An introduction to

Solar System Life

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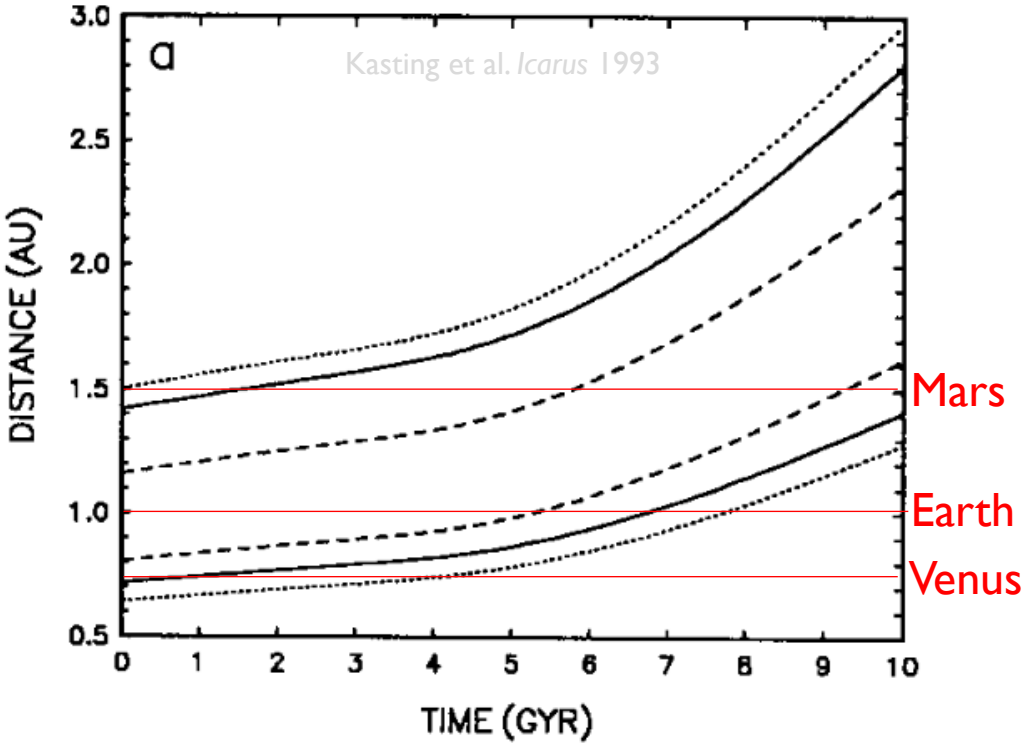
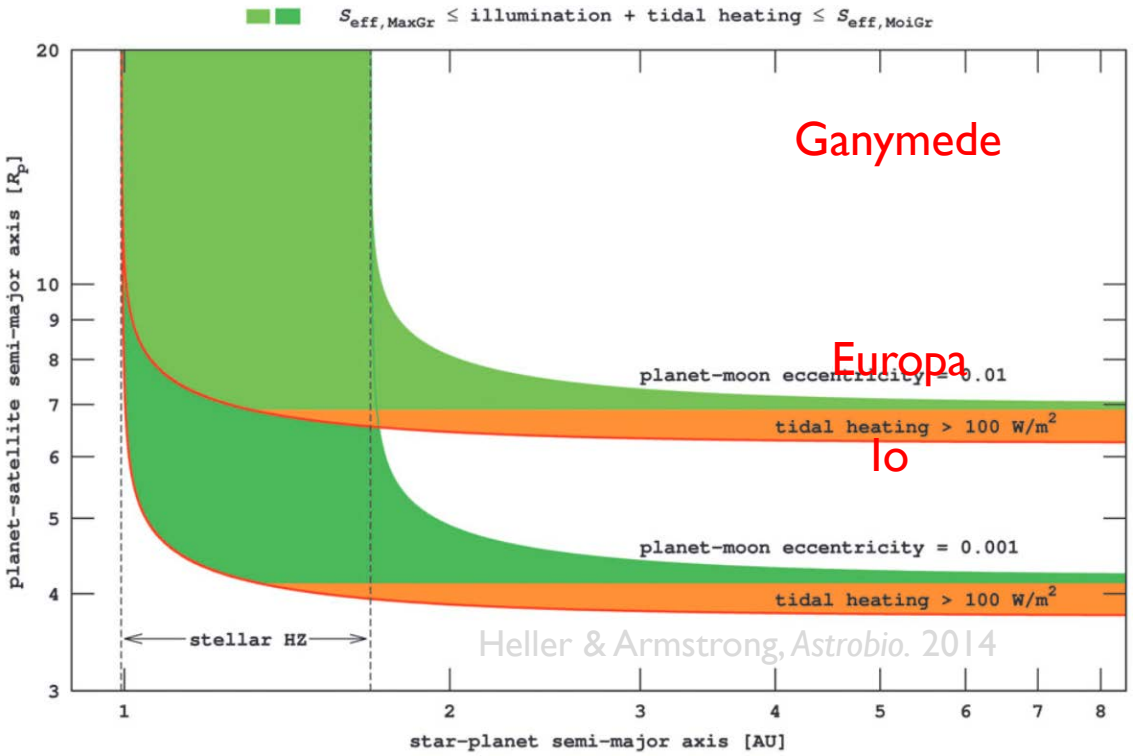
Earth is the only place in the solar system with confirmed life,

- **but** there are several habitable (or formerly habitable) places in our solar system
  - Evidence of past liquid water on Venus, Mars, Ceres, Vesta
  - Evidence or suspicion of subterranean oceans for the Galilean moons, Saturn's Enceladus, and Neptune's Triton + possibility of methanogenic life on Titan

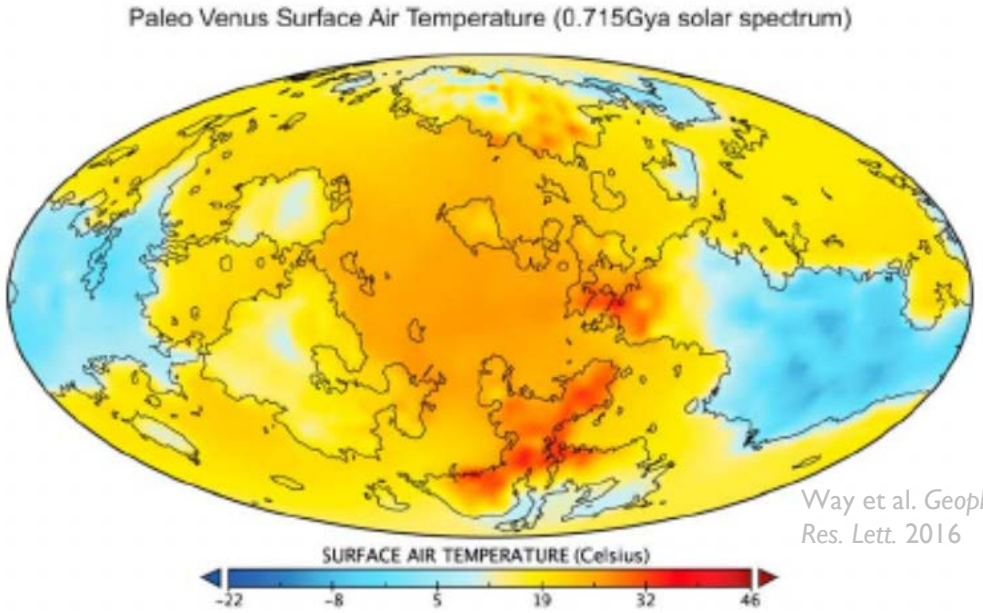


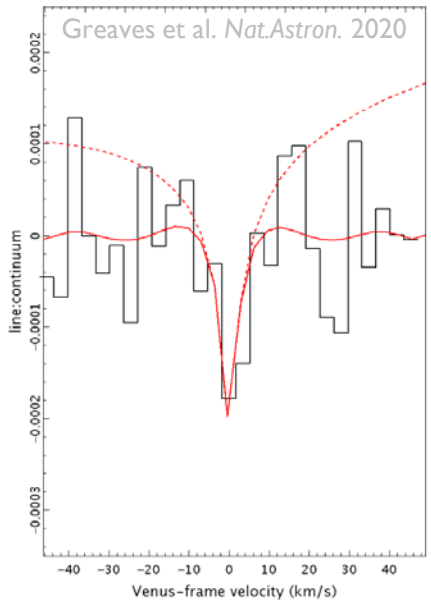
for an Earth-like moon around Jupiter-like planet:

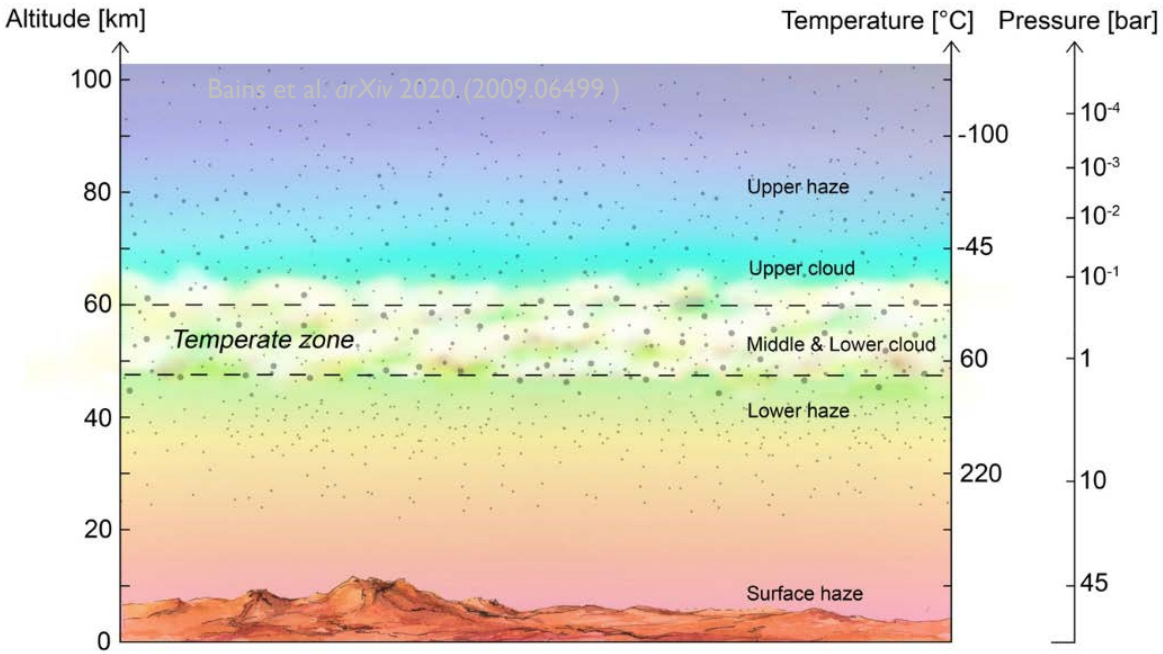


Venus

- Early in the solar system's history, the solar flux was not as high (see Intro to Low Mass Stellar Evolution)
- Also, Venus's atmosphere likely had a lot more water and fewer greenhouse gases
- Therefore, Venus was plausibly habitable for the first few billion years of the solar system
- Present-day Venus could in principle be hospitable to life in the atmosphere, e.g. microbes floating in Venusian clouds
- Phosphine, a product of decaying organic matter, was possibly detected on Venus. However,
  (1) the spectral feature isn't particularly strong,
  (2) it's not clear we know chemistry well enough in these extreme environments



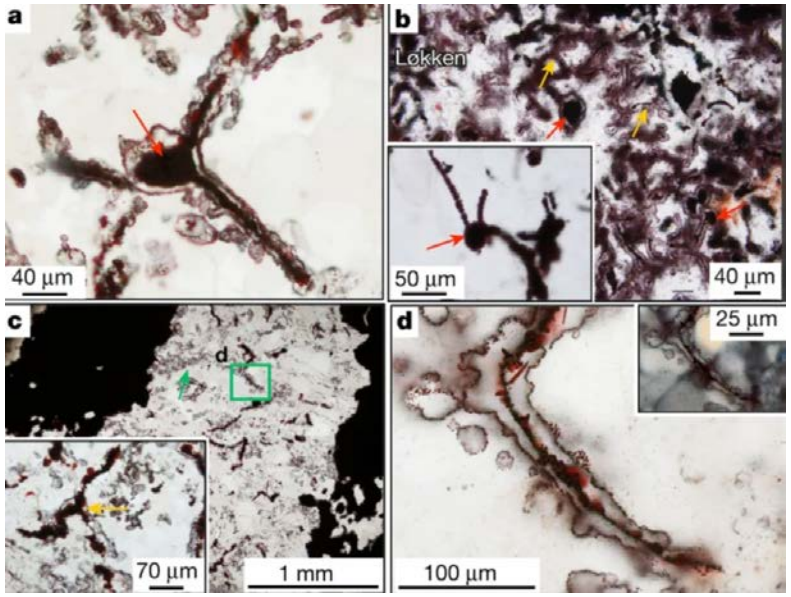


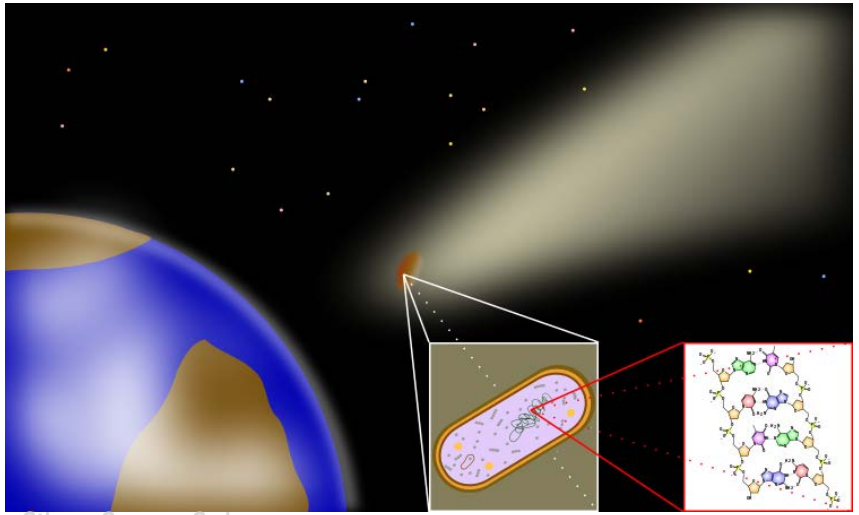


Earth

- We don't know when life on Earth began, though what appears to be fossils of microorganisms date back to 3.8-4.3 Gyr (to be compared to 4.5 Gyr solar system age [See Intro to Solar System Dating])
- We also don't know how life began (see Intro to Habitability) and can keep in mind that it may have began elsewhere and transplanted to Earth by a comet or meteoroid (perhaps a meteoroid from rock blasted off of another life-bearing planet in the solar system)
- Alternatively, life could have began in a soup of molecules existing at one or more locations on the early Earth. Because of the extreme conditions present at that time, "extremophiles" are studied as modern analogues
- Whenever it happened, it had to be pretty early on

Dodd et al. *Nature* 2017

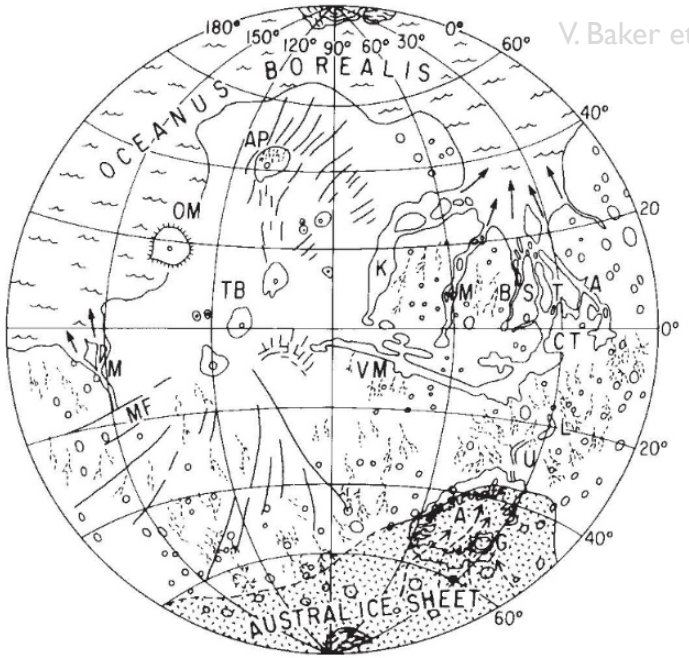




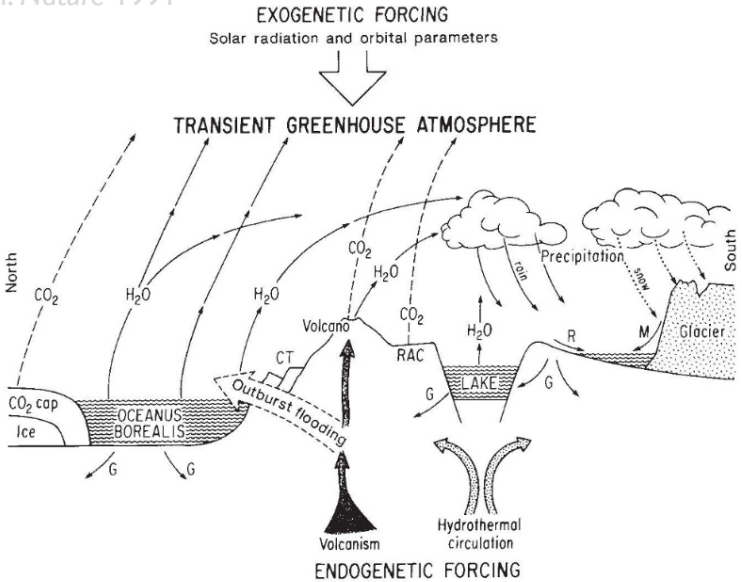
Silver Spoon Sokpop

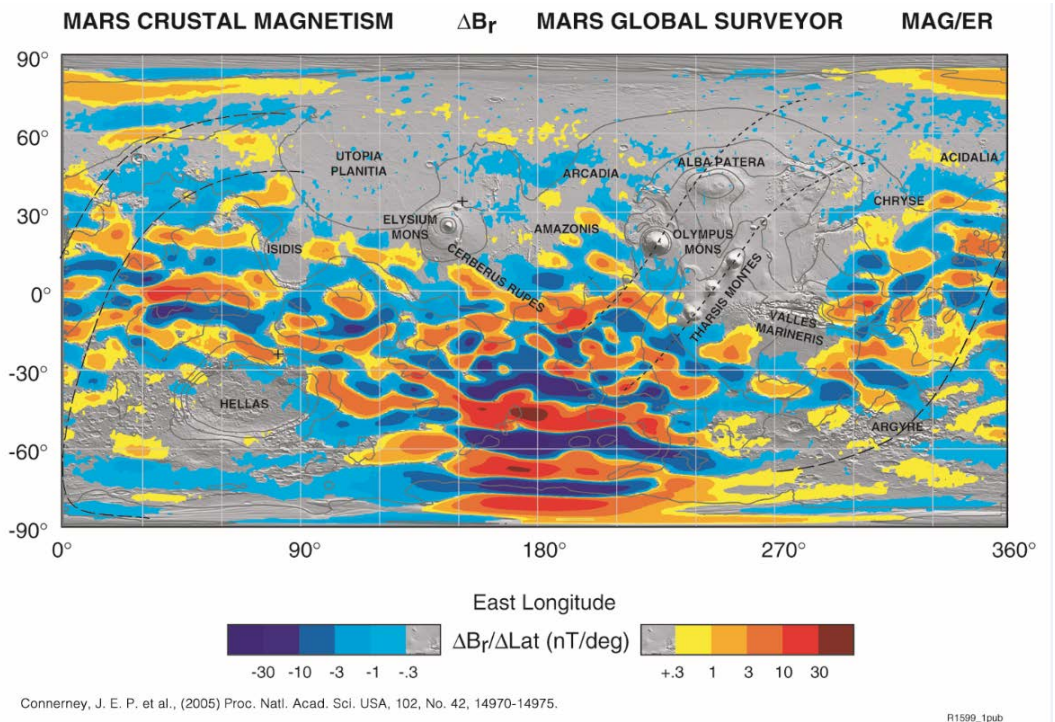
Mars

- Geologic and chemical signatures indicate that Mars once had vast oceans and flowing water, enabled by volcanic activity that enhanced greenhouse gases
- However, water & CO_2 were steadily trapped in the ground and the atmosphere was steadily lost to space
- Magnetized layers in the crust indicate that the planet once had a significant magnetic field, which would have protected the surface from solar radiation
- Making Mars habitable again ("terraforming") would need to deal with the issues of low temperature, atmospheric pressure & composition, and lack of magnetic field



V. Baker et al. *Nature* 1991



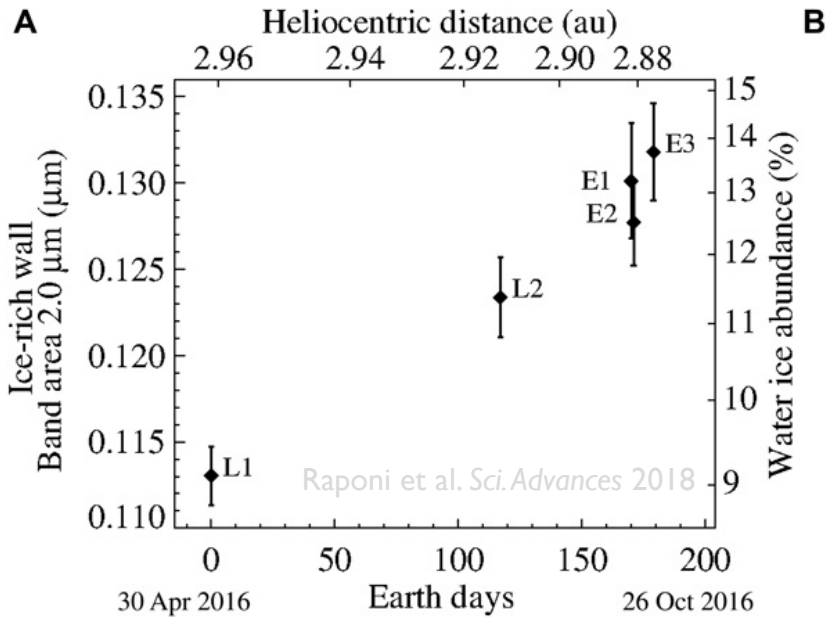


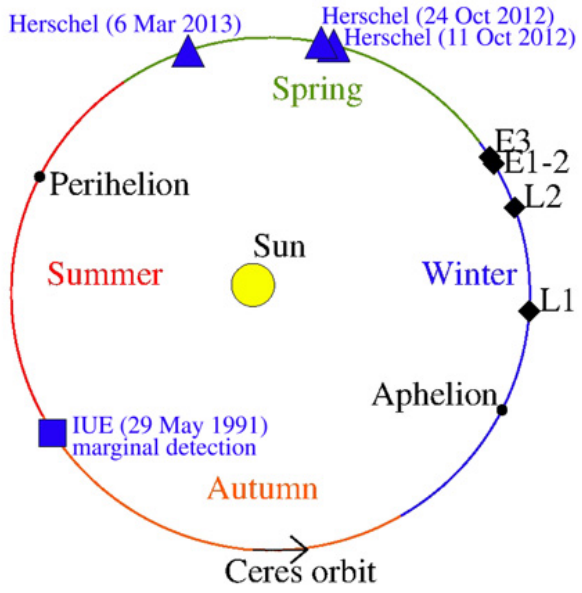
Connerney, J. E. P. et al., (2005) Proc. Natl. Acad. Sci. USA, 102, No. 42, 14970-14975.

R1599_1pub

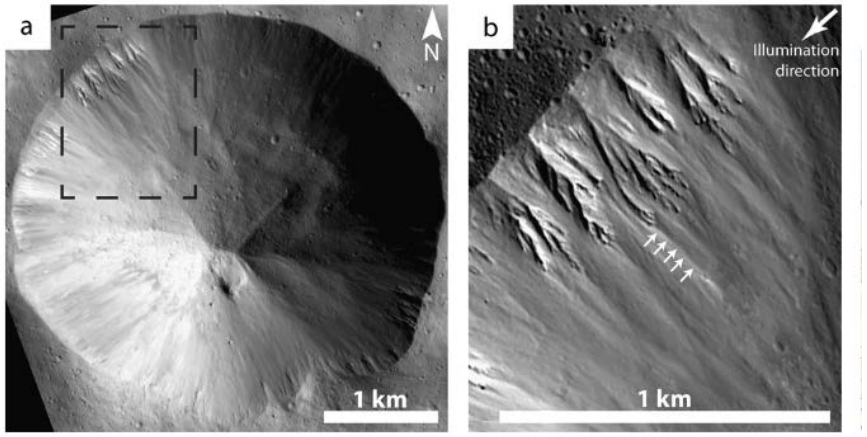
Ceres & Vesta

- Water ice is present on Ceres & Vesta in the asteroid belt, varying in amount over the course of an orbit
- This water is thought to be liquid below the surface, where heating from internal energy is larger
- Geologic evidence suggests that surface water flows may have existed at one point



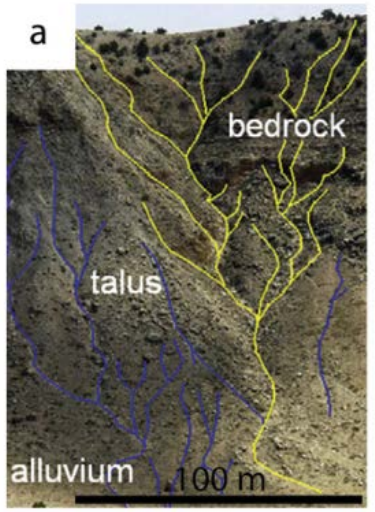


Vesta:



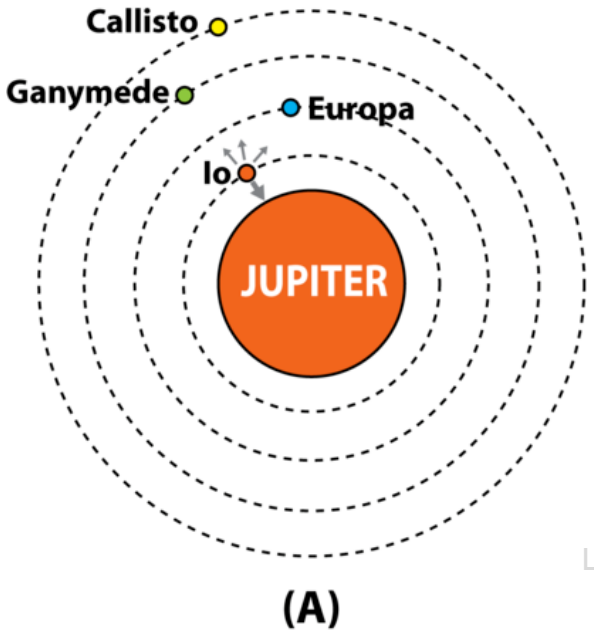
Scully et al. *Earth Plan. Sci. Lett.* 2015

Earth:

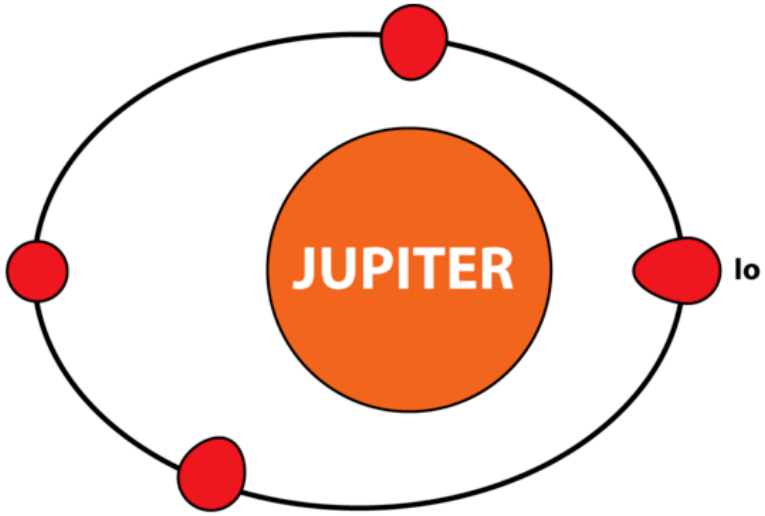


Galilean Moons: Io

- Io has a large flux of irradiation from Jupiter's radiation belt and little water in its thin atmosphere …which sounds like a problem (and it is!)
- But, it is a rocky object with lots of tidal heating & corresponding volcanic activity. Hydrothermal vents are biological hotspots on Earth
- So, perhaps subterranean life could exist, where it is hot with some water, but shielded from surface irradiation



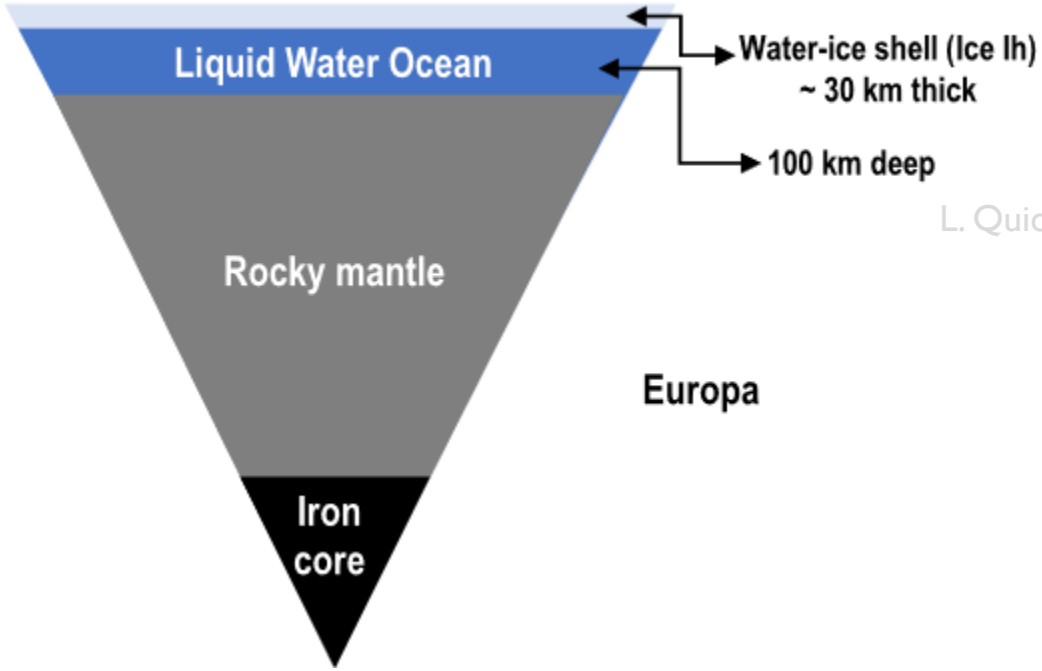
(A)



(B)

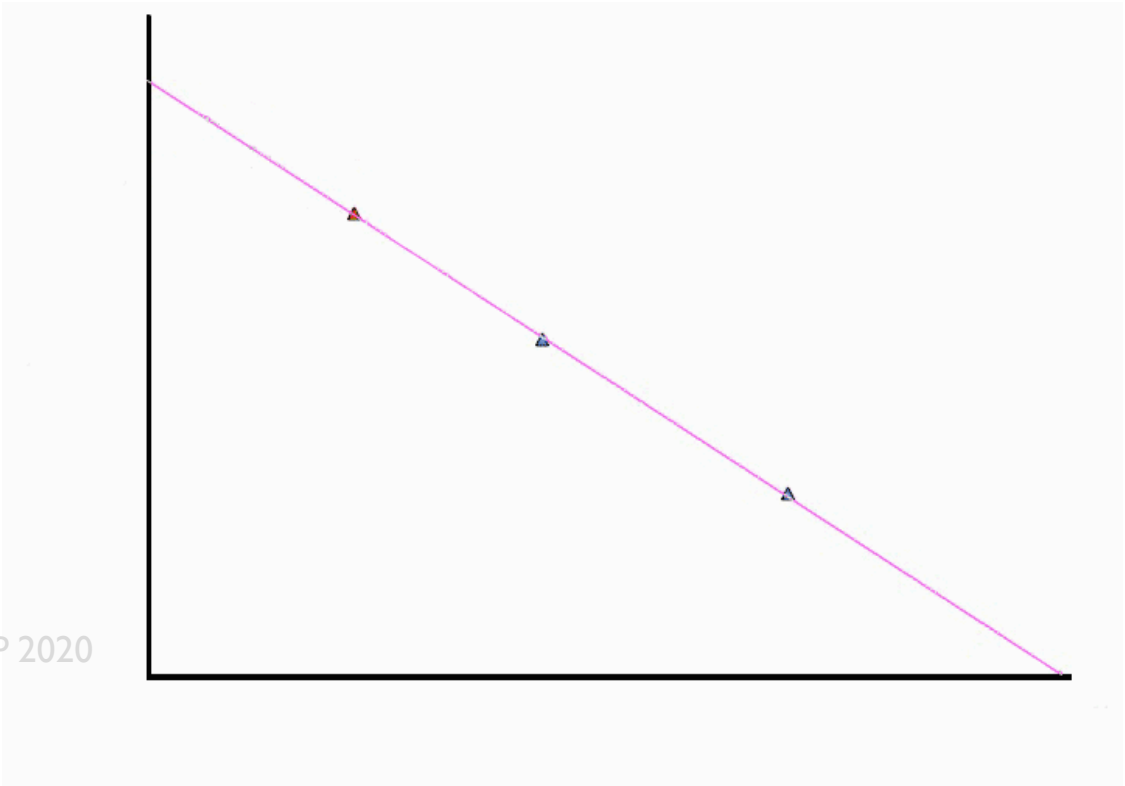
Galilean Moons: Europa

- Europa is highly geologically active, with volcanic activity very similar to Earth
- There is also a subterranean ocean on top of a rocky mantle, making the presence of hydrothermal vents seem likely



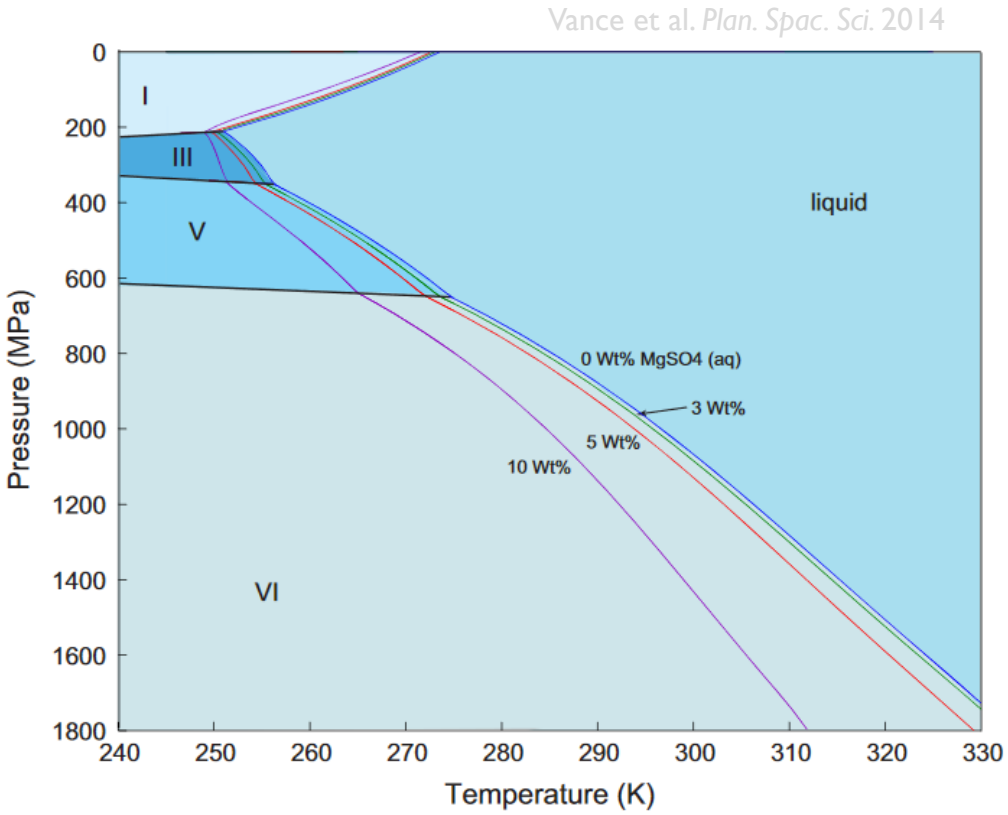
Europa

L. Quick *PASP* 2020



Galilean Moons: Ganymede

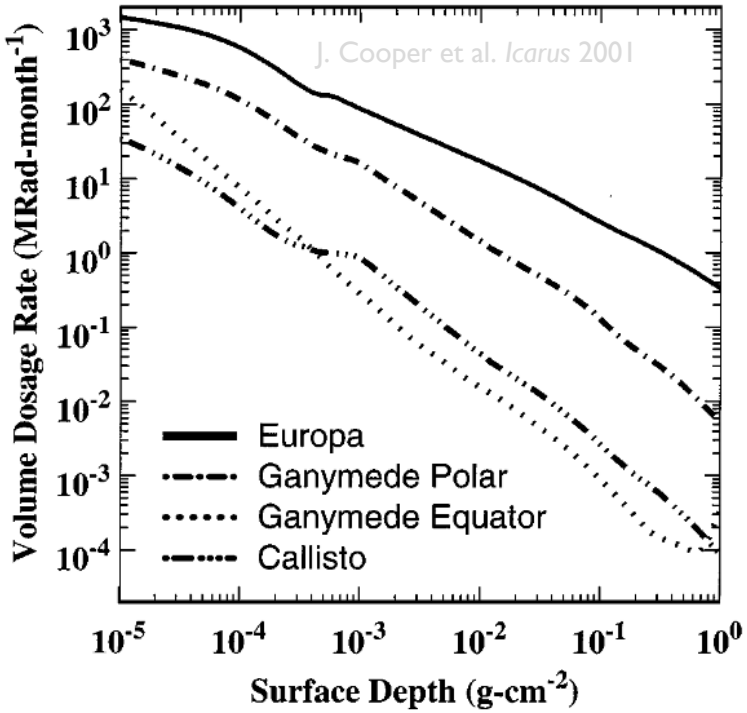
- Like Europa, thought to have a subterranean ocean
- Unlike Europa, models suggest that the sea floor is covered in ice, preventing rock-ocean interaction and therefore preventing hydrothermal vents
- However, concentrations of salts can lower the freezing temperature and maybe allow for water-rock interaction after all



Galilean Moons: Callisto

- Callisto has a heavily cratered surface, suggesting lack of geologic activity for a very long time
- Heating only comes from radioactive decay and not from tidal forces, which significantly reduces internal heat and therefore the likelihood of a significant ocean and especially hydrothermal vents
- However, the radiation levels are very low.
  As such it may be a promising base to use during space exploration in the (far) future

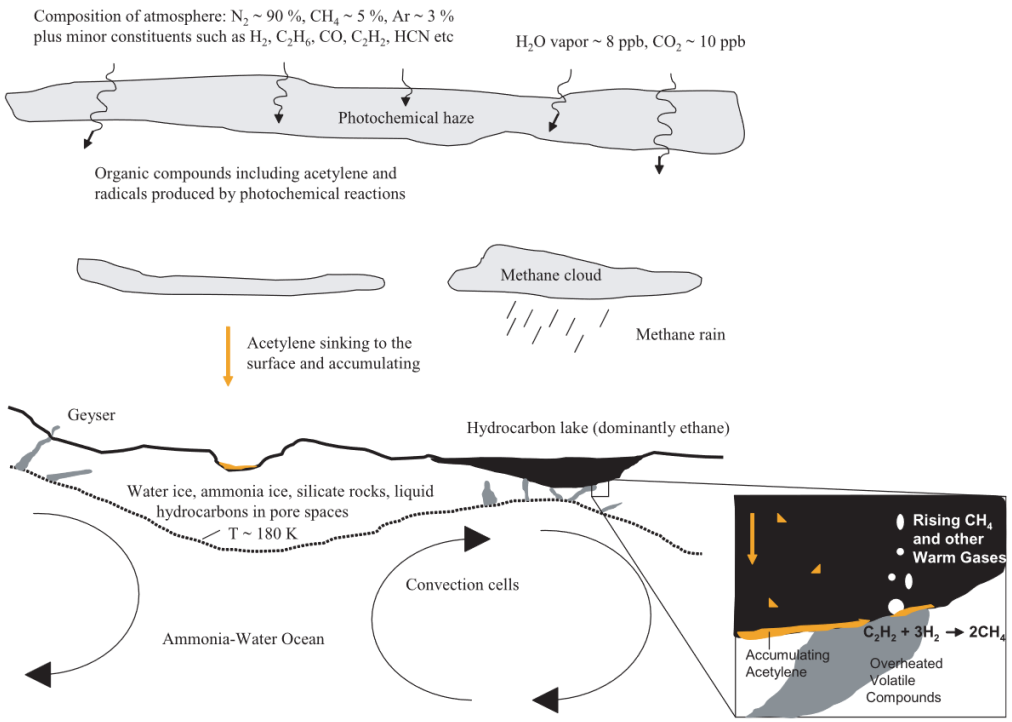
NASA/JPL/DLR



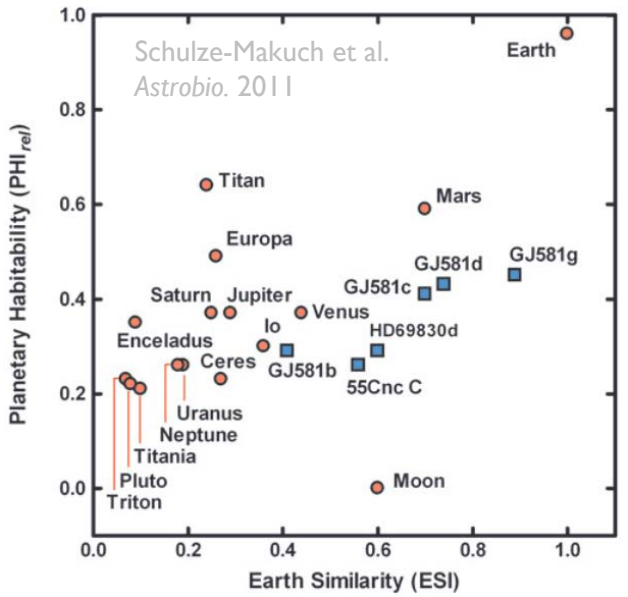
Saturnian Moons: Titan

- Hypothetically, life could maybe exist using methane as a solvent instead of water
- This methanogenic life would breath hydrogen instead of oxygen.
  - i.e. cellular respiration would not be: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$
    glucose
  - but instead would be: $C_2H_2 + 3H_2 \rightarrow 2CH_4$
    acetylene *methane*
- Titan has a relatively thick atmosphere (~1.5atm) and the only liquid oceans in the solar system outside of Earth
- Titan has a high "planetary habitability index", when considering (1) stable substrate, (2) available energy, (3) appropriate chemistry, (4) liquid solvent

Schulze-Makuch & Grinspoon *Astrobio.* 2005

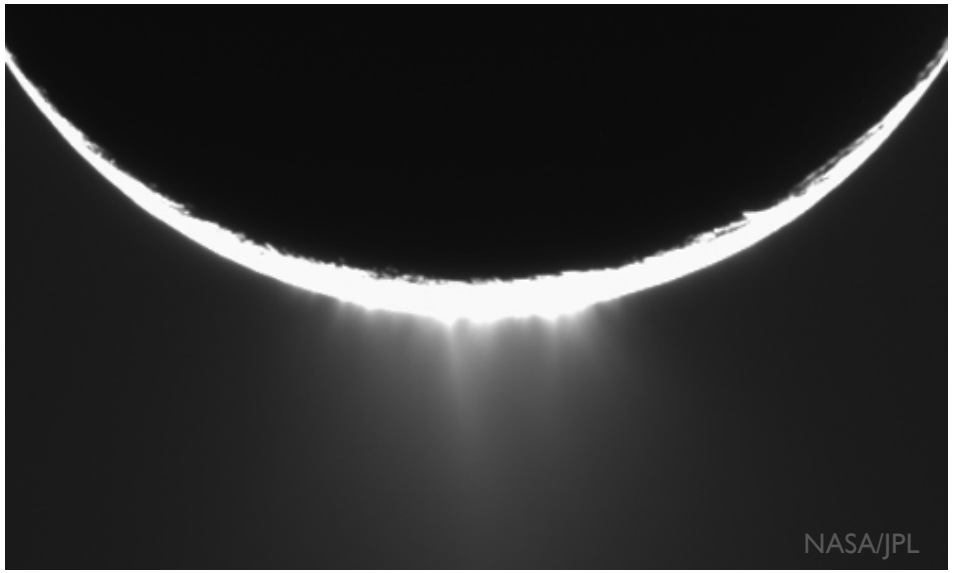


Schulze-Makuch et al. *Astrobio.* 2011



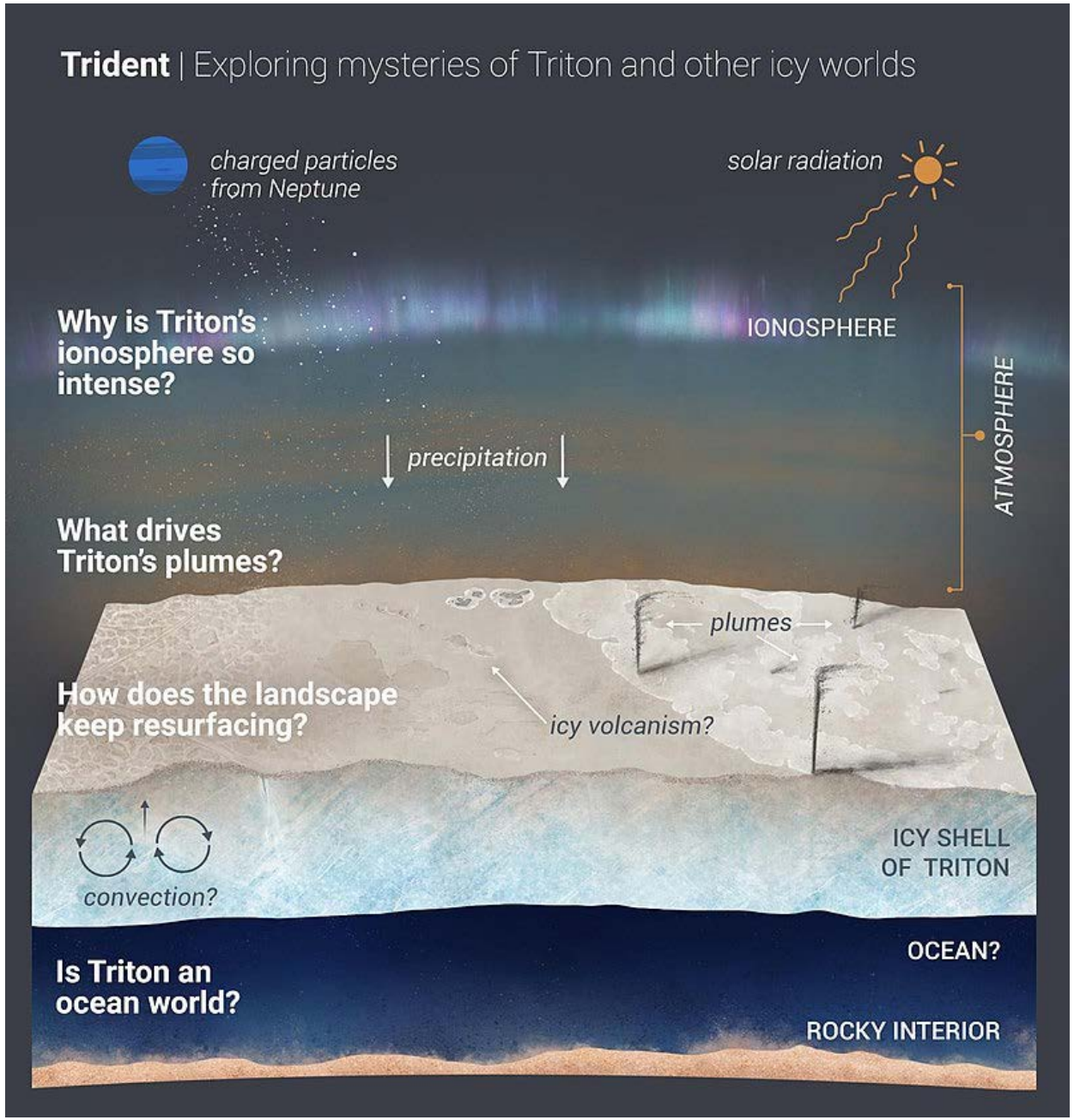
Saturnian Moons: Enceladus

- Enceladus has plumes of water shooting from the surface, indicating hydrothermal activity is present
- This makes Enceladus another favorite possible location for life in the solar system



Neptunian Moons: Triton

- Similar to the icy Galilean moons, tidal heating may have enabled a subterranean ocean and is therefore of interest in terms of habitability for the same reason



NASA/JPL-Caltech