASA astrobiology): "there is an enormous thermodynamic drive to form organic compounds, as seawater and hydrothermal fluids, which are far from equilibrium, mix and move towards a more stable state." The drive is maximised at around 100–150 °C, precisely the temperatures at which the hyperthermophilic bacteria and thermoacidophilic archaea have been found, at the base of the phylogenetic tree of life closest to the Last Universal Common Ancestor…



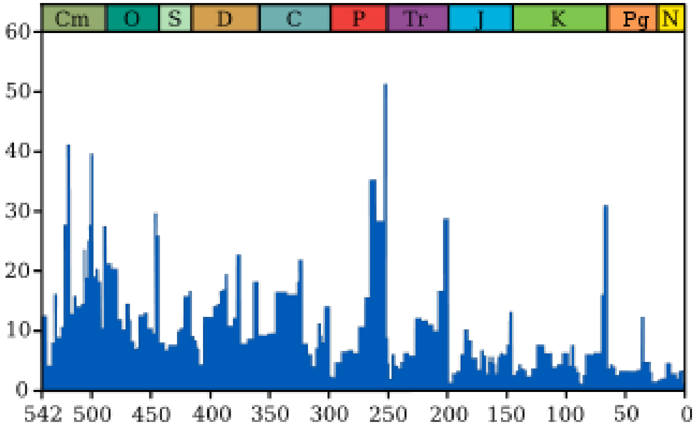


- Reason 3: Life on Earth arose **almost immediately** after the “right conditions” emerged.
    - The Late Heavy Bombardment ended about 3.8 BYA, and life emerged almost immediately after this (fossilized stromatolites date back at least to 3.5 BYA).



    - This suggests the transition from chemistry to biology is **not especially difficult**, and quite possibly life would emerge just as quickly on other worlds in similar conditions.
    - Remember: We have increasingly **plausible origins** scenarios for life on Earth: “exceedingly improbable” has shifted to “not unlikely”, to possibly even “inevitable”.

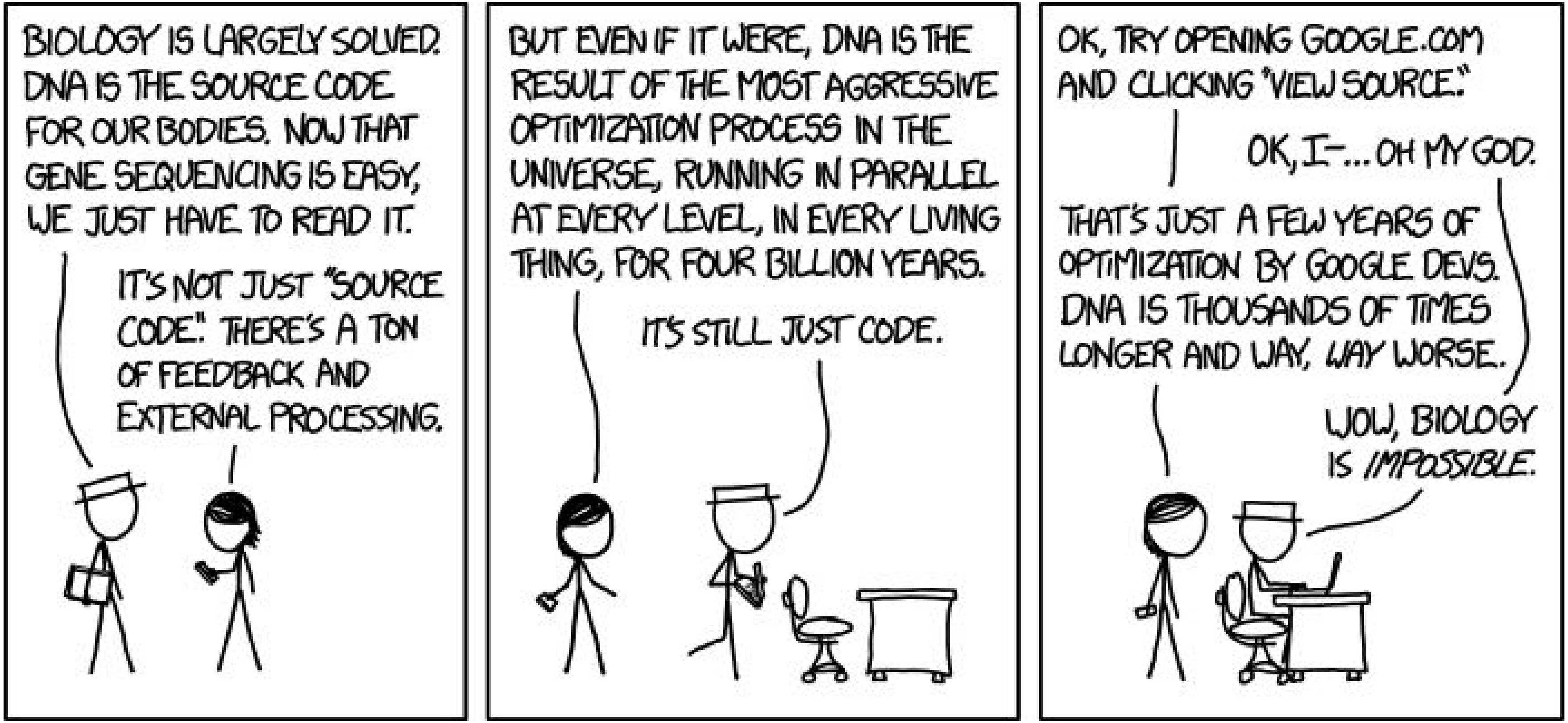
- Reason 3: Life on Earth arose **almost immediately** after the "right conditions" emerged.
    - Also, **life is robust**:
        - ✓ Life quickly "bounced back" after **five mass extinction** events in the last 500 million years (asteroid impacts, volcanism, etc.)
        - ✓ Life can exist in **surprisingly extreme conditions** (extremophiles): extraordinarily hot, acidic, alkaline, dry, high pressure (e.g., in rocks many km underground), etc..
        - ✓ Significantly increases the chances of finding life on **exoplanets**, and also elsewhere in our **Solar System**…



Life inside super dry Antarctic rock

- We have no reason to think that life ought to be rare in the universe, and several reasons to expect it **might be quite common**:
    - Everywhere we have looked in the universe, **the laws of physics are the same**
    - **Organic molecules form easily** and are widespread throughout the universe
    - **Life on Earth arose almost immediately** after the "right conditions" emerged, and can survive under a wide range of extreme conditions (**extremophiles**)

- Videos worth watching:
    - Jack Szostak (Nobel laureate, Harvard): The Origin of Life on Earth (and implications for ET life). Simplified version (to bypass the unfortunate anti-creationist messaging at the beginning, start at 2:39). Trying to create life in the lab. (See also Craig Venter.)
    - Robert Hazen (Carnegie Institution): The Emergence of Life on Earth. Mentions Deep Carbon Observatory at the end. See also this article and this video (rocks & life).


BIOLOGY IS LARGELY SOLVED. DNA IS THE SOURCE CODE FOR OUR BODIES. NOW THAT GENE SEQUENCING IS EASY, WE JUST HAVE TO READ IT.
IT'S NOT JUST "SOURCE CODE." THERE'S A TON OF FEEDBACK AND EXTERNAL PROCESSING.
BUT EVEN IF IT WERE, DNA IS THE RESULT OF THE MOST AGGRESSIVE OPTIMIZATION PROCESS IN THE UNIVERSE, RUNNING IN PARALLEL AT EVERY LEVEL, IN EVERY LIVING THING, FOR FOUR BILLION YEARS.
IT'S STILL JUST CODE.
OK, TRY OPENING GOOGLE.COM AND CLICKING "VIEW SOURCE."
OK, I—... OH MY GOD.
THAT'S JUST A FEW YEARS OF OPTIMIZATION BY GOOGLE DEVS. DNA IS THOUSANDS OF TIMES LONGER AND WAY, WAY WORSE.
WOW, BIOLOGY IS *IMPOSSIBLE*.

Technology

- The question “**Are We Alone**” is of ever increasing interest to scientists.

  ✓ **Why Now?** Scientists have *always* been interested in this question, but in the last few decades this interest has **dramatically intensified**:

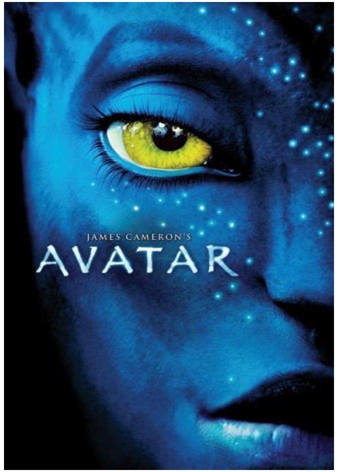
  - We now <u>**know**</u> **there are planets out there**. (Without them, ET life is unlikely.)
  - We now have much better reasons to think that **biology might be universal**.
  - We now have sufficient **technology** to begin **looking for life** (more later…)

  ✓ “…the study of life in the universe [astrobiology] is one of the most rapidly growing fields of active scientific research…”—Bennett & Shostak (2012).

Where Should We Look?

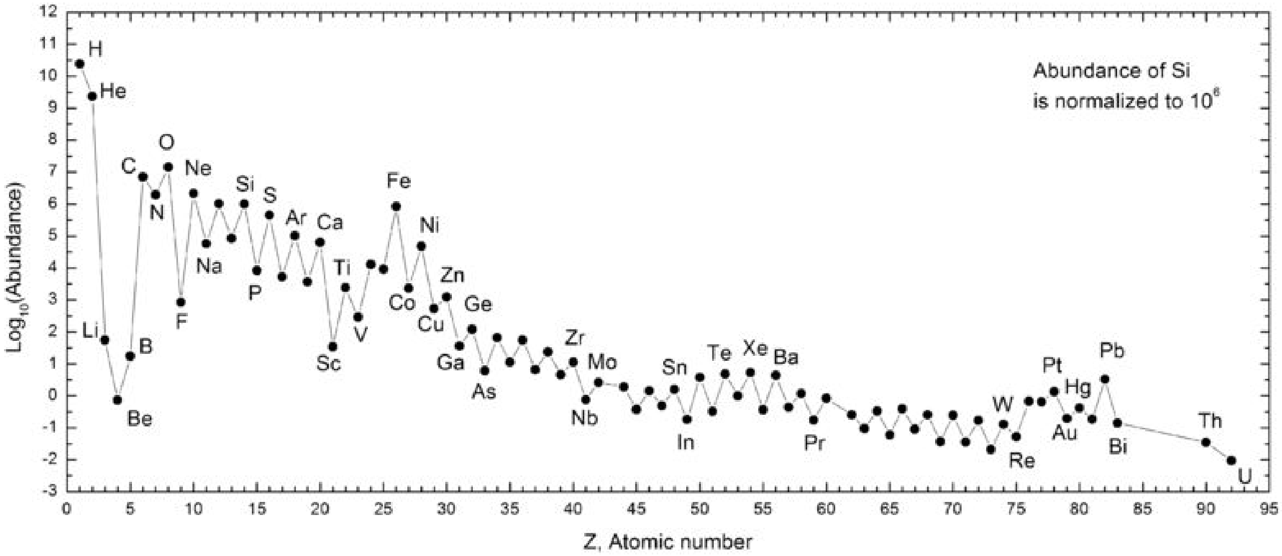
- Where should we look?
  - ✓ On **Earth**: Understand full range of "**right conditions**" for life on Earth [**extremophiles**]
  - ✓ On **planets** and moons in our own Solar System [**robot space probe technology**]
  - ✓ On **planets** orbiting other stars [**telescope technology**]
  - ✓ In the "**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"!



"Right Conditions"

- **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



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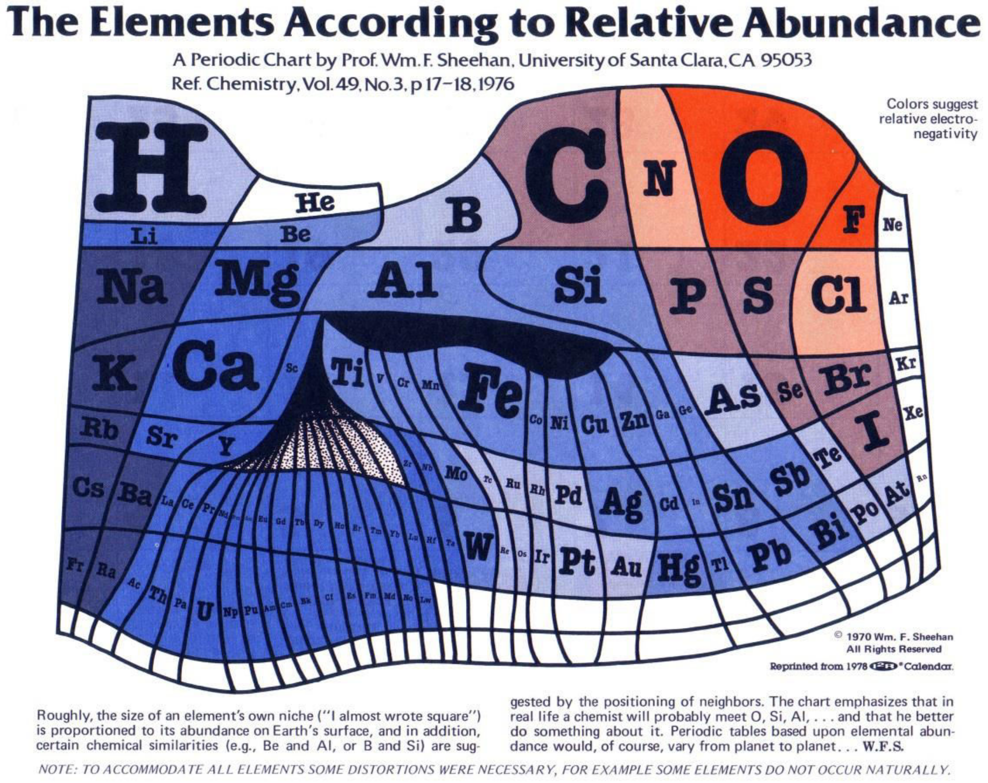


Relative abundances of elements on **Earth's surface**

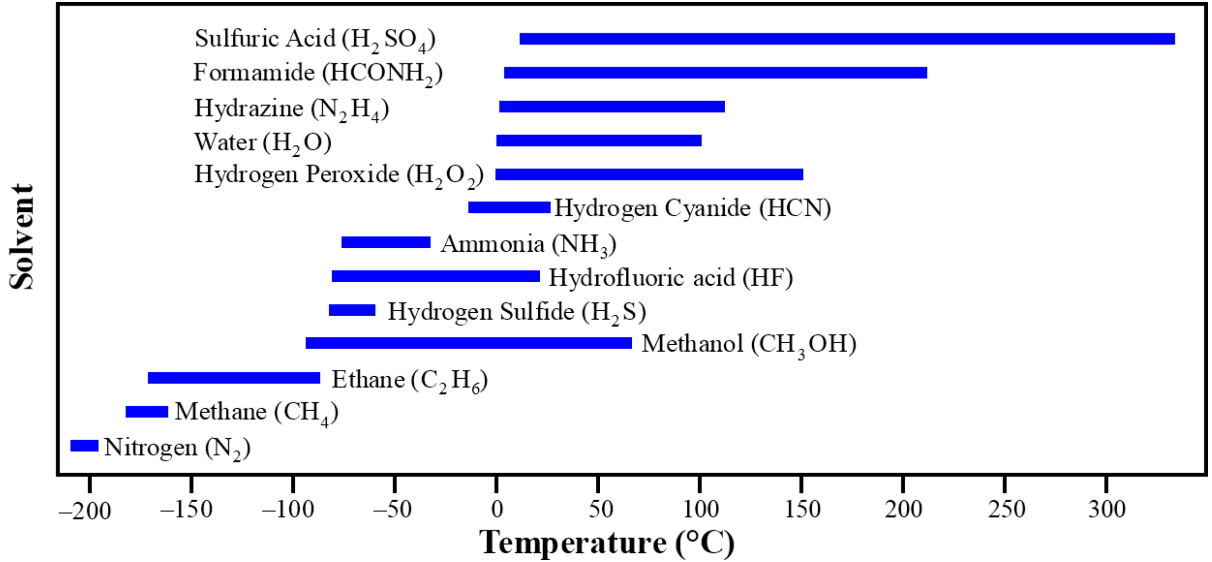
Recall: **H, O, C, N** make up 96% of the mass of living organisms

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**)

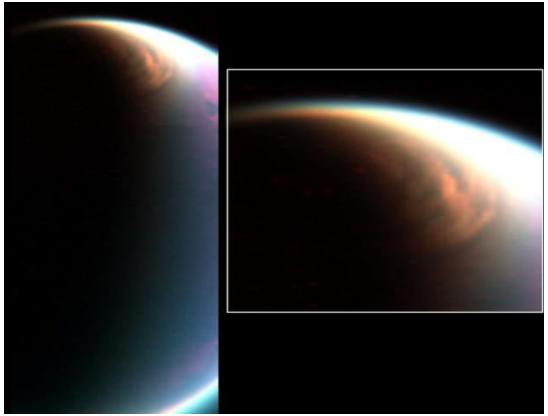
- **Solvent (liquid or gas)** [needed to facilitate chemical mixing and interactions]:
  - ✓ **Liquid**:
    - Apparently, **all** life on Earth **requires liquid water**, e.g., human = sack of seawater
    - Water needed to: (1) **dissolve** organic & inorganic molecules, making them available for chemical 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

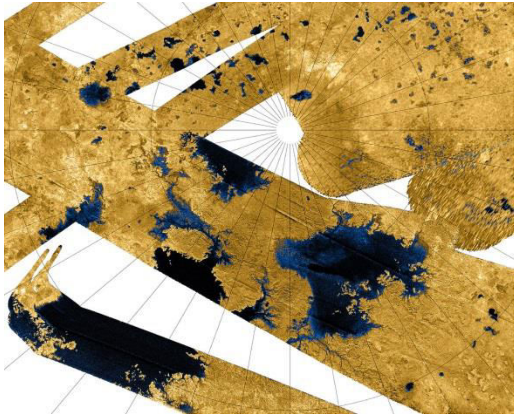
- **Solvent (liquid or gas)** [needed to facilitate chemical mixing and interactions]:
  - ✓ **Liquid**:



← 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)





<u>Titan</u> (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?

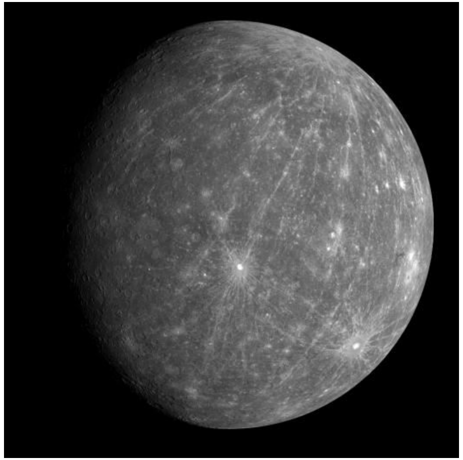
- **Free Energy** [needed to fuel metabolism and allow low entropy structures to form]:
  - ✓ **Light energy** for photosynthesis (e.g., from a nearby star; some deep-sea bacteria seem to get energy from the infrared and visible light emitted by molten volcanic rock!)
  - ✓ **Chemical energy** for chemosynthesis (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)

Europa (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…

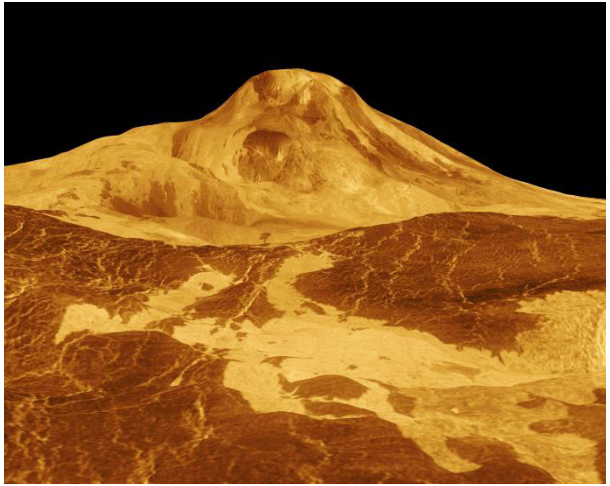
- Moon? Mercury?
  - Small → core has cooled → no volcanism (or tectonics) → no fresh source of atmosphere (outgassing); gravity so weak that any past atmosphere has escaped into space → super hot in the Sun, super cold in the shade
  - Have some water ice at bottoms of polar craters (and the Moon has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

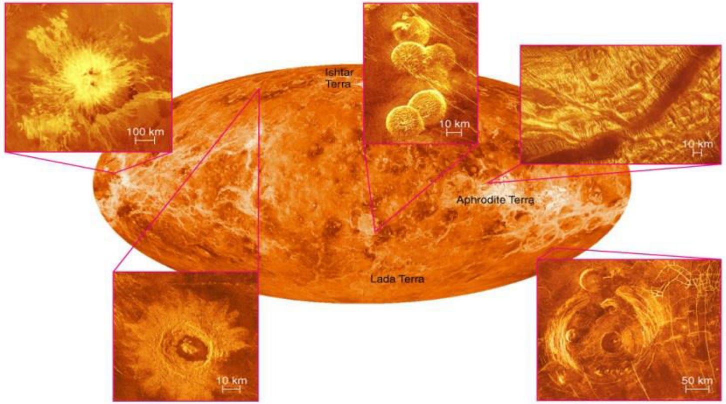


- Venus?

  - **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?





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- 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).

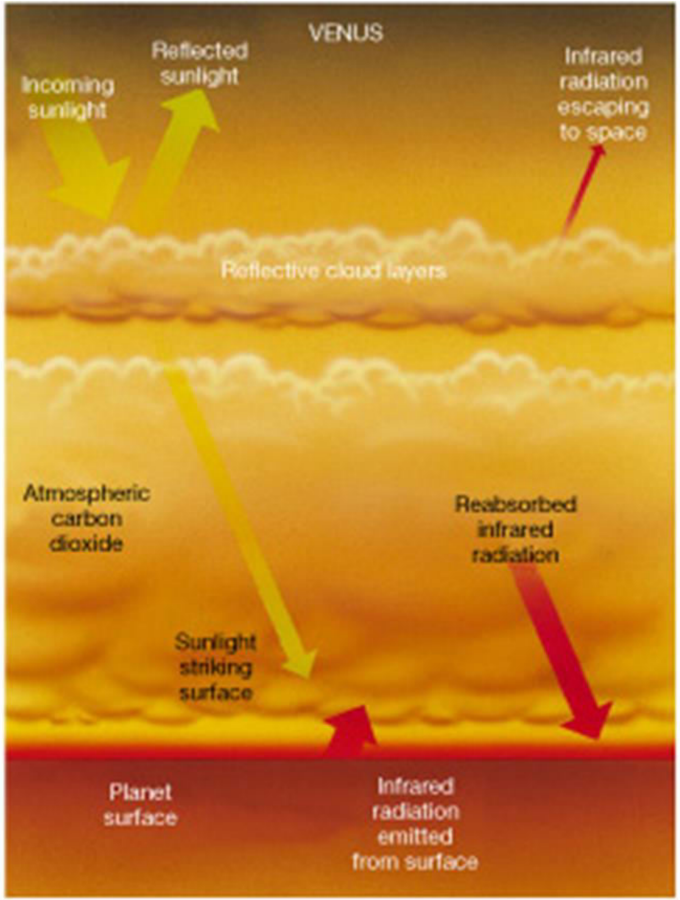
Venus: a bit further from Sun → *warmer*

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

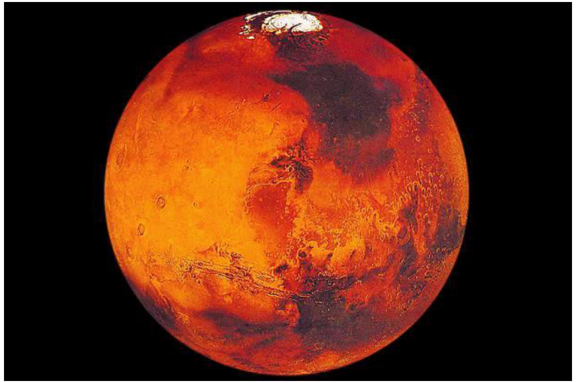
Oceans evaporate, H_2O photo-dissociates. H → space; O → chemically bound up in rocks.

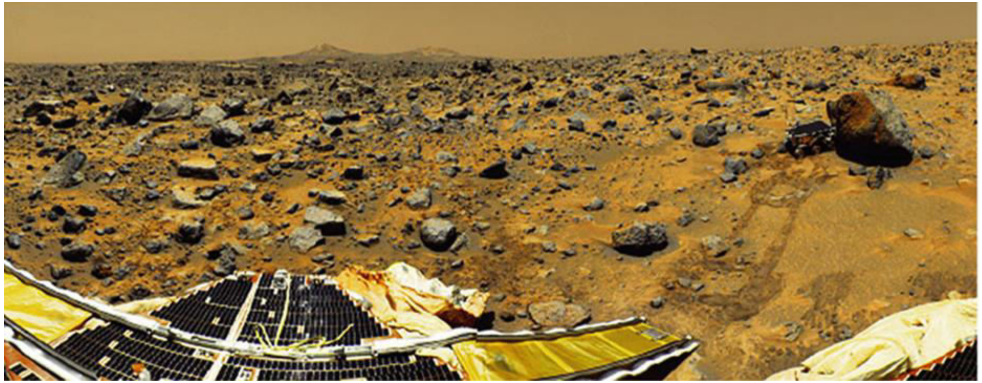
Left with lots of CO_2, no H_2O. Runaway greenhouse effect!

- 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



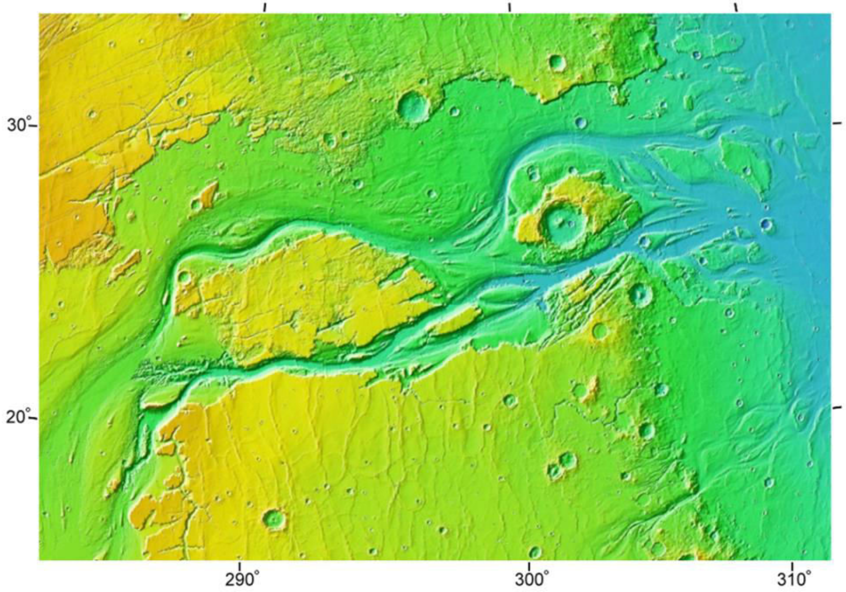
- Mars?
  - Went in opposite direction as Venus:
    - ✓ Evidently **started warm and wet**, with a fairly thick atmosphere (> 2-3 BYA). Volcanic outgassing estimates suggest early atmosphere denser than Earth's today, and enough water to fill planet-wide oceans 10s to 100s of meters deep
    - ✓ …but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

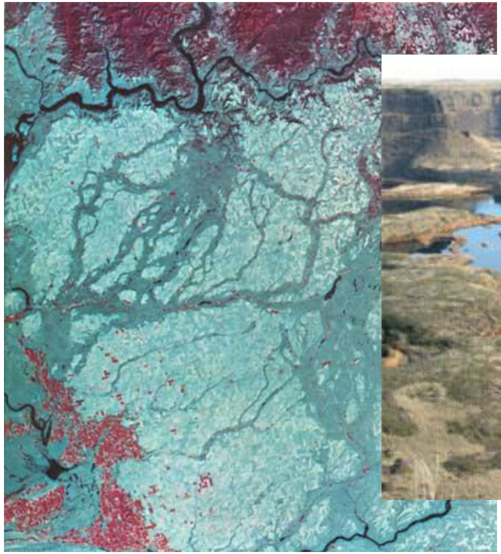




- Mars?
  - **Why?** Basic physics: Mars is half the diameter of Earth → **one-quarter** the surface area, but only **one-eighth** the volume → **twice** the surface-to-volume ratio:
    - ✓ **Lost its internal heat** energy quickly → lost further volcanic outgassing AND lost protective magnetic field. 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 $-143\ ^\circ\mathrm{C}$ to $+35\ ^\circ\mathrm{C}$, average $-63\ ^\circ\mathrm{C}$.

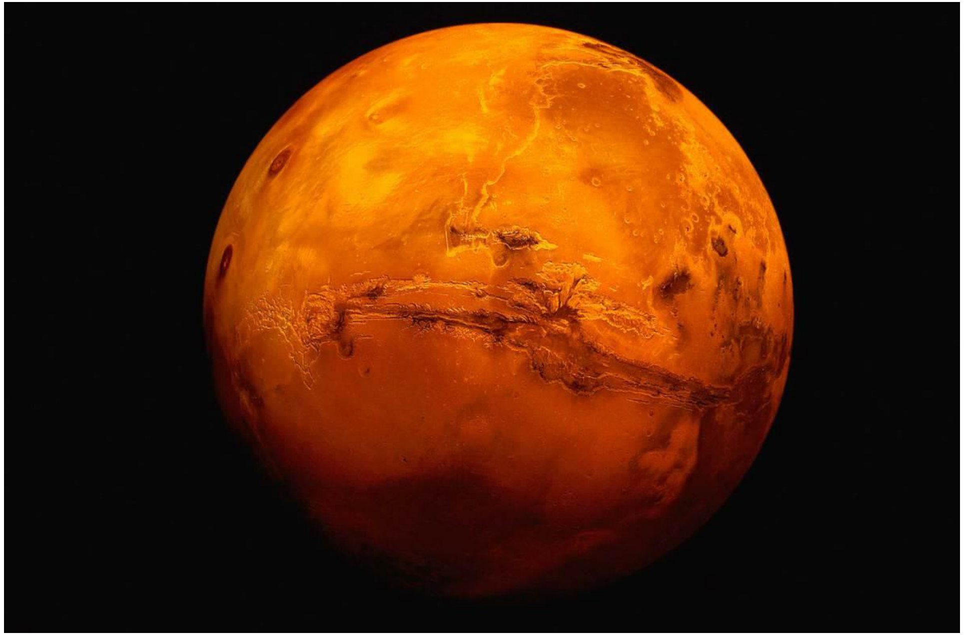
- Evidence of past water on Mars:

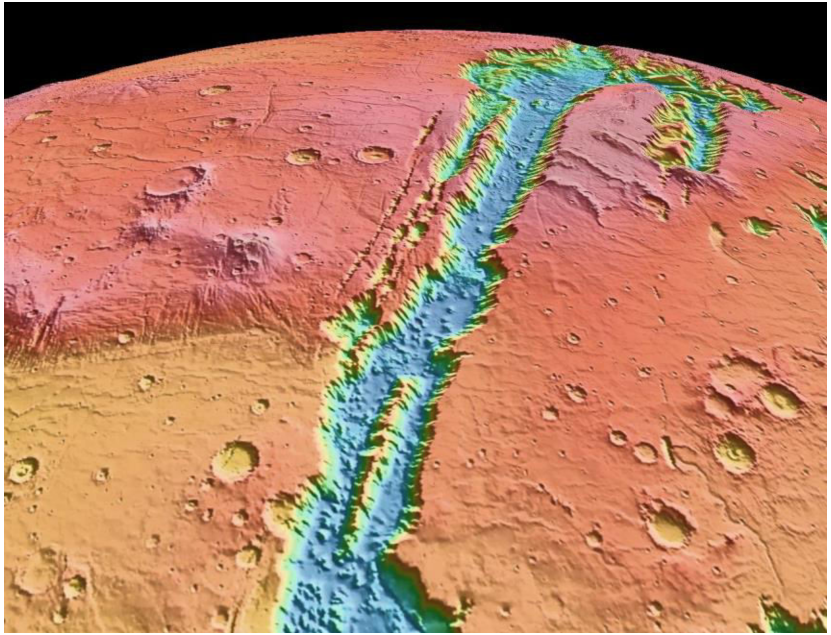




Kasei Valles outflow channel → catastrophic flooding ~ 3 BYA, comparable to largest ever floods on Earth ("scablands"). Some outflow channels on Mars are as recent as 10s MYA (!)

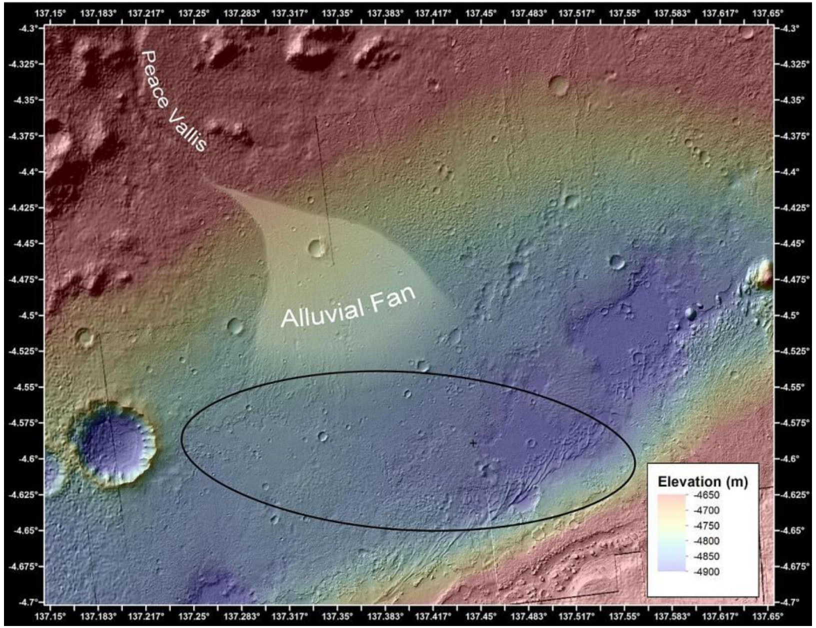
- Evidence of past water on Mars:

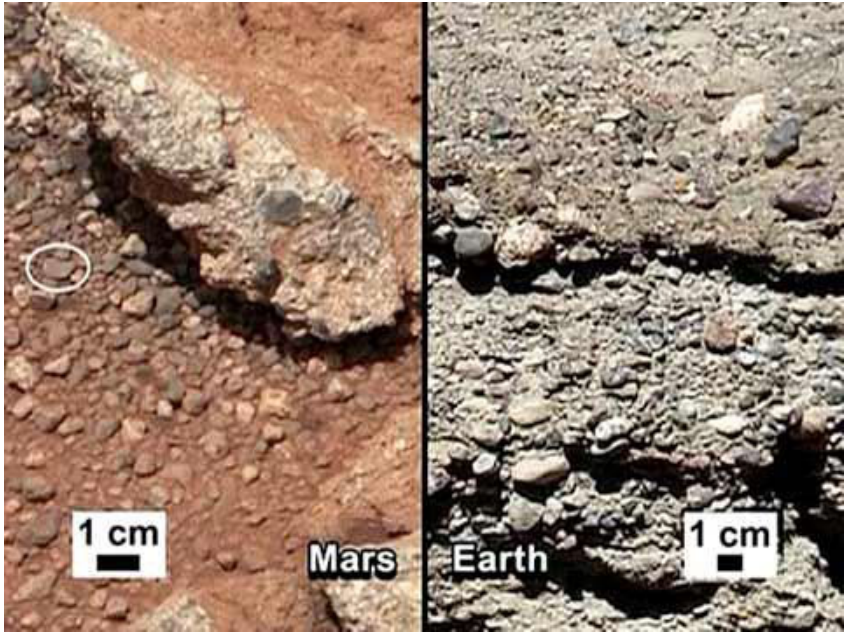




Valles Marineris is long and deep: Large tectonic crack? Widened by erosion? Flow channels?

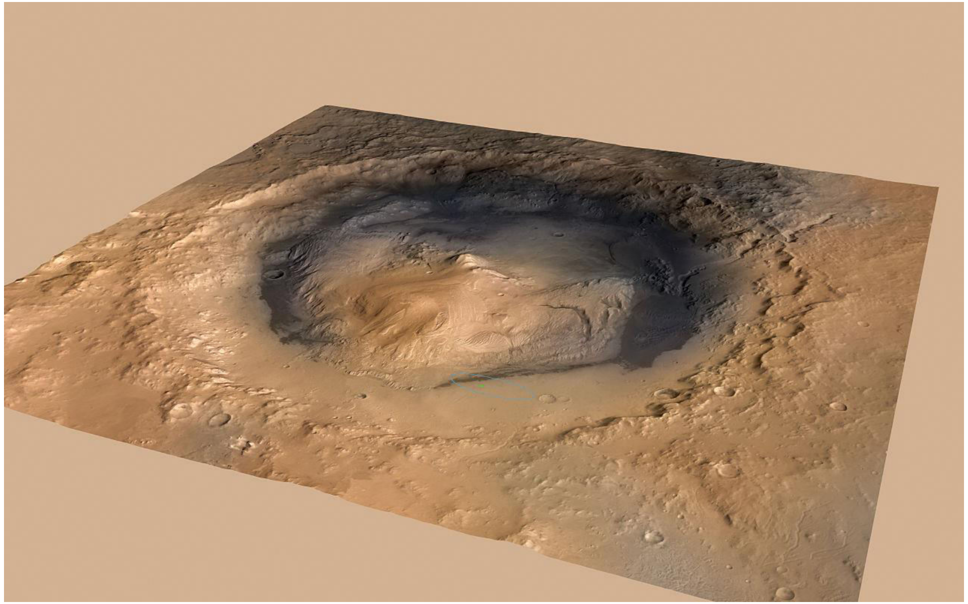
- Evidence of past water on Mars:

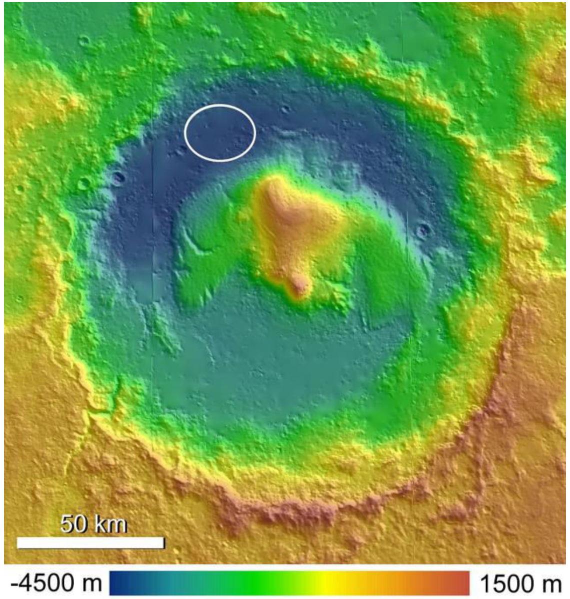




Curiosity rover found ancient river bed. Analysis showed the pebbles were formed in a stream that flowed at walking pace and was ankle to hip-deep

- Evidence of past water on Mars:

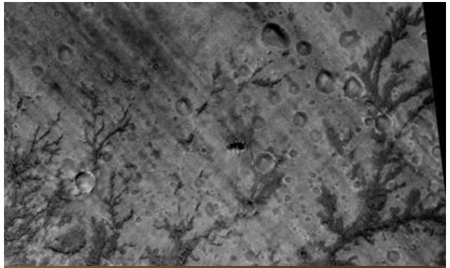


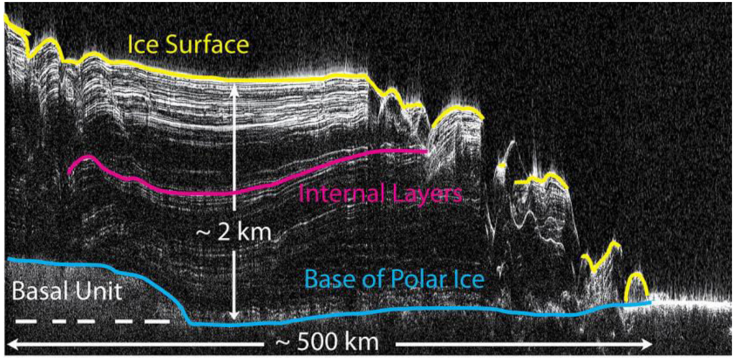


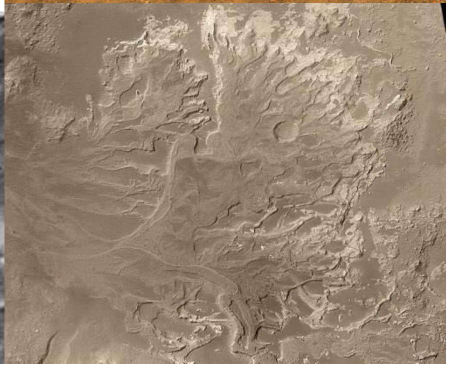
Curiosity rover found that Gale Crater contained an ancient (3.3-3.8 BYA) freshwater lake that could have been a hospitable environment for microbial life.

Life in the Solar System?

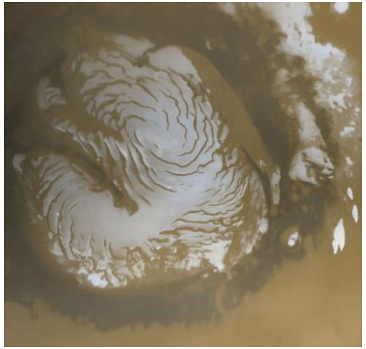
- Past water:
  - **Sensing technology**: Orbital imaging & remote sensing (spectroscopic, radar, etc.), and surface landers and rovers.
  - **Evidence for:** Enormous outflow channels, ancient river valley networks, deltas, and lake beds; and the detection of surface rocks and minerals that could only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

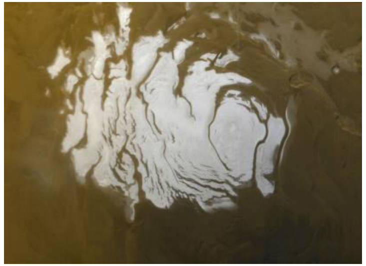






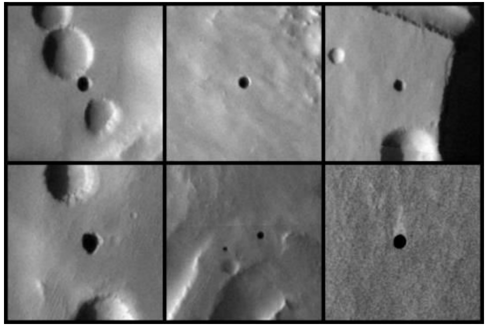
- Present water:
    - **Known:** Almost entirely in the form of ice in the shallow subsurface, and in the polar ice caps. South cap is permanently covered by about 8 m of CO_2 ice, North cap is covered by 1 m of CO_2 ice in the Northern winter only. If the known water ice were melted, it would be enough 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.

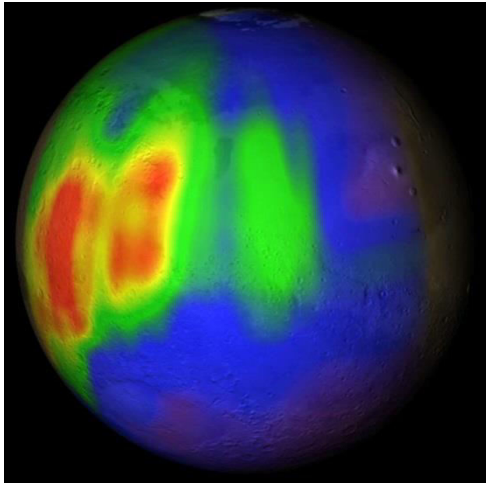




- Life on Mars?
  - **Past:**
    - ✓ Curiosity soil analysis reveals that ancient Mars had the **right chemistry to support living microbes**: S, N, O, C, Phosphorus (recall ADP, ATP), and clay minerals.
    - ✓ Curiosity also revealed evidence for **organic molecules** (e.g., C & H) (complicated by 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.

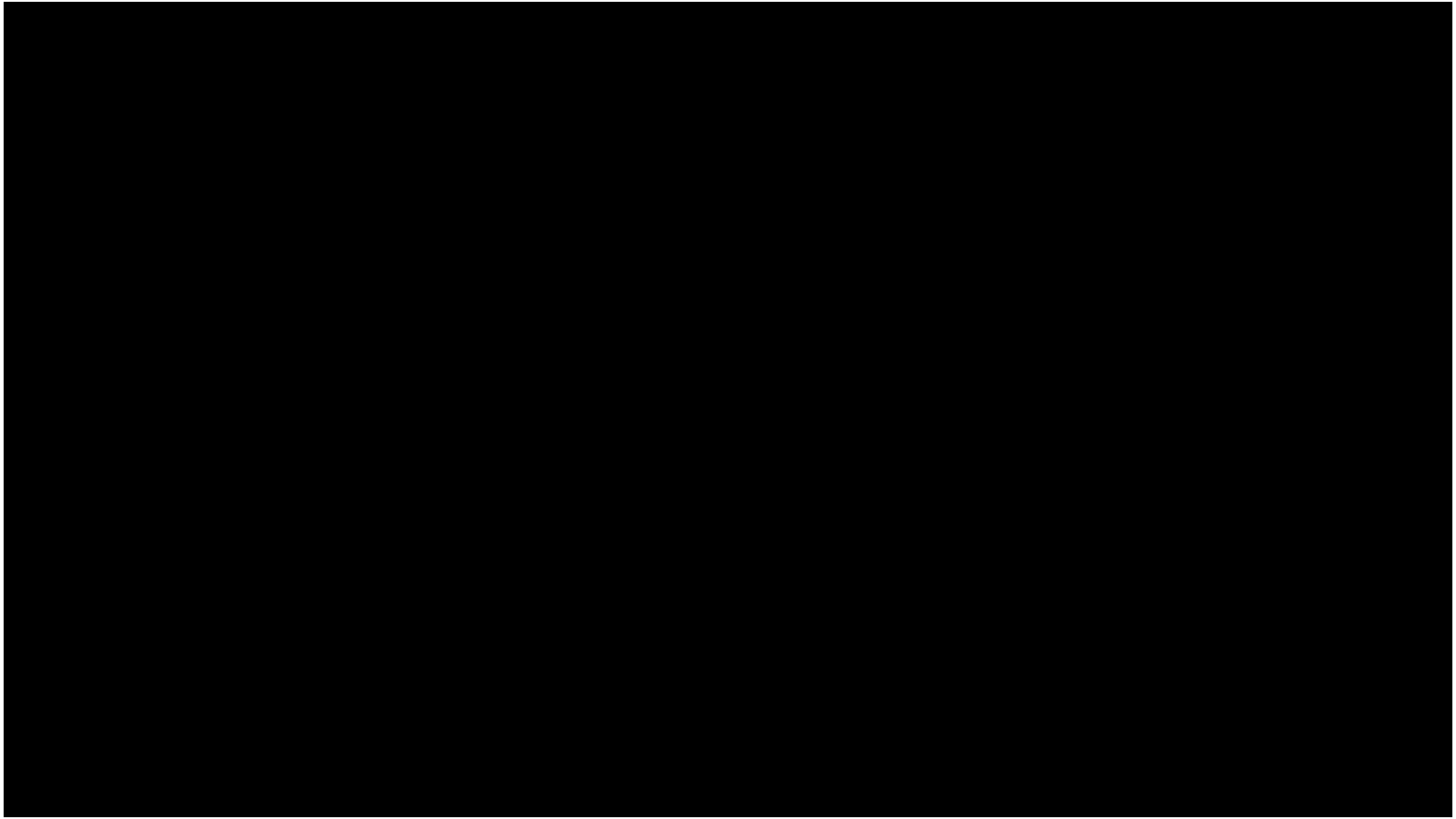
- Life on Mars?
  - **Present:**
    - ✓ The most likely place to find present life is **below the ground**, safe from intense UV & cosmic rays, and warm enough for possible liquid water. Image: cave skylights (scientists really want a sample-return from here!)
    - ✓ Curiosity *seems* to have found 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…



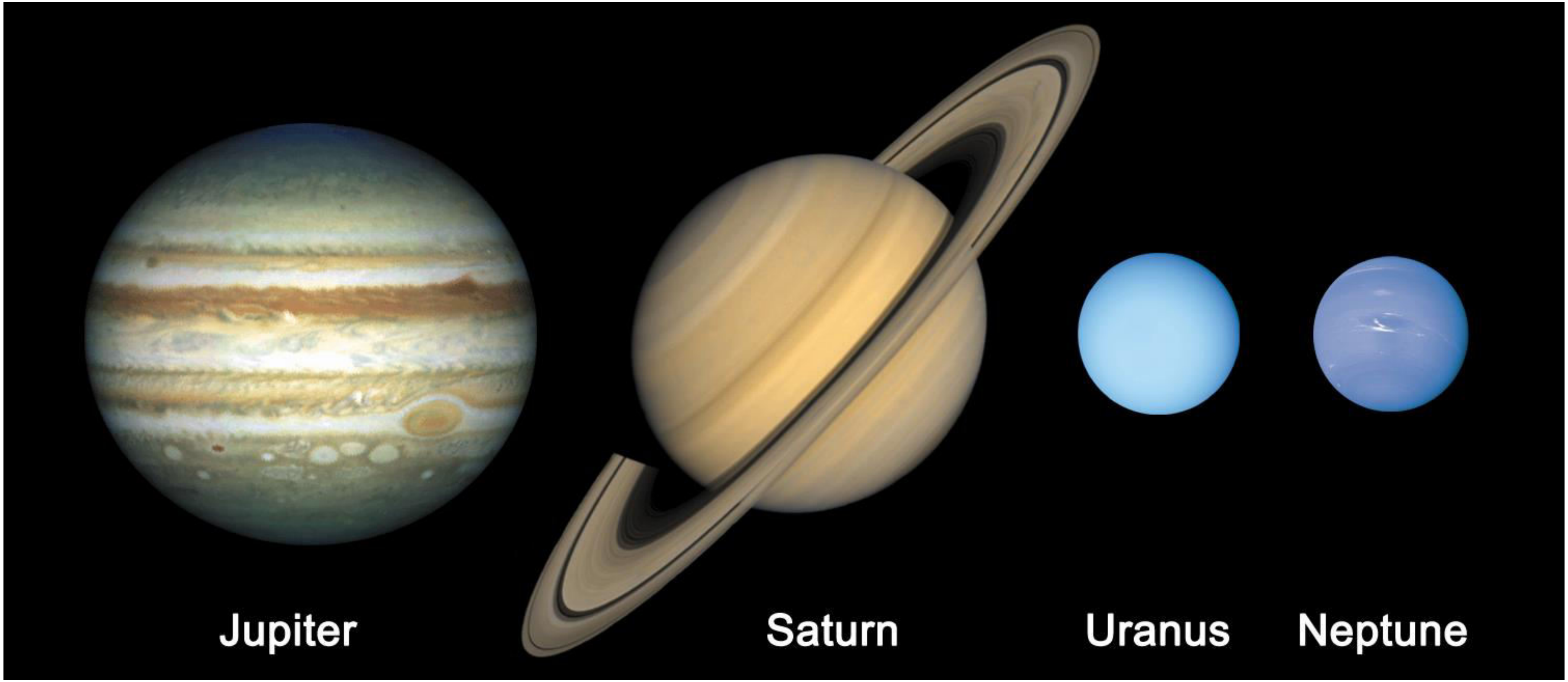


- Life on Mars?
  - **Future plans:** More rovers, drilling down, sample return?
    The **technology** is amazing, but it’s not easy!

Life in the Solar System?



- Gas Giants?



- Gas Giants?

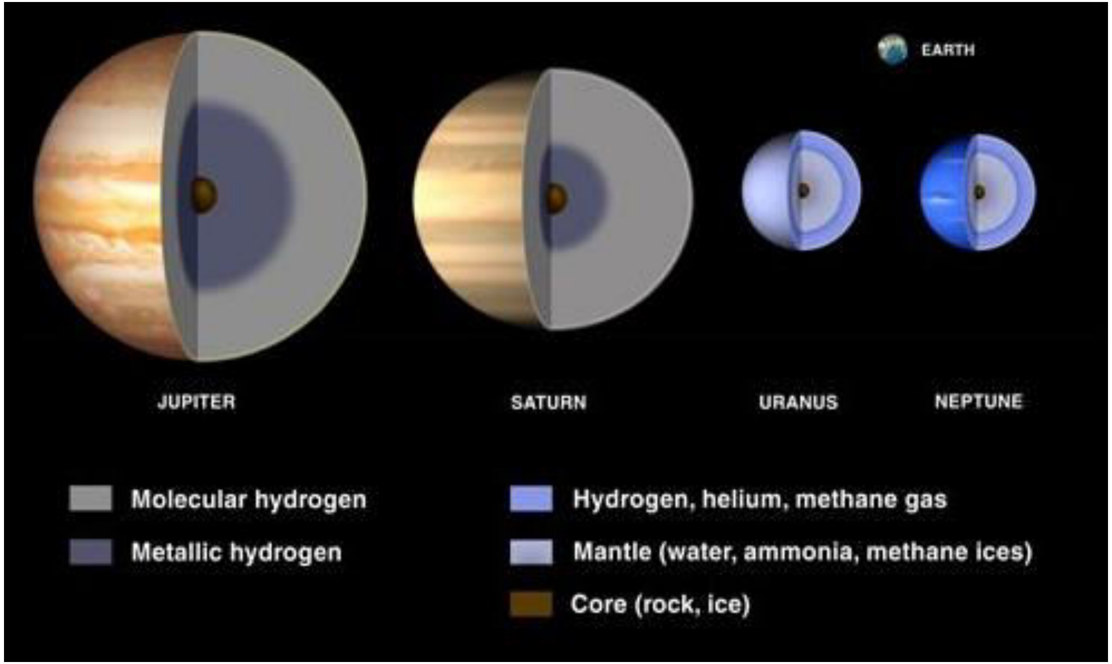
  - Made of hydrogen, helium, and hydrocarbons like water, methane, ammonia

<u>Jupiter & Saturn</u>:

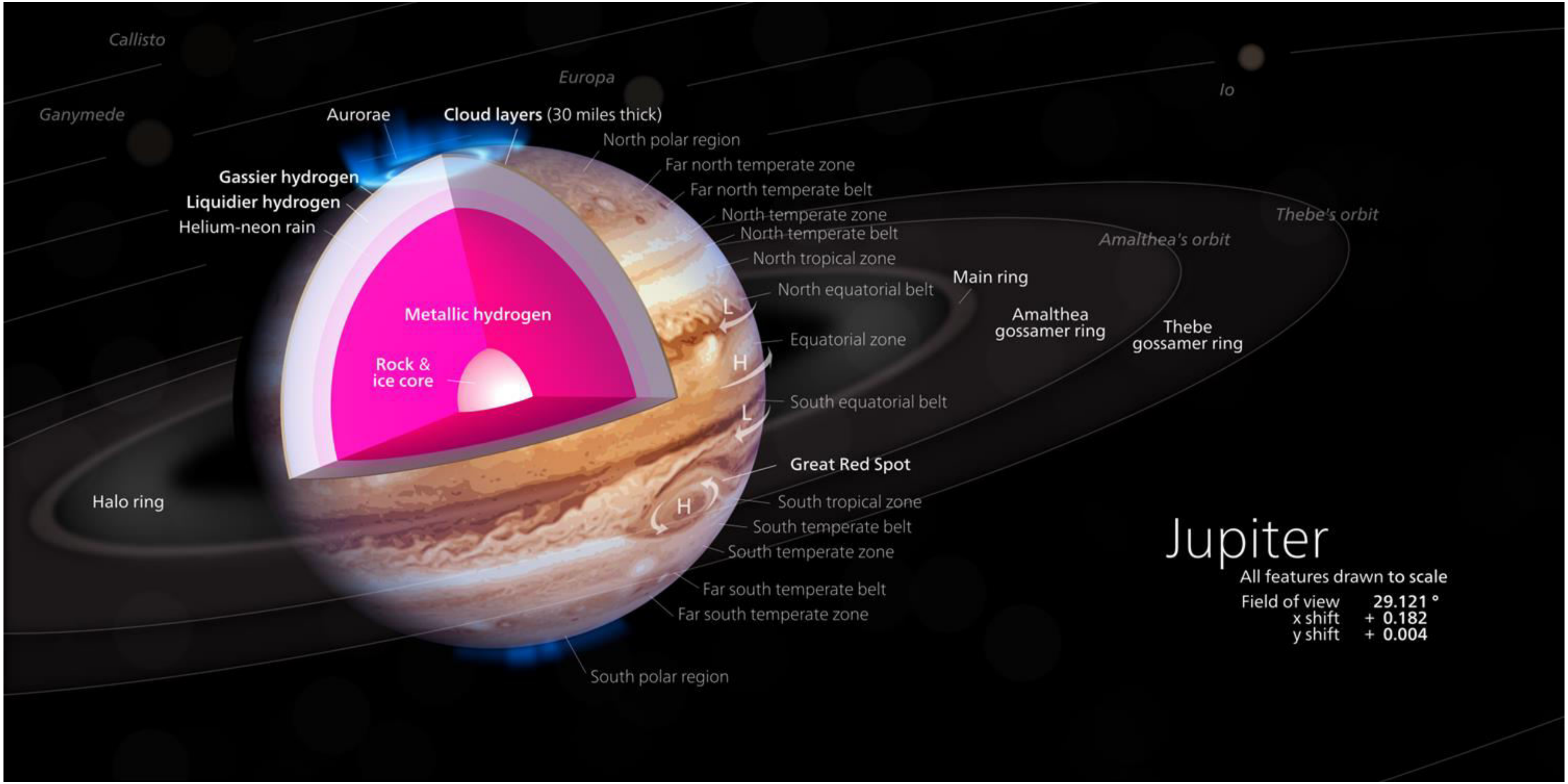
- Gas → liquid → metallic hydrogen (extreme pressure and temperature) → core of rock/metal/ hydrocarbons

<u>Uranus & Neptune</u>:

- Gas → hydrocarbons → core of rock/metal

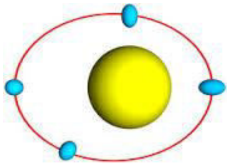


Life in the Solar System?

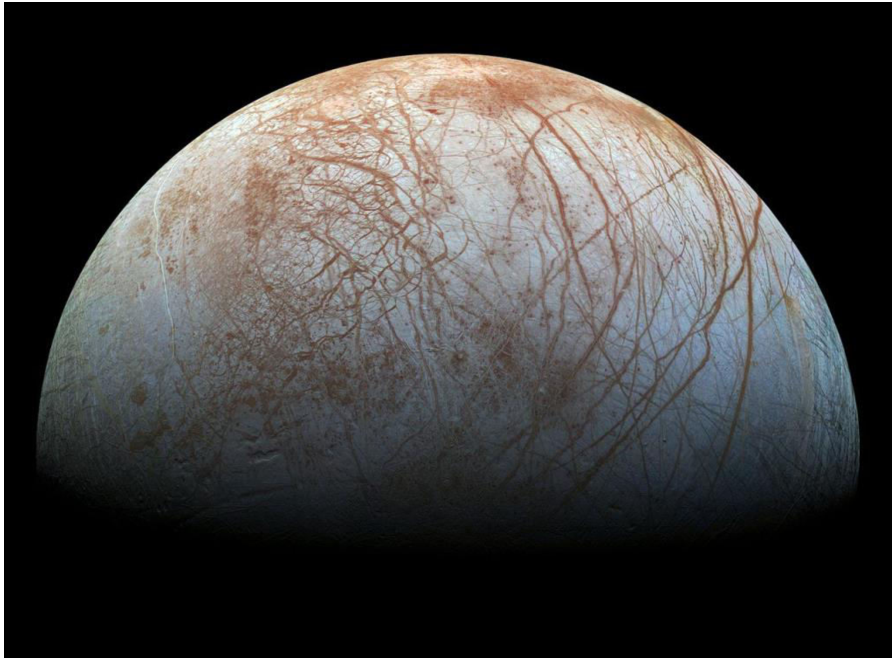


- Gas Giants?
    - **Life?** Not likely.
    - **No solid surface:** If you fell in, you would continue downward till crushed by intense pressure; your remains would sink into a hot liquid in a very strange phase.
    - **Jupiter/Saturn:** About 100 km below the cloud tops, the “right conditions” (water, 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?

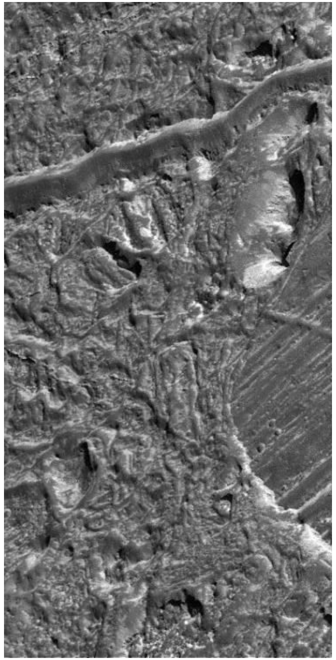
- Moons of Jupiter (e.g., Europa)?



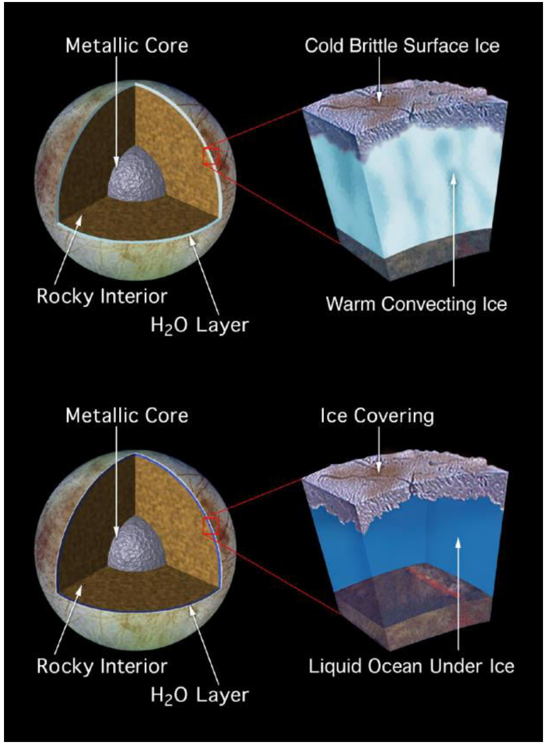
  - **Energy source:** Gravitational tidal flexing (or tidal waves) → Heating



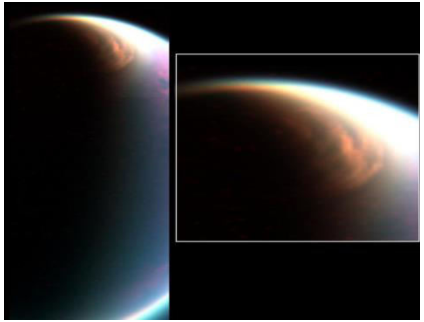
Cracked, icy surface; craggy, 250 m high peaks and smooth plates jumbled together

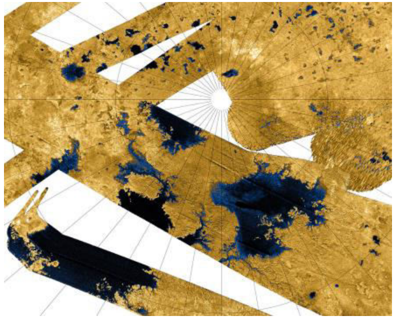


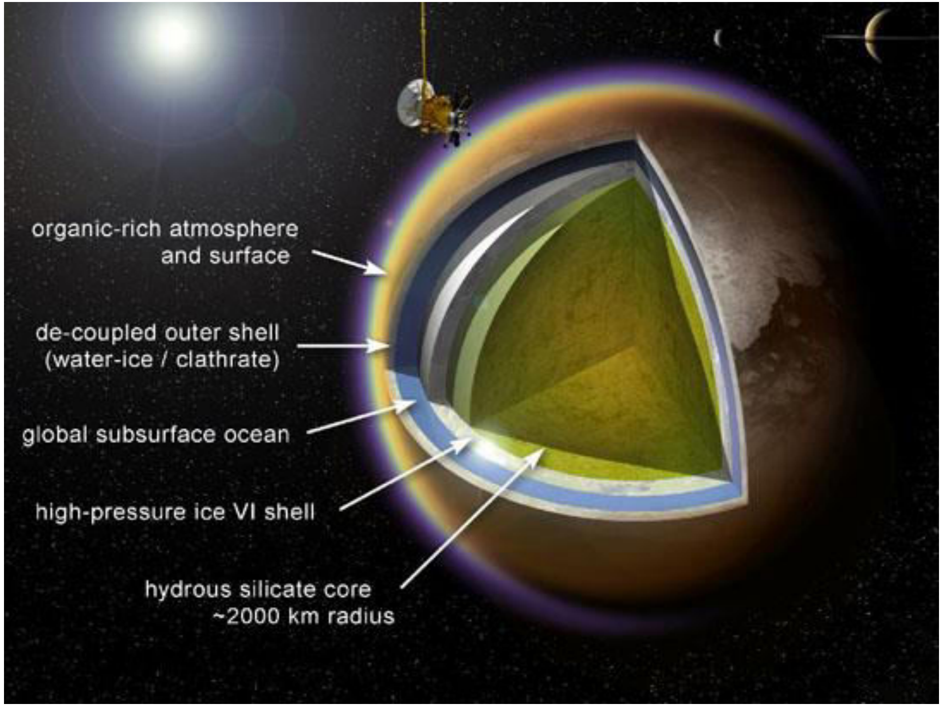
- Moons of Jupiter (e.g., Europa)?
    - Average surface temperature at equator = $-160\ ^{\circ}\mathrm{C}$ → water ice is hard a granite. But (relative) smoothness and youth, plus magnetic field → **salt water ocean underneath**. Different models being debated, but note that a 100 km thick ocean would 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)?



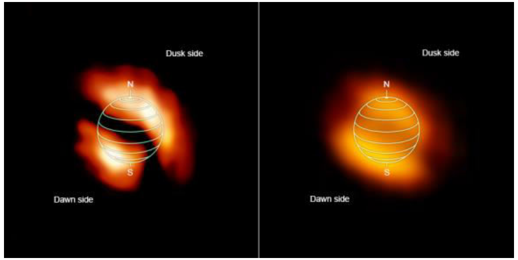




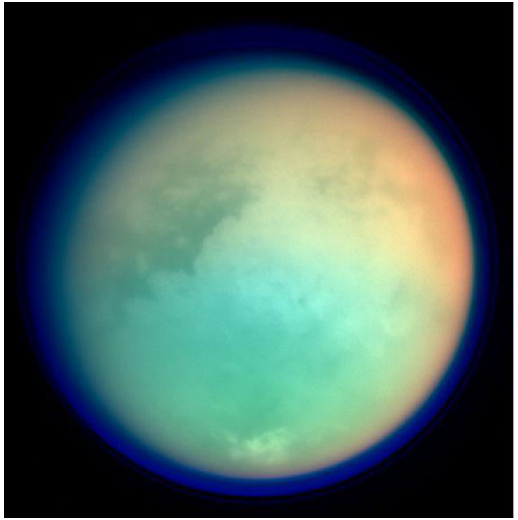
Possible model of Titan's internal structure that incorporates data from NASA's **Cassini spacecraft**. The mantle, in this image, is made of icy layers, one that is a layer of high-pressure ice closer to the core and an outer ice shell on top of the sub-surface ocean.

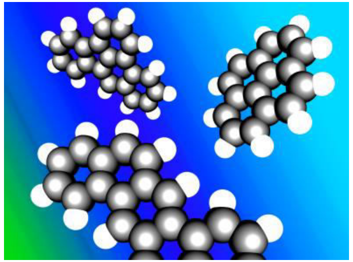
Life in the Solar System?

- 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.



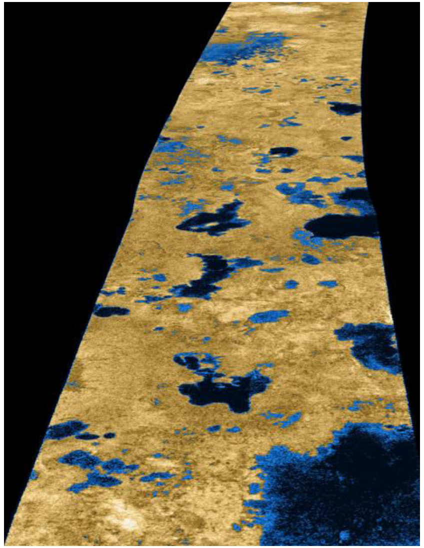
Trace HNC & HC_3N

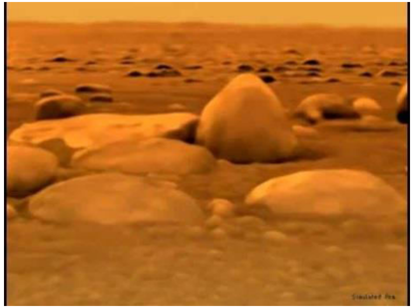




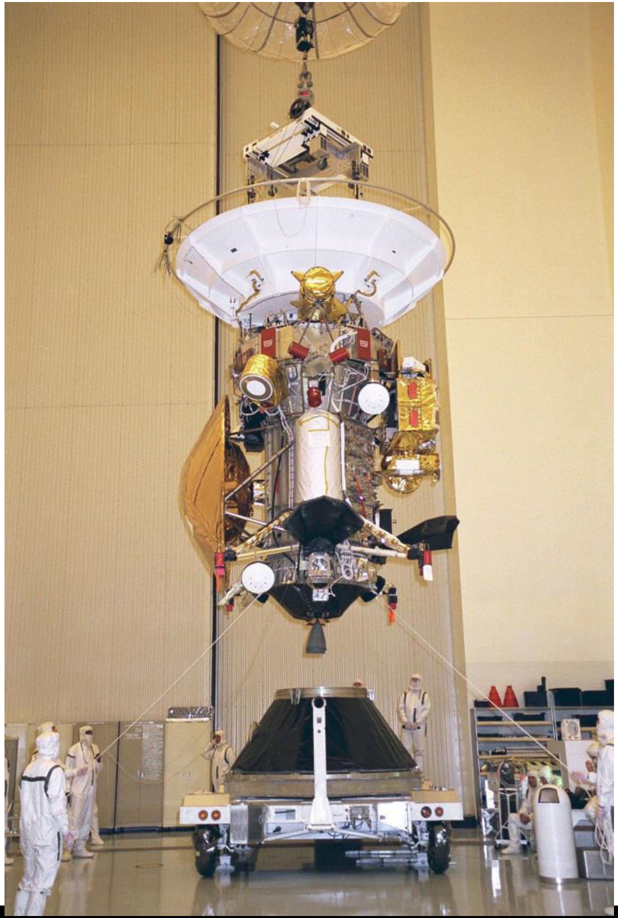
Life in the Solar System?

- 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?



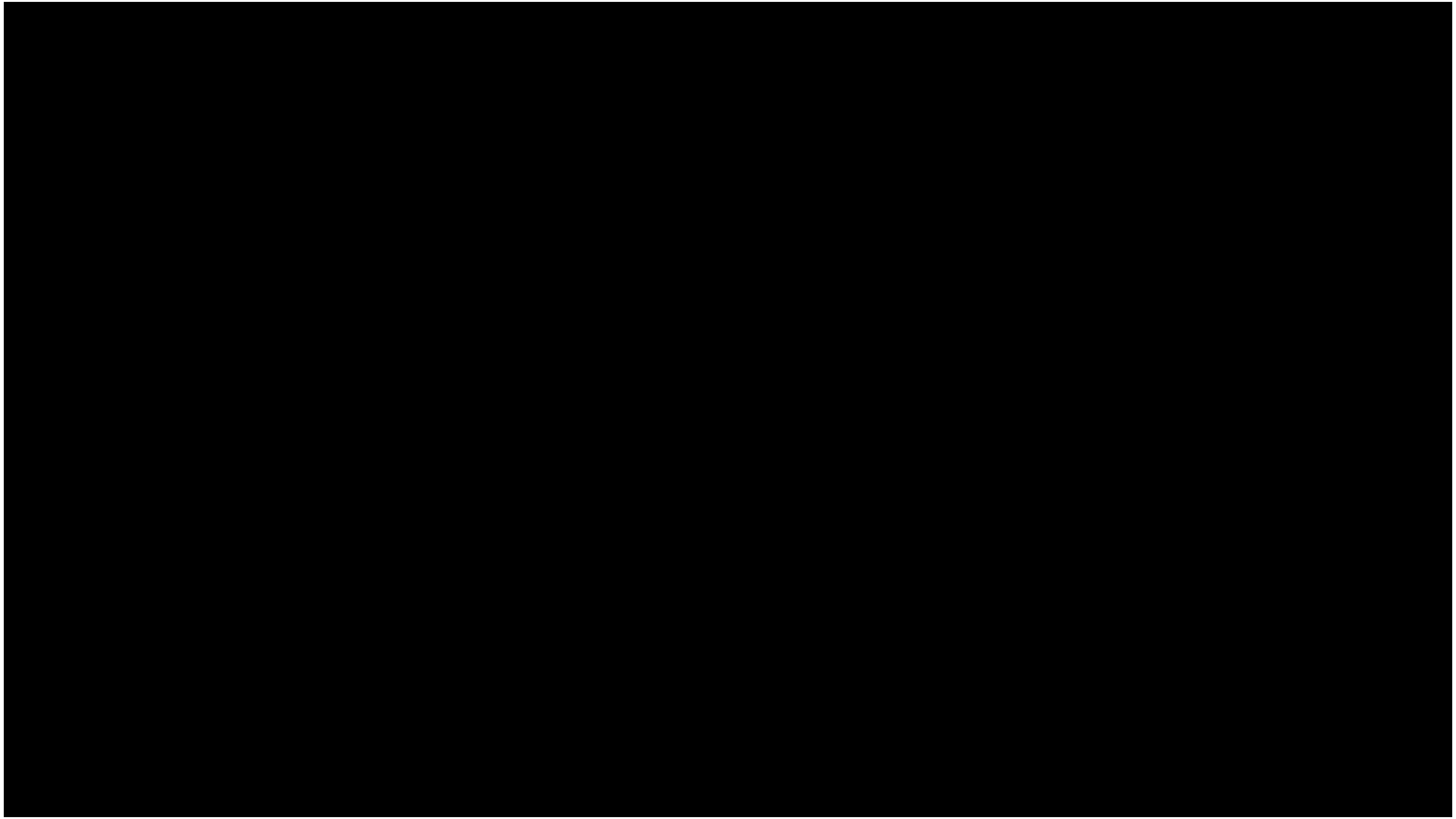


- **Technology** of Cassini-Huygens mission—amazing!

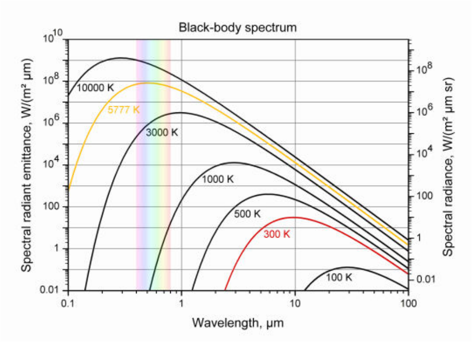


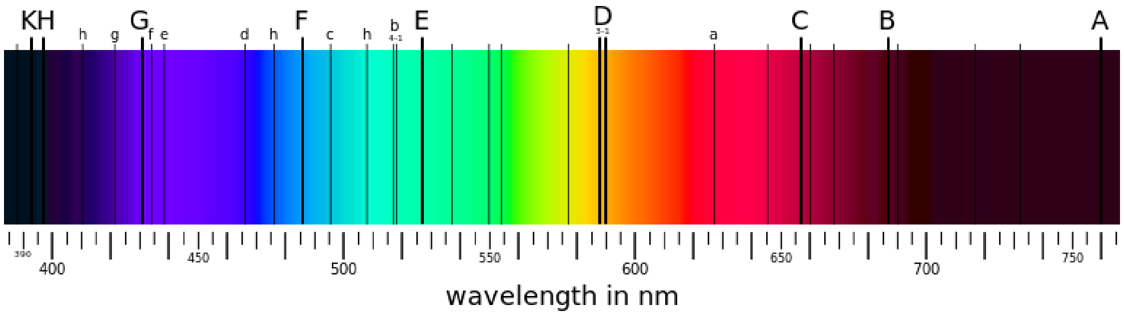
Huygens' landing on Titan (next slide)

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.

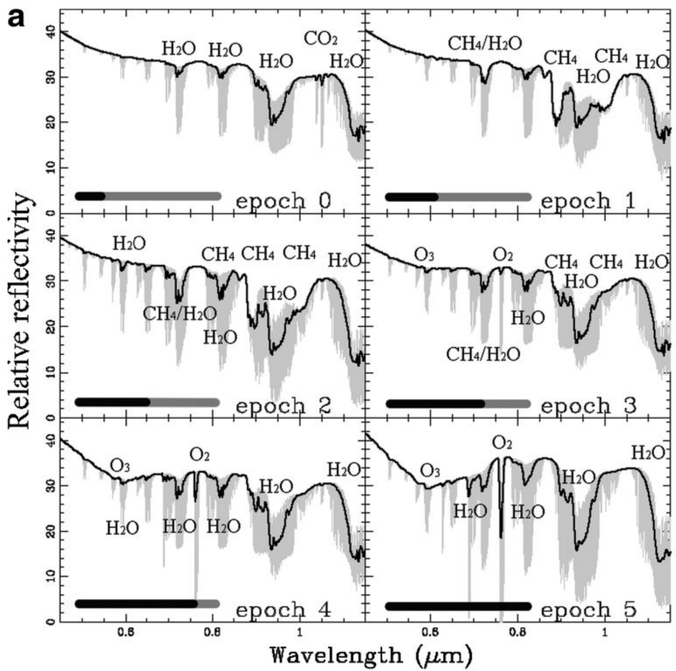




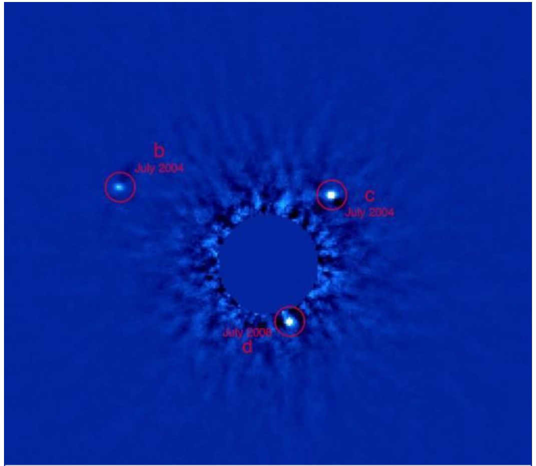
- **Basic idea**: Measure the light (visible and IR) coming from an exoplanet…

  - 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)

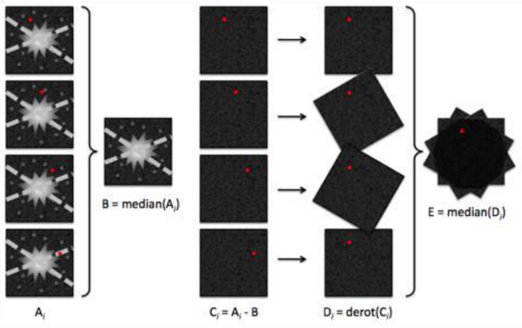


- **Problem:** It's hard to detect light from an exoplanet due to **million-fold glare of parent star**

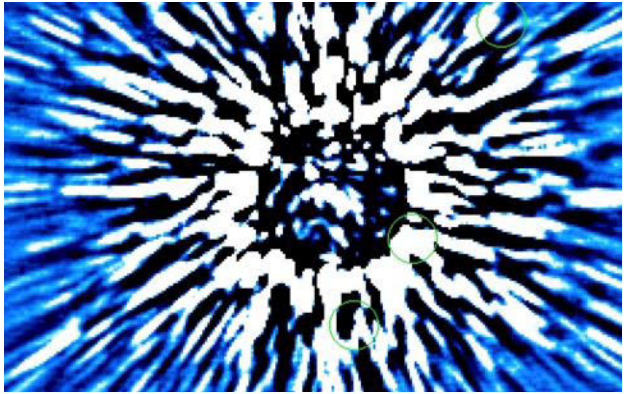


  - 2008: team led by C. Marois of Canada's NRC announced first direct image of 3 exoplanets at 24, 38, and 68 AU around star HR8799 (1.5x mass of Sun, 5x luminosity of Sun).

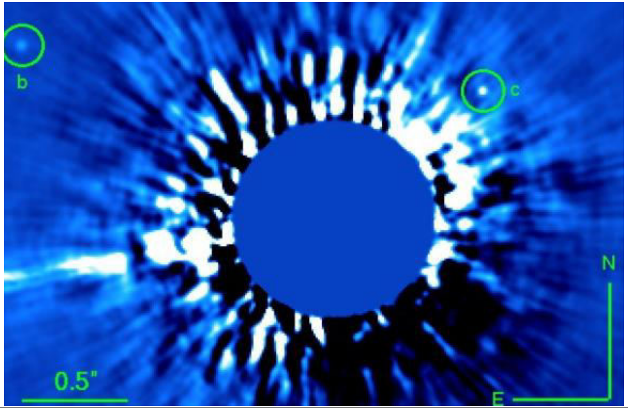
  - They invented "Angular Differential Imaging (ADI)": Find pixel-wise median of many rotated images (B); subtract from original images (Ci); de-rotate and median-average…



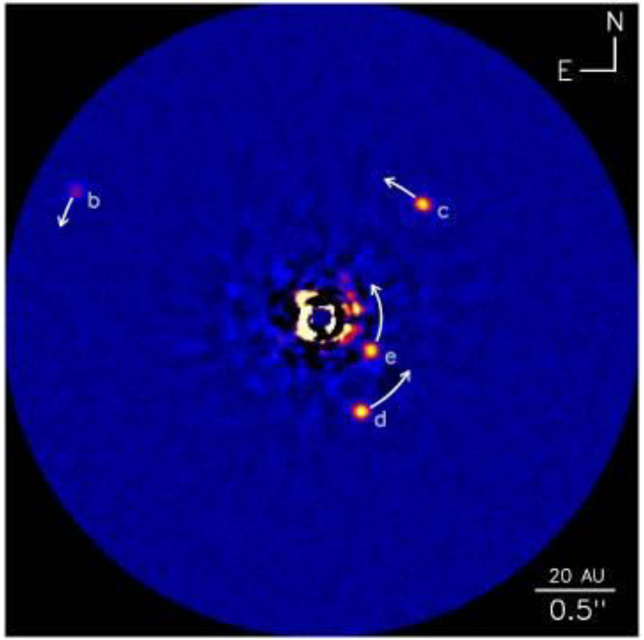
- **Problem:** It's hard to detect light from an exoplanet's due to **million-fold glare of parent star**



Without ADI



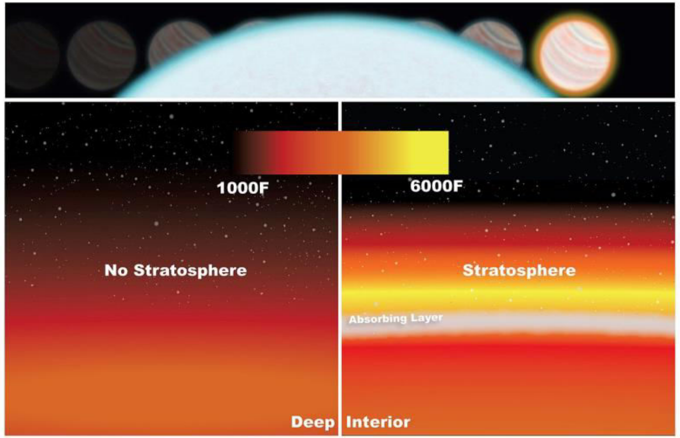
With ADI



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

- 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”

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

SETI

- Search for Extraterrestrial Intelligence
    - Listening for radio (or other) signals from a technologically advanced alien civilization
        - ✓ Other astrobiology research makes slow and steady progress. SETI seeks absolute proof in one fell swoop that **we are not alone**
        - ✓ Difficult to estimate chance of success. Nevertheless, we have no hope of success unless we try. Success would be one of the **greatest discoveries in human history**
        - ✓ Scientifically, SETI represents our **only current** hope of detecting alien civilizations (historically, SETI came first, before the kind of serious astrobiology we have today)

SETI

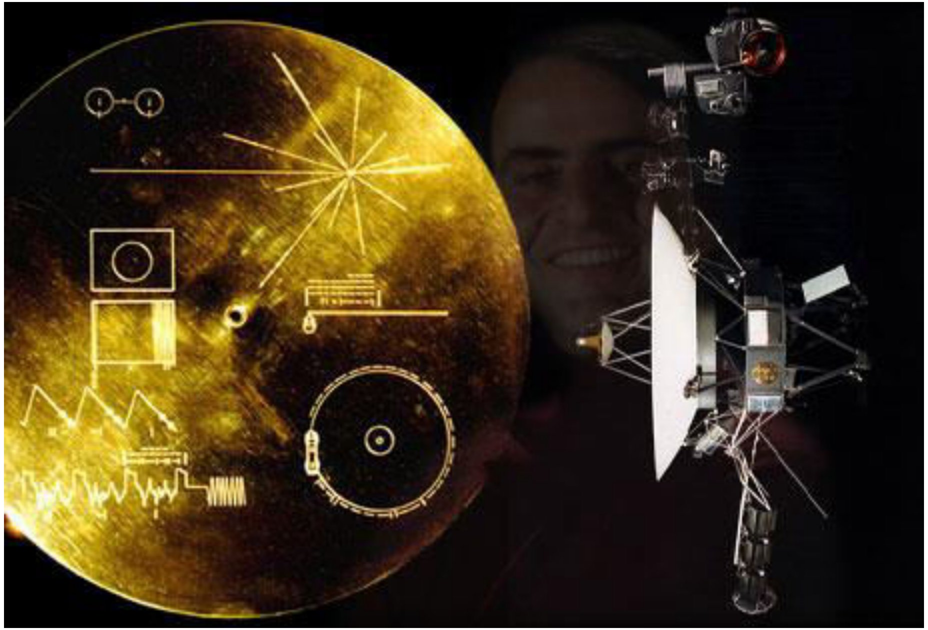
- Search for Extraterrestrial Intelligence
    - Listening for radio (or other) signals from a technologically advanced alien civilization

Are we an isolated, lone civilization, in an incomprehensibly vast cosmos?

Or is there another consciousness out there, amongst the stars?

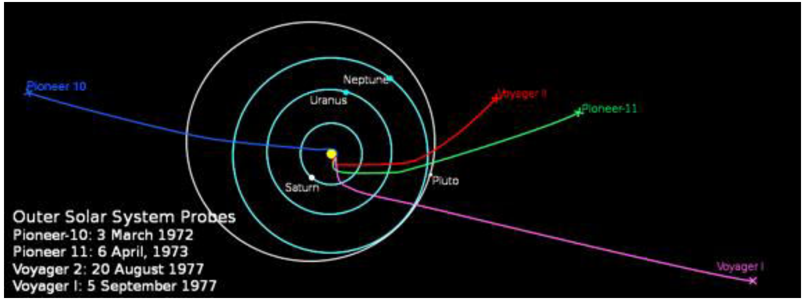
Humans are intelligent, curious, and aware of the cosmos: looking up, and listening.

- Search for Extraterrestrial Intelligence
    - Voyager 1 & 2: Galactic “message in a bottle” expresses human spirit of hope

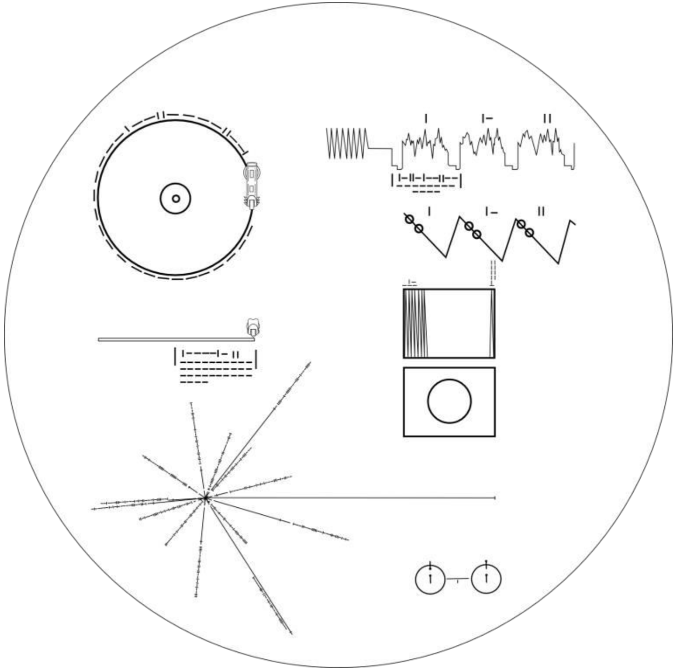


Voyagers 1 & 2 were launched in 1977 to explore the outer solar system.

Now streaking through interstellar space (133 AU out), headed for the stars (reach in 10s of 1000s of years…).



- Search for Extraterrestrial Intelligence
  - Voyager 1 & 2: Galactic “message in a bottle” expresses human spirit of hope



Bolted to the side of each is a gold record containing “sights and sounds of Earth”. And also a map: **How to find us**!

Info to play audio and video. Also defines **location of Sun** relative to 14 nearby pulsars.

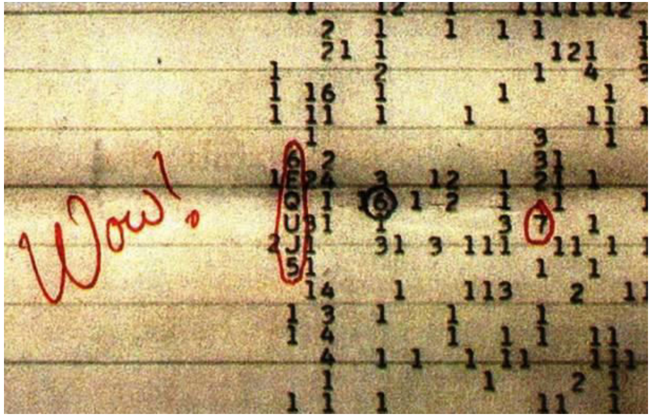
Frequencies coded in binary, relative to hyperfine 21 cm radio emission of hydrogen. (Hopefully, any civilization that knows physics would “get it”)

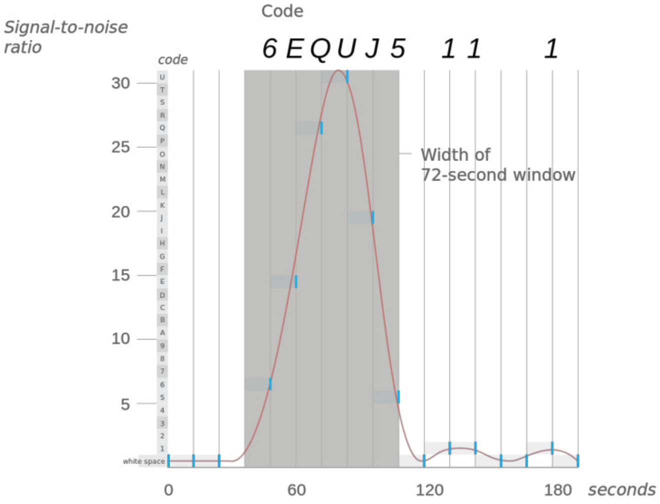
SETI

- Search for Extraterrestrial Intelligence
  - SETI originally proposed by physicists **Giuseppe Cocconi** and **Philip Morrison** in 1959
  - First organized search by astronomer **Frank Drake** in 1960 (Project Ozma)

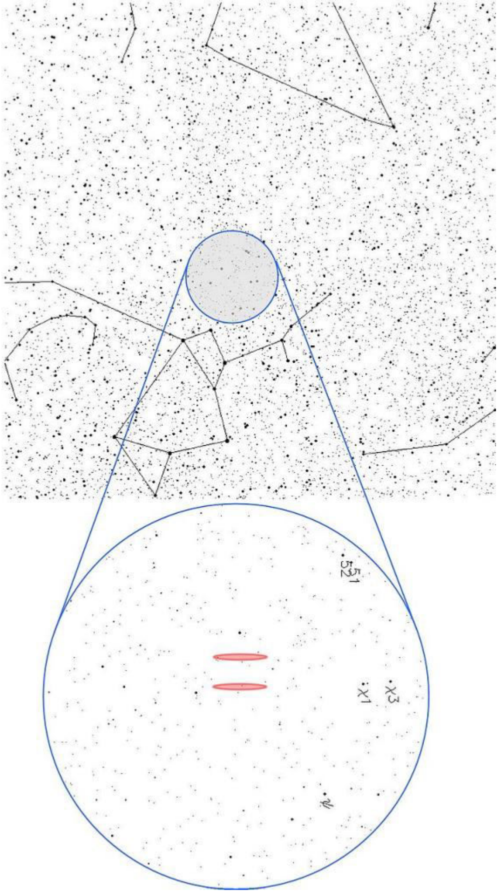
- Search for Extraterrestrial Intelligence
  - Current SETI radio search: Allen Telescope Array in California.
  - Operating near 21 cm, can detect alien civilizations (with power we have) within about a thousand light-years (about a million stars)

- Search for Extraterrestrial Intelligence
  - No success to date…but there is hope!
  - 1977 “**Wow! signal**”:
    - ✓ Noticed by Jerry Ehman, a volunteer astronomer at “Big Ear Radio Observatory”
    - ✓ Peak intensity over 30 times the galactic background, at the natural, 21 cm hydrogen line (the wavelength SETI believes would be natural for aliens to communicate with)
    - ✓ Problem: Never repeated. No explanation. Not science. Just a curious anomaly…



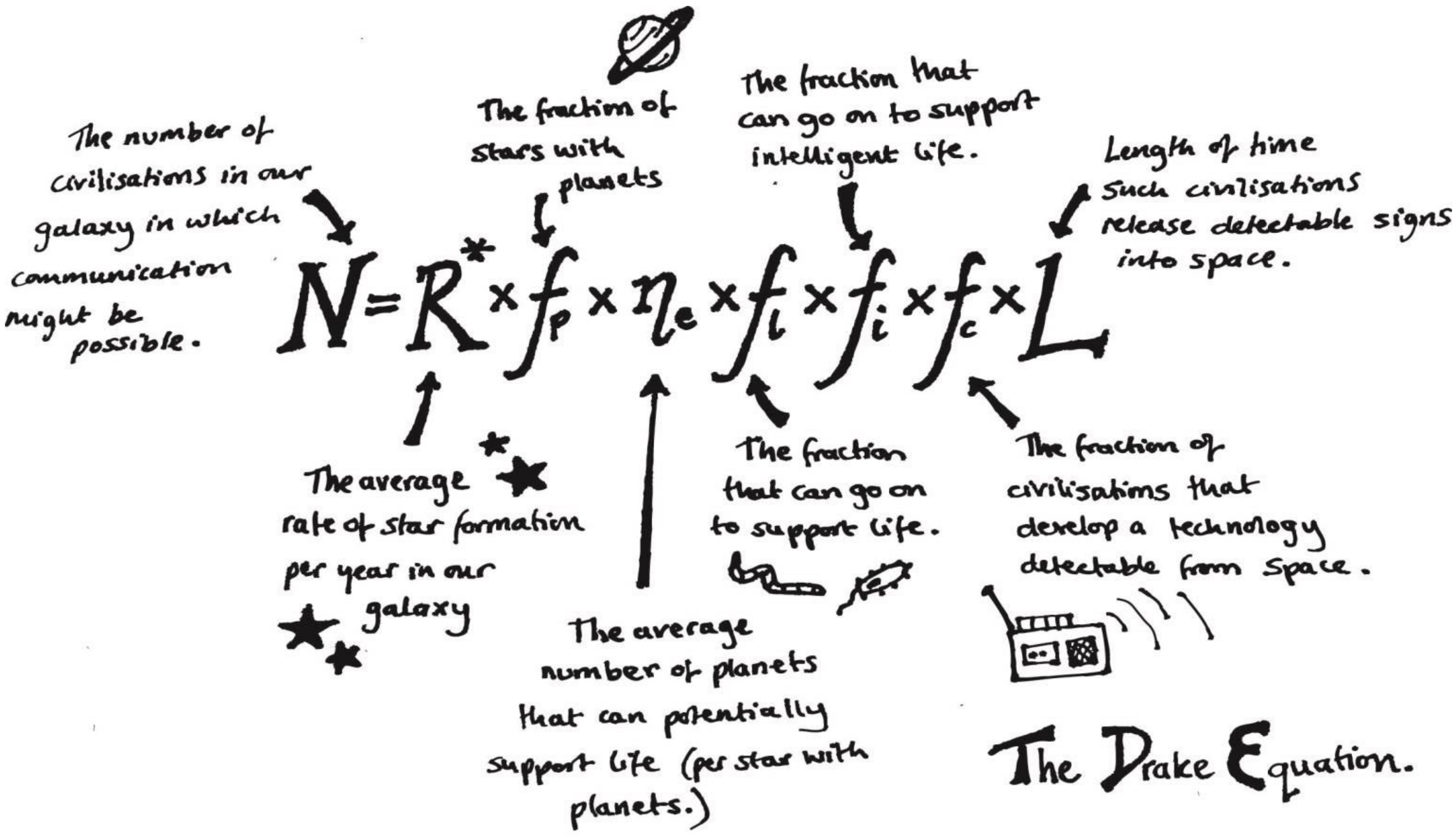


- Search for Extraterrestrial Intelligence
  - No success to date…but there is hope!
  - 1977 "**Wow! signal**":
    - ✓ 2012: Arecibo Observatory beamed a response, containing 10,000 Twitter messages



What happens if SETI succeeds?

What is the chance that SETI will succeed?


The number of civilisations in our galaxy in which communication might be possible.
The fraction of stars with planets
The fraction that can go on to support intelligent life.
Length of time such civilisations release detectable signs into space.
N = R* × fp × ne × fl × fi × fc × L
The average rate of star formation per year in our galaxy
The average number of planets that can potentially support life (per star with planets.)
The fraction that can go on to support life.
The fraction of civilisations that develop a technology detectable from space.
The Drake Equation.

Students come and go. The number of students in college **now** is:

$$N = (number\ of\ students\ entering\ college\ per\ year) \times (time\ they\ spend\ in\ college)$$

Stars come and go → Civilizations come and go. The number of civilizations present **now** is:

$$N = (number\ of\ civilizations\ born\ per\ year) \times (life\ span\ of\ a\ civilization)$$

$$= (stars\ born\ per\ year) \times (civilizations\ per\ star) \times (life\ span\ of\ a\ civilization)$$

$$= R^{*} \times (\ f_{planet} \times n_e \times f_{life} \times f_{intell} \times f_{comm}\ ) \times L$$

$$N = R^* \times (f_{planet} \times n_e \times f_{life} \times f_{intell} \times f_{comm}) \times L$$

$$= (R^* \times f_{planet} \times n_e) \times (f_{life} \times f_{intell} \times f_{comm}) \times L$$

$$= \text{Astronomy} \times \text{Biology} \times \text{Sociology}$$

- **Astronomy:** Until we discovered exoplanets (especially the Kepler mission), f_p and n_e were just guesses. We now have good estimates:
  - ✓ R^* = average rate of star formation in our galaxy $\approx$ 10 per year
  - ✓ $f_{planet} \times n_e$ = average number of planets (per star) that can potentially support life
    $\approx$ (10 billion Earth-sized planets in habitable zone of Sun-like stars) / (100 billion stars in the galaxy)
    $\approx 1/10$
  - ✓ Astronomy $\approx$ 1 per year

$$N = R^* \times (f_{planet} \times n_e \times f_{life} \times f_{intell} \times f_{comm}) \times L$$

$$= (R^* \times f_{planet} \times n_e) \times (f_{life} \times f_{intell} \times f_{comm}) \times L$$

$$= \text{Astronomy} \times \text{Biology} \times \text{Sociology}$$

- **Biology:** This is hard. We have no good estimates. ***Maybe***:
  - ✓ f_{life} = fraction of habitable planets that actually develop **simple life** at some point

    ≈ 1? (simple life seems maybe “inevitable”, and on Earth began immediately)
  - ✓ f_{intell} = fraction of planets with life that actually develop **intelligent life** (civilizations)

    $\ll 1$ or ≈ 1? (is *complexity* inevitable? bottle neck? “Cambrian explosion”)
  - ✓ f_{comm} = fraction of civilizations that develop sufficient communication technology

    $\ll 1$ or ≈ 1? (is technology inevitable? would they use it? could they avoid it?)

$$N = R^* \times (f_{planet} \times n_e \times f_{life} \times f_{intell} \times f_{comm}) \times L$$
$$= (R^* \times f_{planet} \times n_e) \times (f_{life} \times f_{intell} \times f_{comm}) \times L$$
$$= \text{Astronomy} \times \text{Biology} \times \text{Sociology}$$

- **Sociology:** This is **even harder** to estimate. It is the real “**wildcard**”.
  - ✓ $L =$ length of time for which such civilizations release detectable signals into space.
  - ✓ L may be **small**: 50 years after we invented radio, we invented the atomic bomb. Are advanced civilizations doomed to self-destruct? What about destruction by “natural causes”—we do, after all, live in a dangerous universe (asteroid impacts, etc.)
  - ✓ L may be **large**: Maybe civilizations can learn to survive their technological infancy and thrive (in spite of technology, or with its help) for millions or even billions of years, like Star Trek?

Drake Equation

$$N = R^* \times (\, f_{planet} \times n_e \times f_{life} \times f_{intell} \times f_{comm}\,) \times L$$

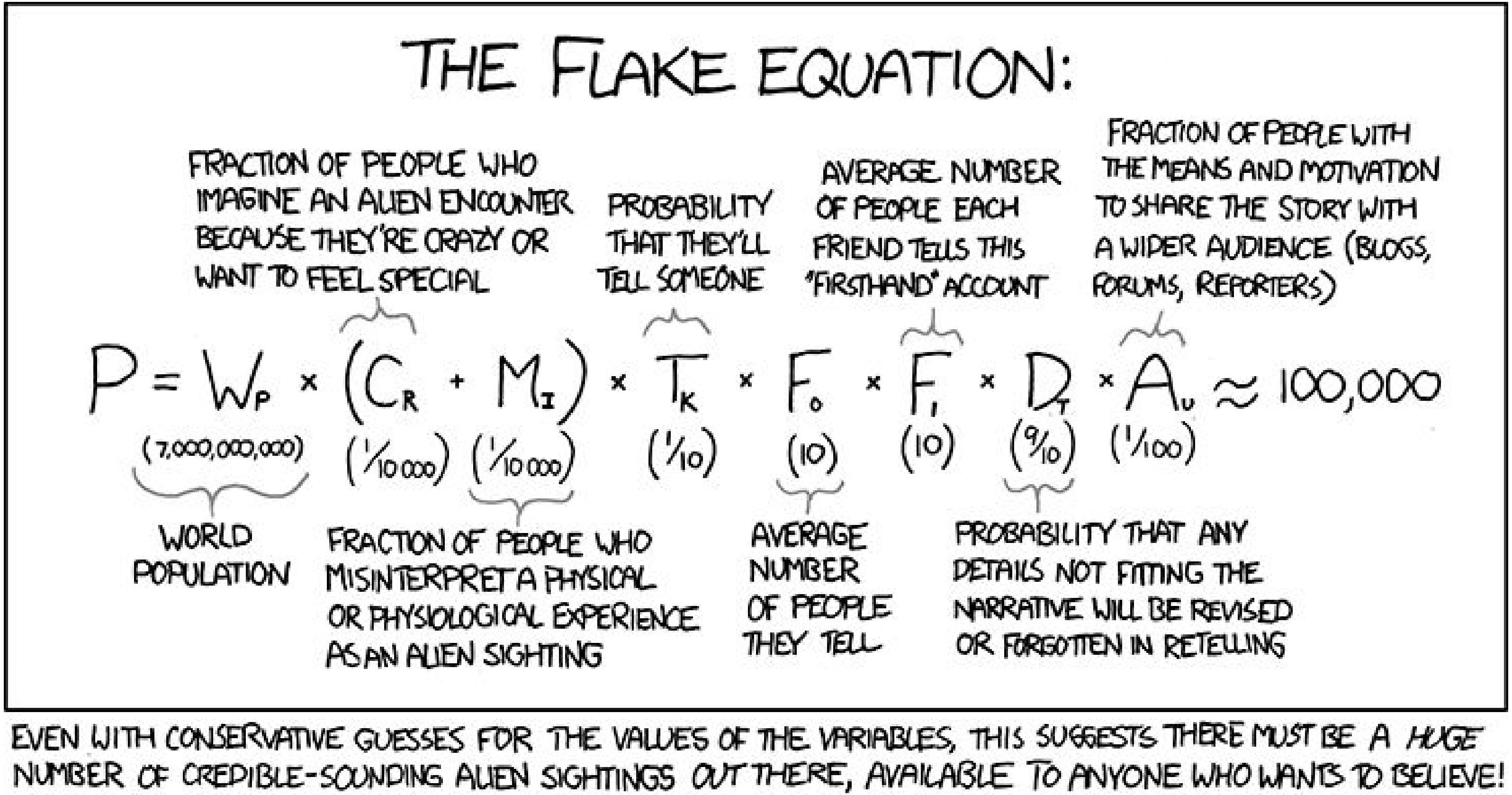
$$= (\, R^* \times f_{planet} \times n_e\,) \times (\, f_{life} \times f_{intell} \times f_{comm}\,) \times L$$

$$= \text{Astronomy} \times \text{Biology} \times \text{Sociology}$$

- **Main Point: $\boldsymbol{N \propto L}$. $\boldsymbol{N}$ will be small unless $\boldsymbol{L}$ is large.**

  ✓ If SETI succeeds relatively easily, it's because L is relatively large, i.e., not all technologically advanced civilizations are doomed to early self-destruction. This would be good news for us, since it gives us hope that the human race **can** have longevity.

  ✓ Estimates for N range from $\ll 1$ (what does this mean?) to **millions**. Therefore, the Drake equation is *not* useful to estimate N. It *is* useful, however, to **focus our attention on interesting & important questions**.


THE FLAKE EQUATION:
FRACTION OF PEOPLE WHO IMAGINE AN ALIEN ENCOUNTER BECAUSE THEY'RE CRAZY OR WANT TO FEEL SPECIAL
PROBABILITY THAT THEY'LL TELL SOMEONE
AVERAGE NUMBER OF PEOPLE EACH FRIEND TELLS THIS "FIRSTHAND" ACCOUNT
FRACTION OF PEOPLE WITH THE MEANS AND MOTIVATION TO SHARE THE STORY WITH A WIDER AUDIENCE (BLOGS, FORUMS, REPORTERS)
$P = W_P \times (C_R + M_I) \times T_K \times F_0 \times F_1 \times D_T \times A_U \approx 100{,}000$
(7,000,000,000) (1/10 000) (1/10 000) (1/10) (10) (10) (9/10) (1/100)
WORLD POPULATION
FRACTION OF PEOPLE WHO MISINTERPRET A PHYSICAL OR PHYSIOLOGICAL EXPERIENCE AS AN ALIEN SIGHTING
AVERAGE NUMBER OF PEOPLE THEY TELL
PROBABILITY THAT ANY DETAILS NOT FITTING THE NARRATIVE WILL BE REVISED OR FORGOTTEN IN RETELLING
EVEN WITH CONSERVATIVE GUESSES FOR THE VALUES OF THE VARIABLES, THIS SUGGESTS THERE MUST BE A HUGE NUMBER OF CREDIBLE-SOUNDING ALIEN SIGHTINGS OUT THERE, AVAILABLE TO ANYONE WHO WANTS TO BELIEVE!

However, the Drake equation *is* useful to **focus our attention on interesting & important questions**.

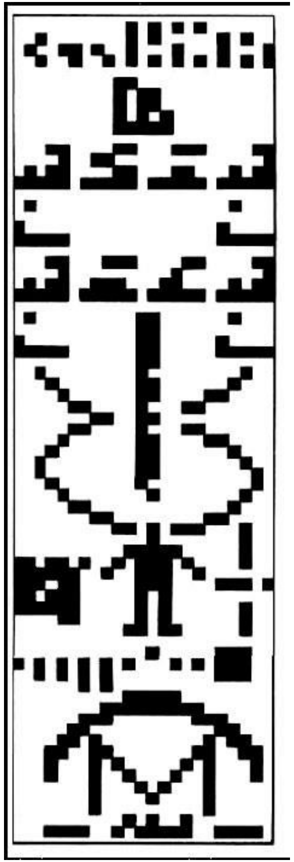
- **Questions:**

  - ✓ Even if complex life is widespread, would **intelligence** be common? Think about "**convergent evolution**" (e.g., fish body shape, eyes, brains, etc.)

  - ✓ How do we define intelligence, anyway? Would it **necessarily spawn science and technology** capable of, or even interested in, interstellar communication?

  - ✓ What **kind of communication** should we be looking for? Radio? Light? Other? What form? Could we **recognize/decode** intelligent messages?

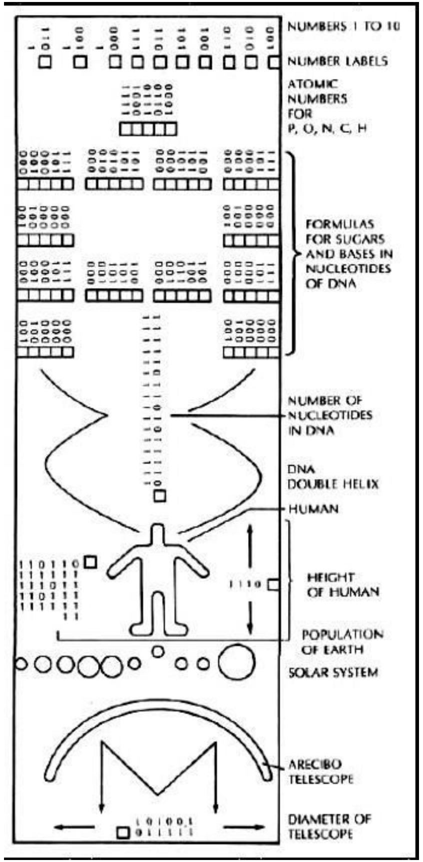
  - ✓ We've hardly transmitted anything. Why would we expect others to? Why might we **not** want to transmit anything? If we do, what **should** we transmit?



← If you detected this image…

(Beamed by the Arecibo telescope at the globular cluster M13 in 1974)

…could you figure out it meant this? →



The Fermi Paradox

- Assuming that neither we nor our planet is in any way special (Copernican principle), suggests that **aliens should have colonized the galaxy by now**. Why?

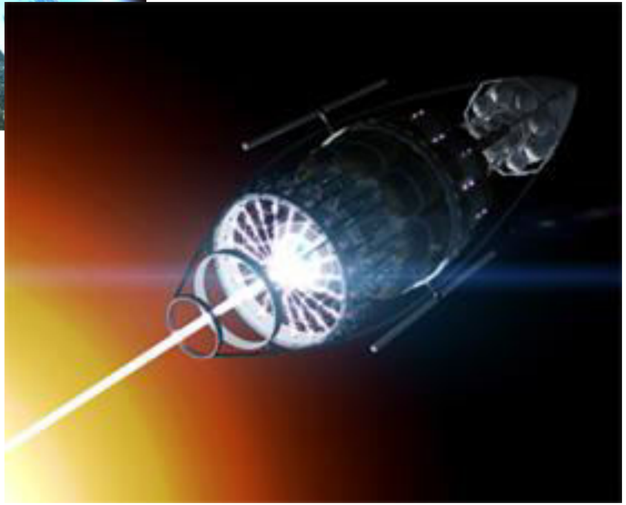
  - ✓ Not special → civilizations are common.

  - ✓ Stars in our galaxy would have had Earth-like planets starting about 5 billion years before Earth was born…giving those aliens a **5 billion year head start on us**!

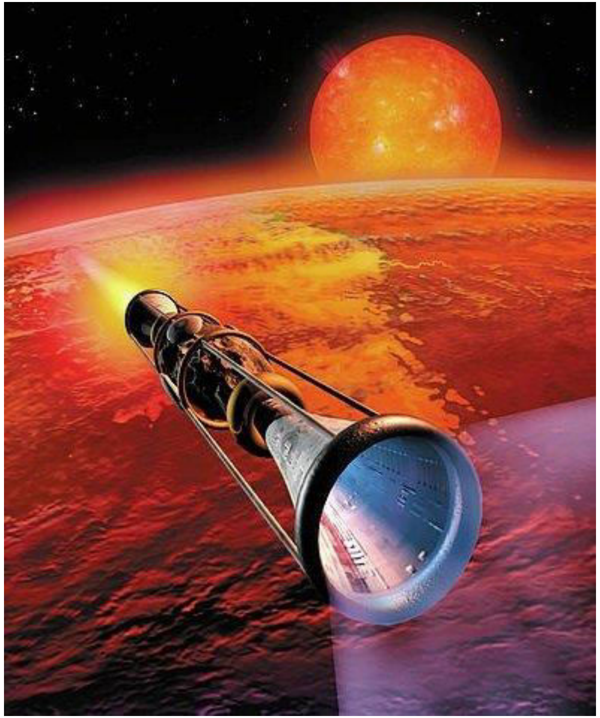
  - ✓ Interstellar space travel seems exceedingly difficult for **us**, but in just one century we have imagined **many possible ways**…

nuclear fission/fusion rocket

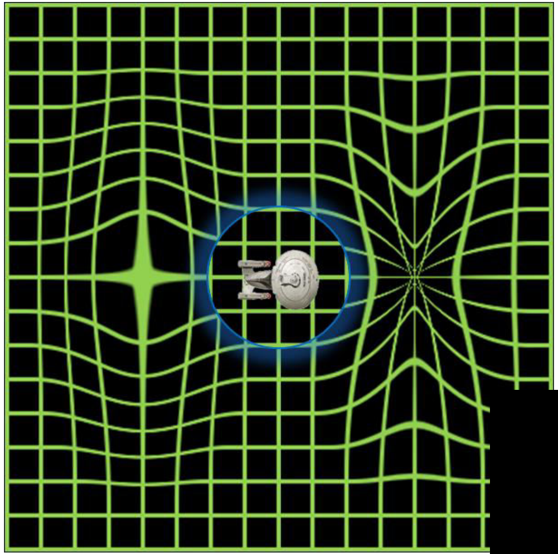
matter-antimatter
photon rocket

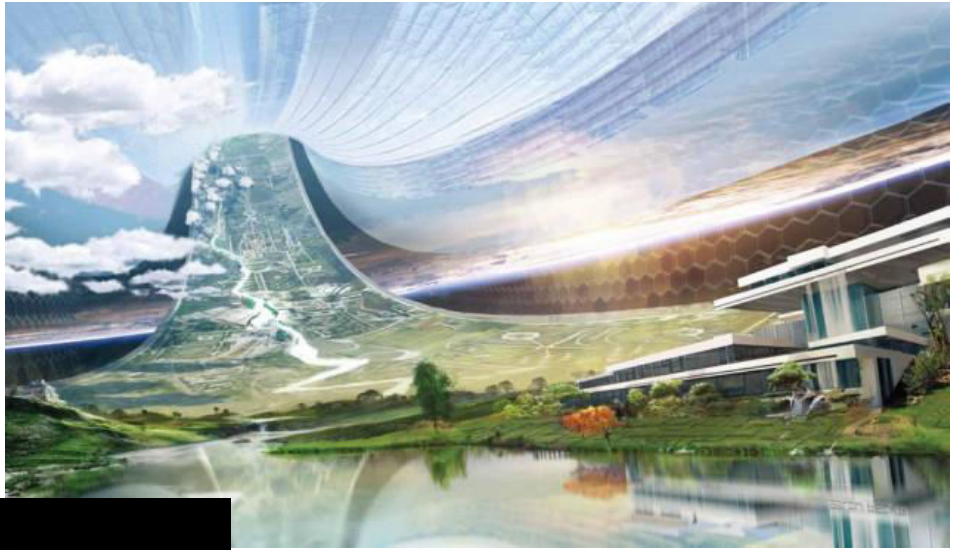


nuclear fusion ram-jet



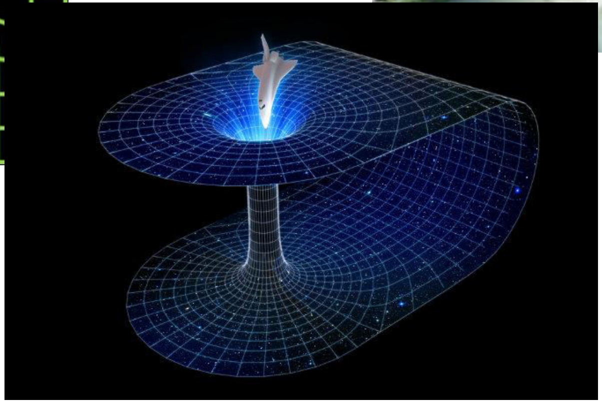
Einstein-friendly warp drive





Interstellar
biological ark

hyperspace/wormholes

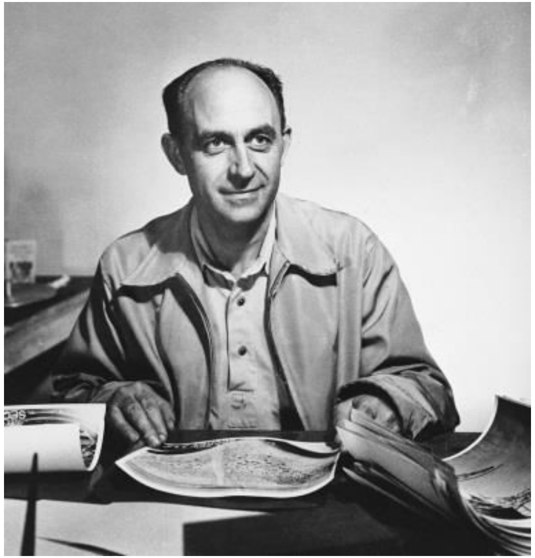


The Fermi Paradox

- Assuming that neither we nor our planet is in any way special (Copernican principle), suggests that **aliens should have colonized the galaxy by now**. Why?
  - ✓ Surely, with a 5 billion year head start, said civilizations could master interstellar travel
  - ✓ …especially if they sent **self-replicating (Von Neumann) machines** instead of themselves

- On the other hand, if such a galactic civilization existed, we should be surrounded by evidence of it. But **apparently** we’re not.

Where is Everybody?



Physicist Enrico Fermi

- **Fermi Paradox**:

  - ✓ Assuming that neither we nor our planet is in any way special suggests that aliens should have colonized the galaxy by now.

  - ✓ If such a galactic civilization existed, presumably we should be surrounded by evidence of it. But it appears we are not.

- Something is wrong with our assumptions. **What?**

- There either **is** a galactic civilization or there **is not**. There *is* a solution to the paradox, but what is it?

- **Possible Solutions**:
  - ✓ Galactic civilizations are extremely rare. Ours is the first. **We are alone**.
    - So what?
  - ✓ Galactic civilizations are common, but none have widely colonized the galaxy.
    - Why not? (Technology? Desire? Life Span?)
  - ✓ There is a galactic civilization, but it has deliberately avoided revealing itself to us.
    - Why?
- **Note:** Similar considerations apply to the **eerie silence** so far detected by SETI…

One of these two statements is true:

- There are **billions** of habitable Earth-like worlds out there in the galaxy, and yet **we are alone**.
- There are **billions** of habitable Earth-like worlds out there in the galaxy, and **we are not alone**. There are others.

Either way, the implications for us are **profound**

Life—Summary

- “Origin of Life,” “Nature of Life,” & “Extraterrestrial Life” are all very active areas of science

- Like poetry, science finds deep **connections** and **unity** between superficially disparate things:

    - *Biology & Chemistry*: Evolution & genetics have shown that all life on Earth is part of the **same family**: humans are cousins to chimpanzees, trees, fungus, etc. Biology & chemistry are even beginning to hint at how rocks themselves may have “come alive”.

    - *Physics*: All physical processes, inanimate (rain and sunshine) or animate (life), obey the **same laws** of physics. At the level of basic physics, there is no distinction between a human and a steam engine. Both operate by the laws of thermodynamics; life ***may*** even be a **necessary consequence** of those laws!

- We will now extend these connections and unity even deeper, to the **entire universe itself**…