

Chap 10 - The Atmospheres of the Inner Planets

- ***Atmosphere*** – gas in the form of individual atoms or more typically, of molecules.
- **Common molecules and their atomic weight:**
 - --carbon dioxide $\text{CO}_2 \rightarrow 12+2 \times 16 = 44$
 - --Argon Ar (a noble gas) = **40**
 - --nitrogen $\text{N}_2 \rightarrow 2 \times 14 = 28$
 - --water $\text{H}_2\text{O} \rightarrow 16+2 = 18$
 - --methane $\text{CH}_4 \rightarrow 12+4 \times 1 = 16$
 - --hydrogen $\text{H}_2 \rightarrow 2 \times 1 = 2$

How are Density, Pressure, and Temperature Related?

- Atmosphere's are well-approximated by the Ideal Gas Law
- $P = nkT$ (k=Boltzmann's constant)
- P= pressure, n the density of the gas, in terms of number of particles per volume, and T temperature
- Pressure (P) proportional to Temperature and to Density
- ***P* proportional to density x Temperature**

How does a planet retain an atmosphere?

- ***Surface gravity*** must be high enough and
- ***Surface temperature*** must be low enough, so that the atmosphere molecules don't leak away during the 4.6 billion years since formation.

Three ways a planet loses atmosphere: First...leakage

Lighter molecules move faster, because on average, *at a given temperature, heavier molecules move slower and lighter ones move faster... The kinetic energy of a particle (atom or molecule) is equal to:*

- $(\frac{1}{2})m\langle v^2 \rangle = (3/2)kT$
- For a given temperature, higher mass molecule means lower velocity molecule, is what this equation is telling us
- Molecules are continually bouncing off of each other and changing their speed, but if the average speed is higher, a few may be speedy enough to escape the planet's gravity.
- So the lighter gases leak away more quickly over time
- A Slow leak! Like air from a bicycle tire
- **Hydrogen and Helium = 97%** of the mass of the solar nebula, and these are the lightest and easiest molecules to lose, and the inner planets are too hot and too low gravity to retain them
- ***Ergo, ALL the inner planets have THIN atmospheres made of the rare HEAVY molecules***

To Avoid Leakage...

- A planet should have HIGH gravity (be massive)
- Should have LOW surface temperature (so molecules move slowly)
- Should have heavy molecules (like CO₂, not like H₂ or helium) unless the first two above are sufficiently favorable so that even the H₂ and He don't leak away

The second way to lose atmosphere...

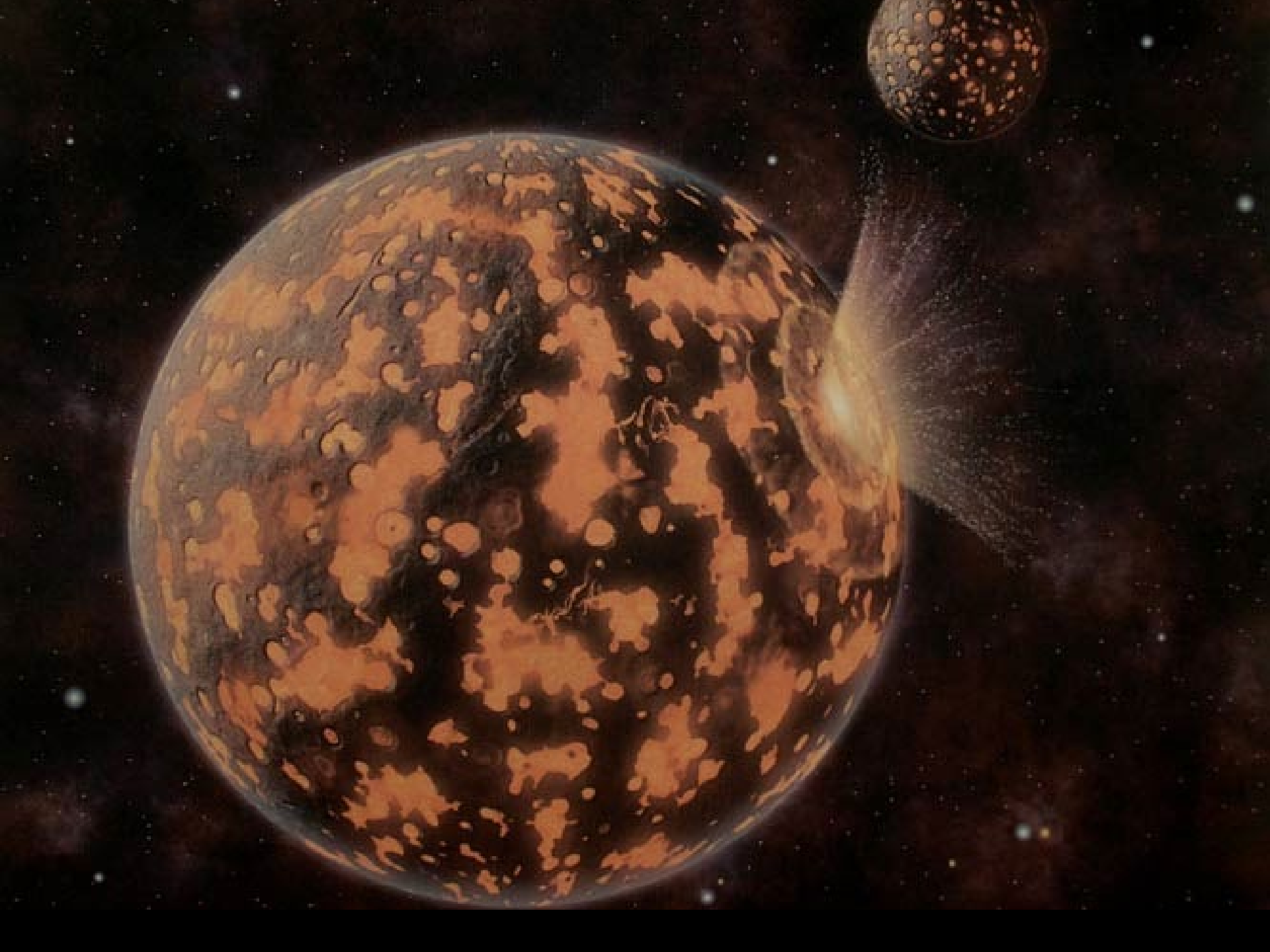
- ***Impact Cratering:*** Big comets and asteroids hitting the planet will deposit a lot of kinetic energy which becomes heat, blowing off a significant amount of atmosphere all at once.
- This is a Big issue especially in dense areas (inner solar system), and dense times (soon after formation).

The third way – “Sandblasted” away by the solar wind

- If a planet has a very weak magnetic field, the field can't deflect the high speed charged particles (electrons, protons, helium nuclei mostly) from the solar wind
- This is not a rapid process, but it can be effective if your planet doesn't have a lot of gravity to start with. **Mars fits this scenario**

So where did most of the solar nebula material go?

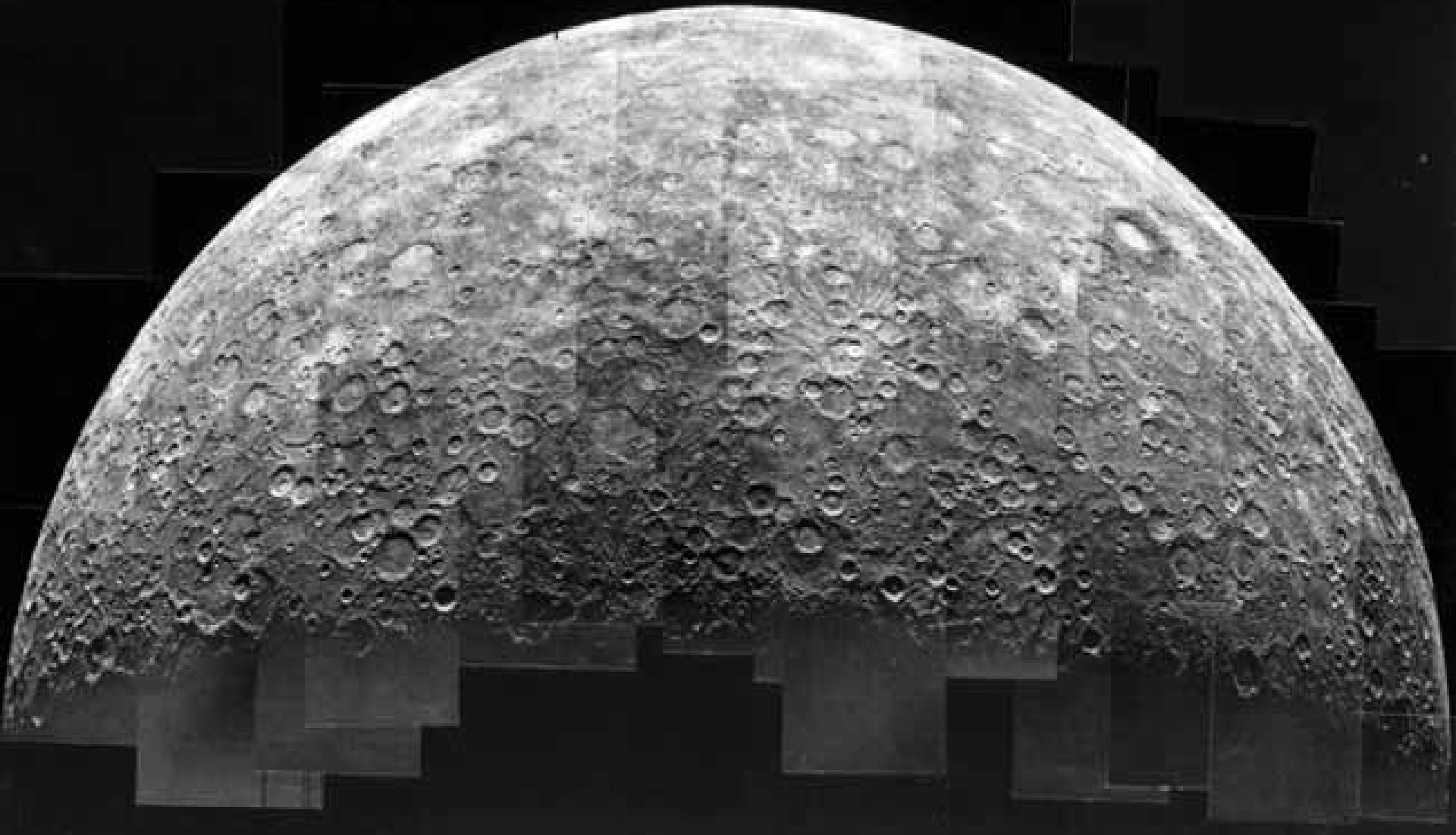
- It's hot close to the sun. So no ices. Only the rocky material (~3% of the solar nebula) could collect into self-gravitating objects. Not hydrogen and helium since the escape velocities on the inner planets are too low to retain them at warm temperatures; **these atoms were blown away; calculations indicate this is what halted planet formation,**
- Atmosphere histories for each planet are unique...as we'll see



Mercury

- Smallest planet, only 3,000 mi across.
- 600F on daylight side, too hot to retain significant amount of atmospheric molecules at all. Doesn't help that the sun is so close and solar storms can rack the planet and help carry off any atmosphere.
- Heavy cratering demonstrates an ancient surface, shows it hasn't had atmosphere for most of solar system's history
- Early volatiles baked away.
- Today, atmospheric pressure is **1 ten trillionth** that of Earth. Composition is heavy elements baked out of the crust and also some contributed by the solar wind. All are streaming away from Mercury on the tail side.

Mariner 10 flyby of Mercury in 1974

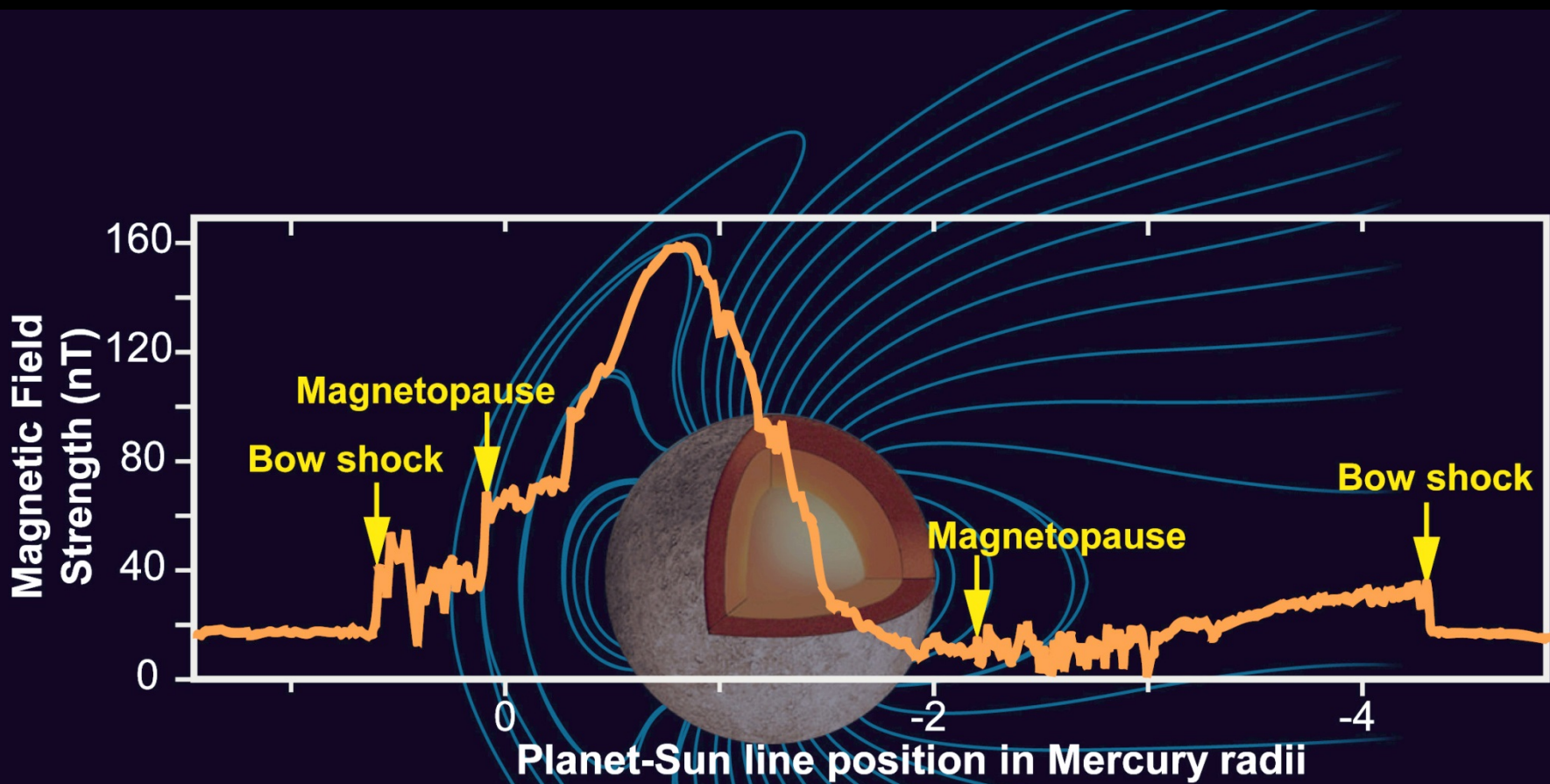




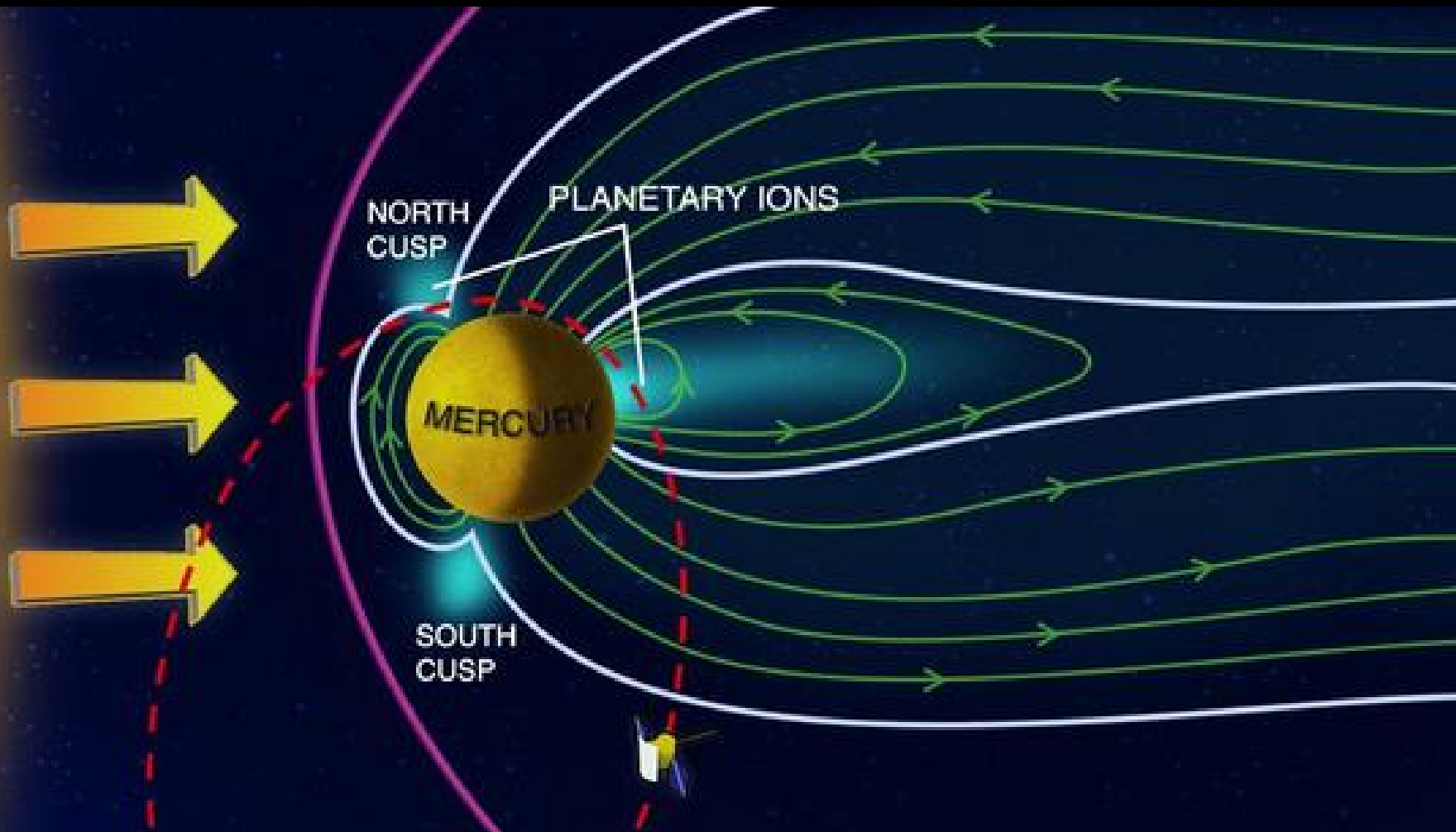
Much
sharper
cameras on
the 2014
Messenger
Mission to
Mercury

Mercury's magnetic field: Only 1% as strong as Earth's

- This was surprising – since Mercury has a massive iron core twice as large (relative to the planet itself) as the Earth.
- The explanation seems to be, the strong solar wind so distorts the magnetosphere that it has almost eliminated the magnetic field
- Weak field may also help explain the lack of atmosphere



Mercury's Distorted Magnetopause and Weakened Magnetic Field



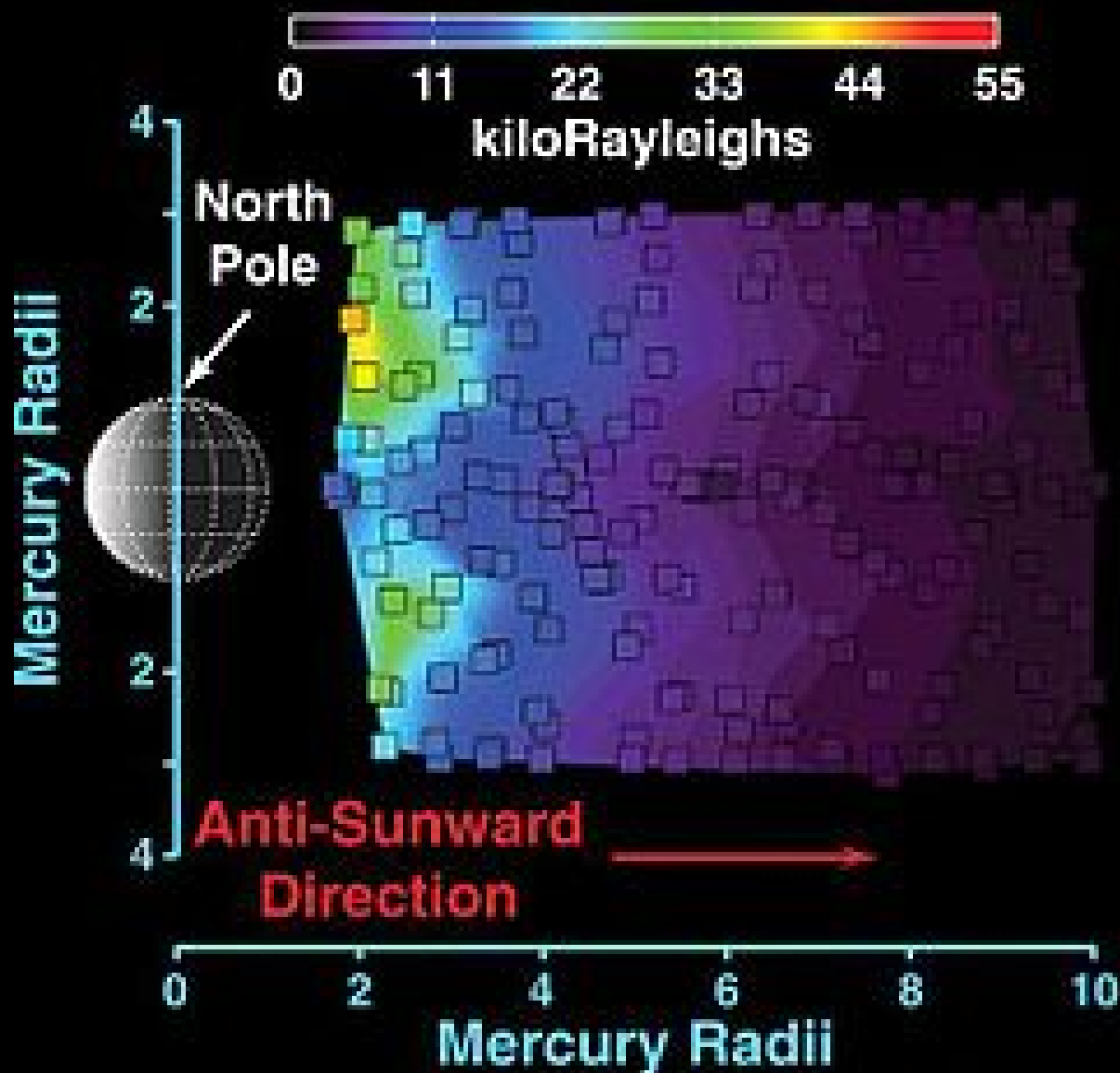
See Anything Interesting Here?



Evaporation Cracks

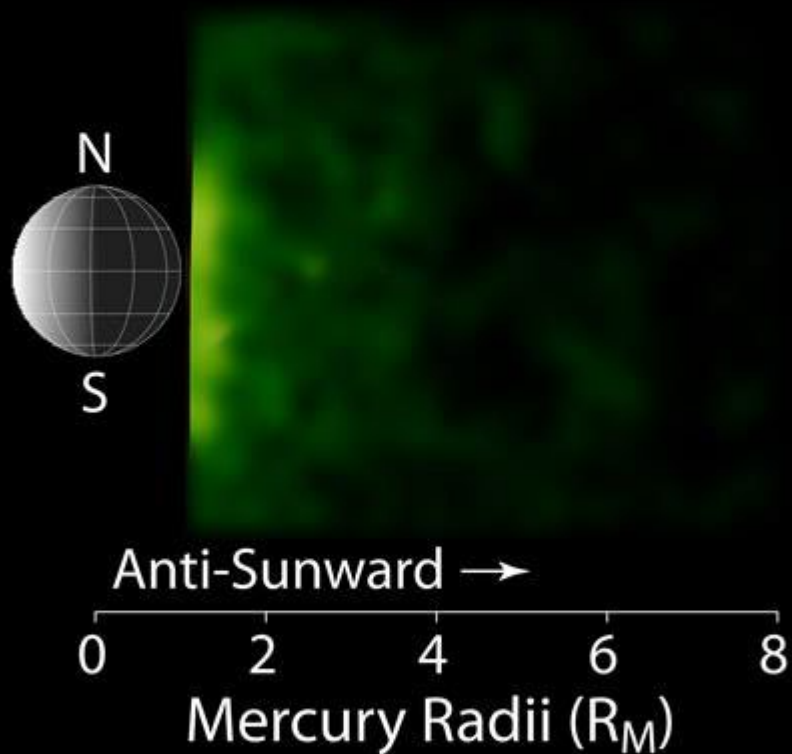
- Indicating early in Mercury's history, it had volatiles (water?) as part of its crust, which were baked out, lowering the volume, and opening these cracks.
- This must have happened after Mercury had developed a solid crust

Mercury's Sodium Tail

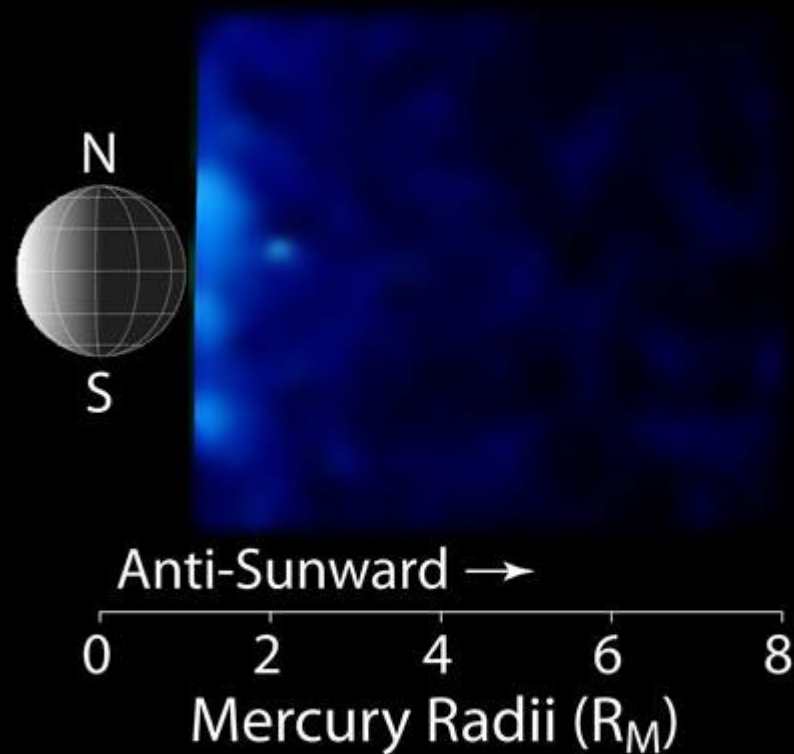


Calcium and Magnesium Emission

Calcium



Magnesium



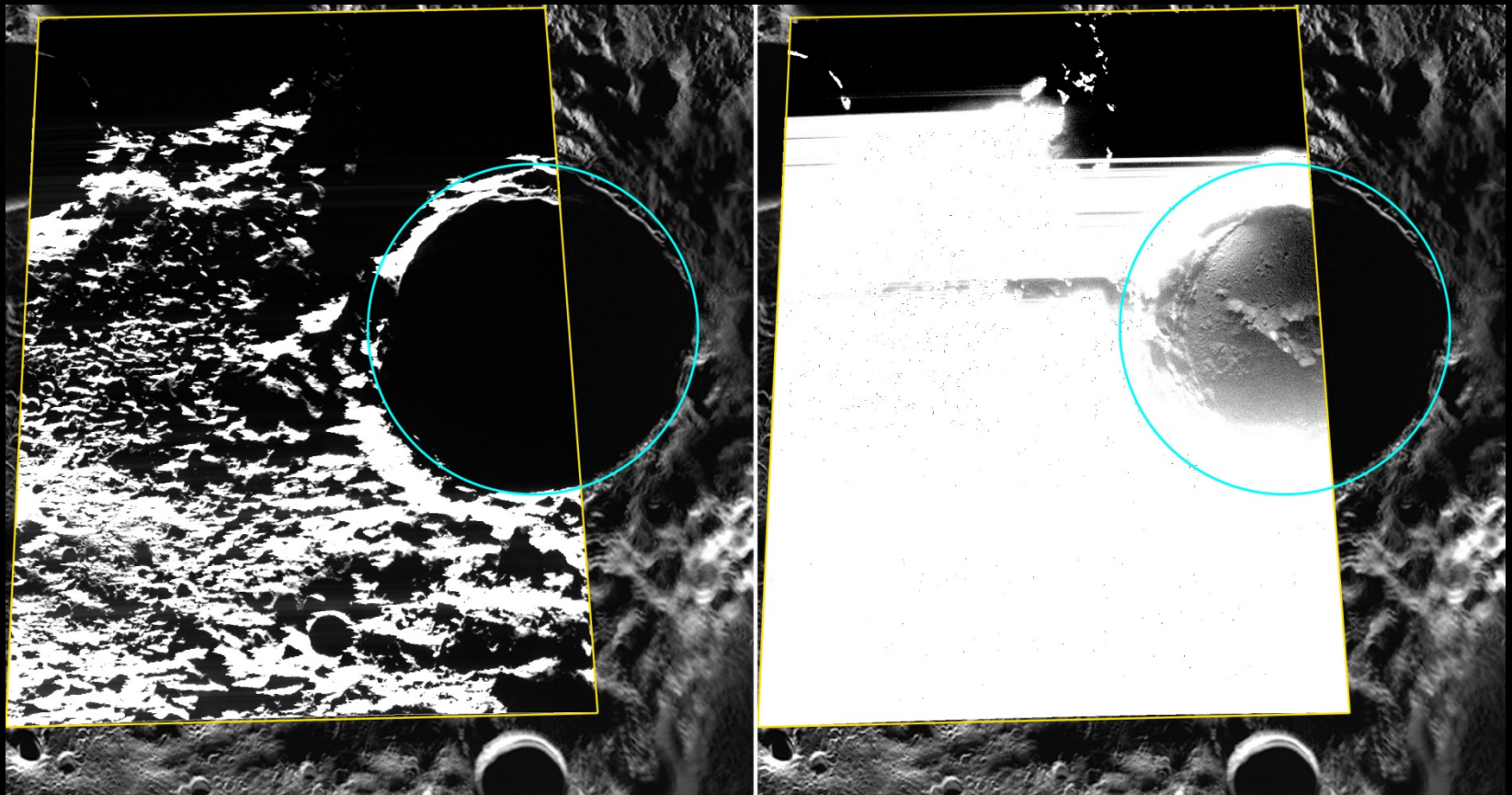
These Heavy Atoms Are Blasted off of Mercury's Surface

- By the solar wind
- Then blown away
- Very very low density

Without an atmosphere, climate is simple

- Mercury rotates 3 times for every 2 times around the sun.
- The day is 59.3 days long; that's 30 days of intense sun, and 30 days of black cold
- 600F on the day side
- -100F on the night side, after it cools off
- Except at the bottoms of a few craters at the poles, which never get sunlight and are perpetually frozen cold

**Icy crater at the pole which
never sees the Sun. Comet
impacts over the eons??**

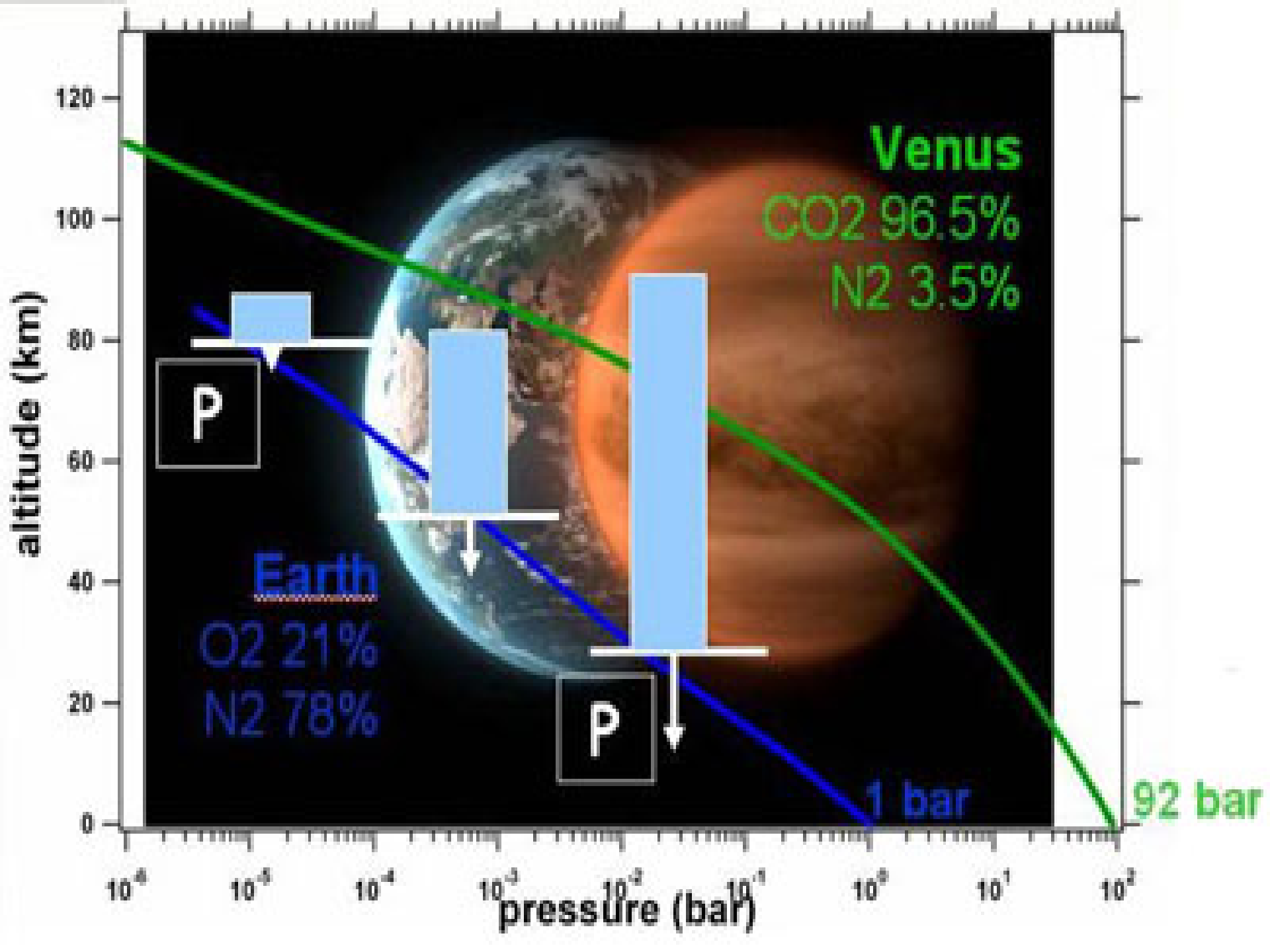


Venus – Similar to Earth in Size and Surface Gravity

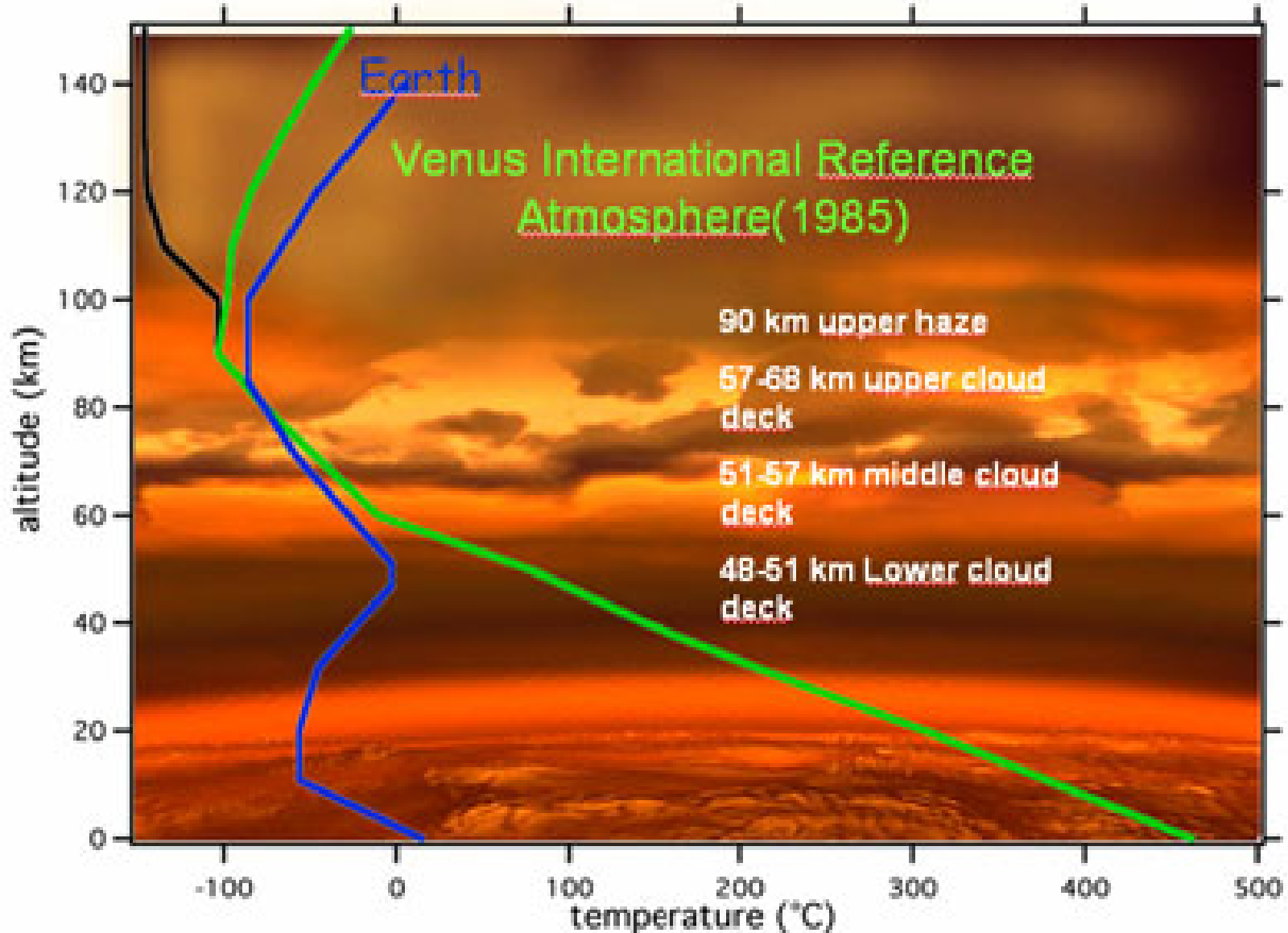


Early Venus

- With sun 25% dimmer, climate may have been similar to present Earth
- Water is a very common molecule, delivered to all planets via comet impacts and meteorites – likely meaning...
- Venus had an ocean.
- Early atmosphere composition? No direct evidence, of course, so we don't really know.
- Today's atmosphere... 95% CO₂



Before “Venus Express” – Best guess atmosphere profile...



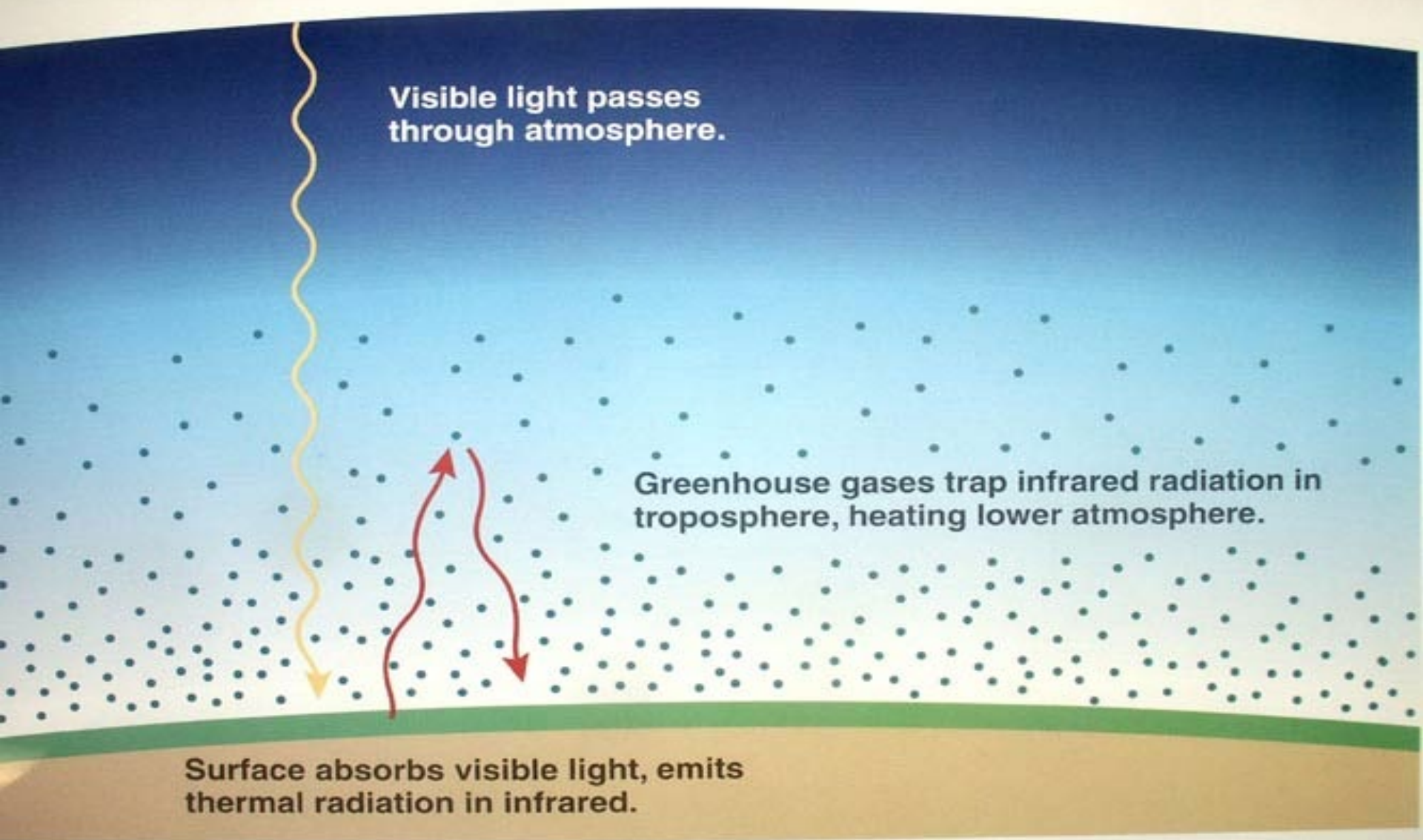
Key discovery of Venus express...

- Dry! The water vapor in the atmosphere at present, if condensed to liquid, would make a layer around the planet of only 3 cm deep (vs. ~500,000 cm for Earth)
- At top of atmosphere, solar UV breaks apart H_2O into H and O_2 . O_2 combines with surface geology to make oxides, while the Hydrogen escapes to space.
- The current measured escape rate of H strongly suggests that Venus had an ocean, and it lost it fairly early in its history

The Greenhouse Effect

- The sun radiates as a 5800K thermal radiator, putting most of its light into the visible band. A Greenhouse gas is transparent at these wavelengths – the light goes down to the surface and heats it up.
- The surface then will radiate as a thermal radiator, in this case, a few hundred K and this is in the far Infrared band
- The IR band has large absorption bands for GHG's, so heat transport through the atmosphere back out into space is slow, requiring a higher surface and lower atmosphere temperature to drive the gradient high enough to transmit the heat upward.
- The atmosphere heats up, reradiates and some of this radiates back to the surface where it further heats the ground.
- This continues until the upper atmosphere is hot enough to radiate all that is received from the sun and temperature equilibrium is restored.
- Net effect – a hotter lower atmosphere and surface

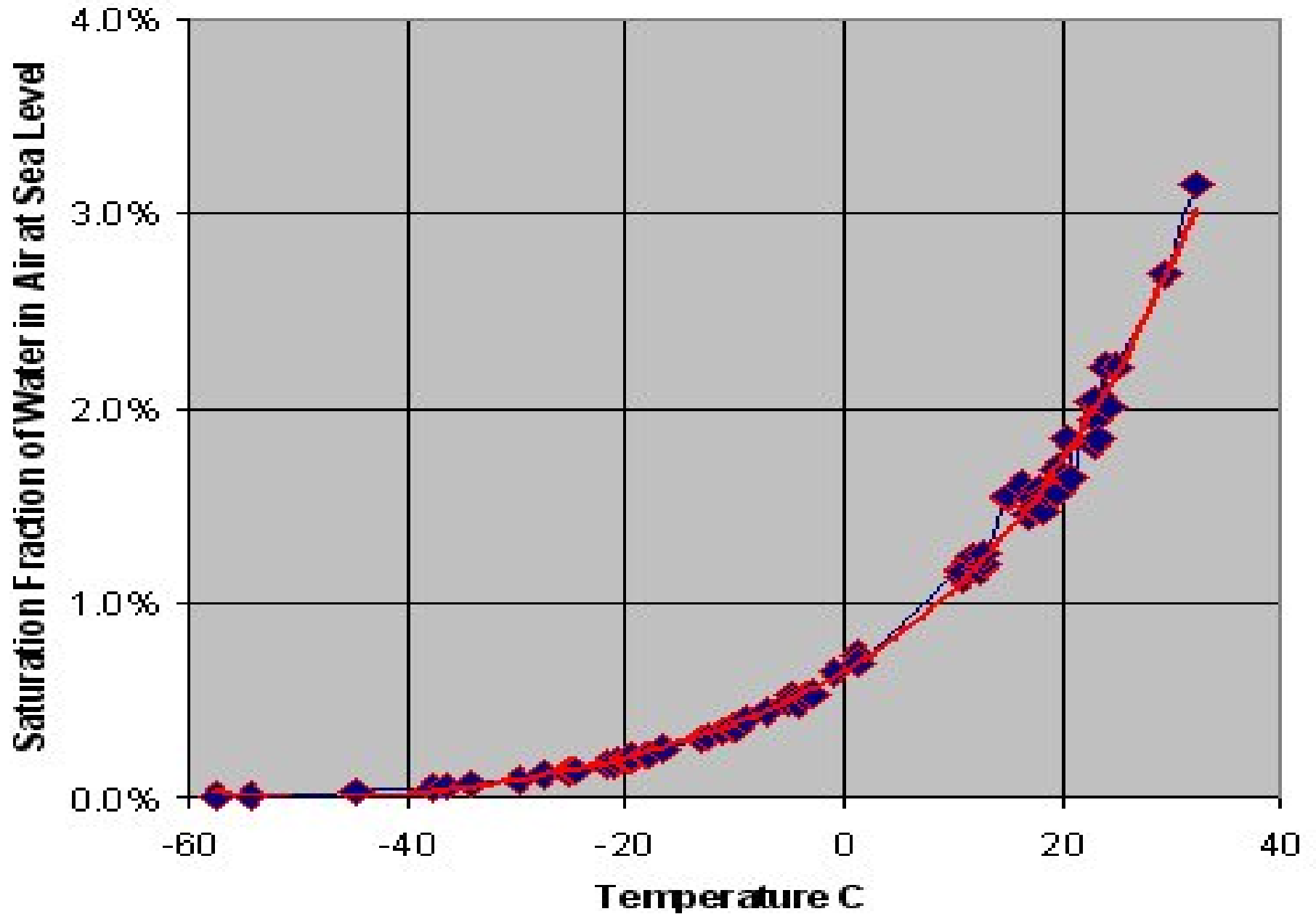
The Greenhouse effect



The Runaway Greenhouse Syndrome

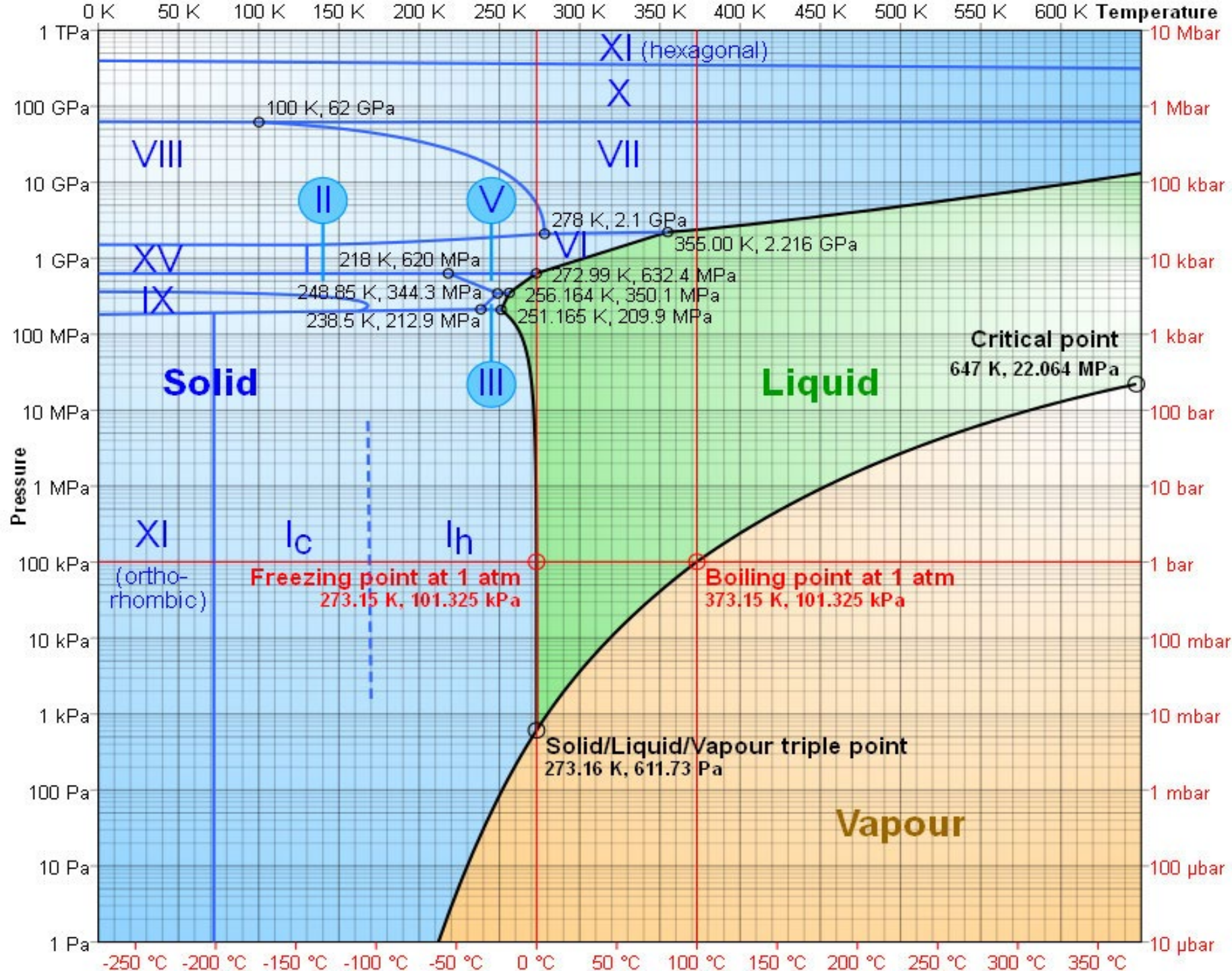
- CO₂ greenhouse causes rising temperatures, which cause more water to evaporate from the ocean, raising the absolute humidity of the atmosphere because warmer air can hold more water vapor.
- But water vapor is itself a greenhouse gas and so raises the temperature further...
- **This is an amplifying feedback cycle! This is also true on Earth, at this point**
- Runaway occurs if the temperature raises the water vapor fraction so high that it migrates all the way to the stratosphere where solar UV can dissociate the H₂O into H and O, so that the H, being so low-mass and therefore so fast-moving, escapes to space.
- Thus, a leakage which removes water from the planet, till it turns bone-dry. Thankfully, this looks highly unlikely on Earth until the incoming solar luminosity becomes much higher

Saturation Fraction of Water in Air at Sea Level

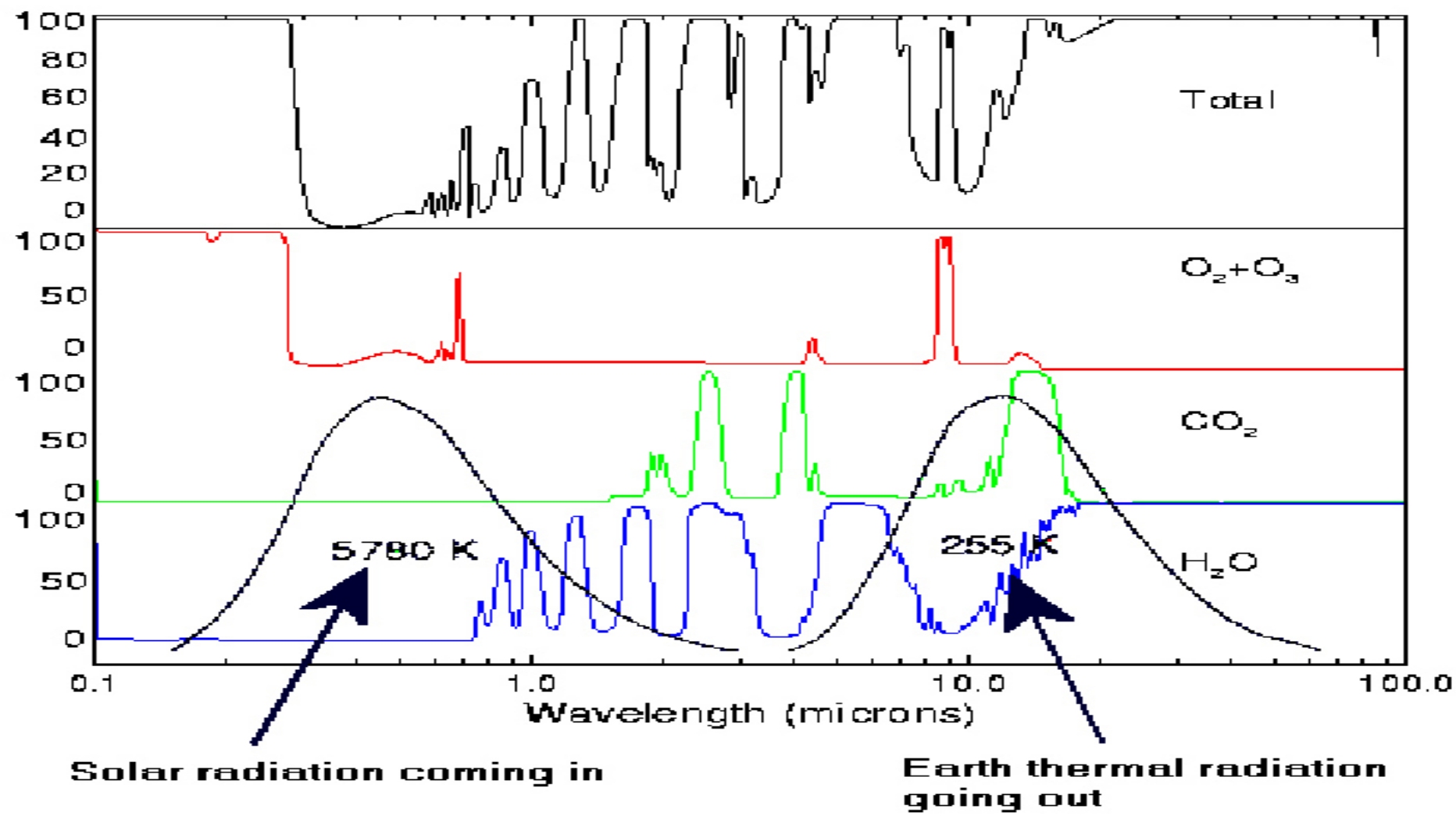


Notice: Saturation humidity is sharply non-linear with Temperature.

- We in this room are about 20 C on this curve.
- The acceleration in this curve helps initiate the “runaway” feedback cycle.
- When water vapor levels rise into the upper stratosphere, where they cannot rain back out, and where the solar UV is strong...
- UV will dissociate the H₂O and thus lower the humidity and this readies this air to accept more H₂O from below
- This continues until all water has been destroyed.



Notice how CO₂ and H₂O absorption bands combine to blanket outgoing IR



As the Water Vapor Level Rises...

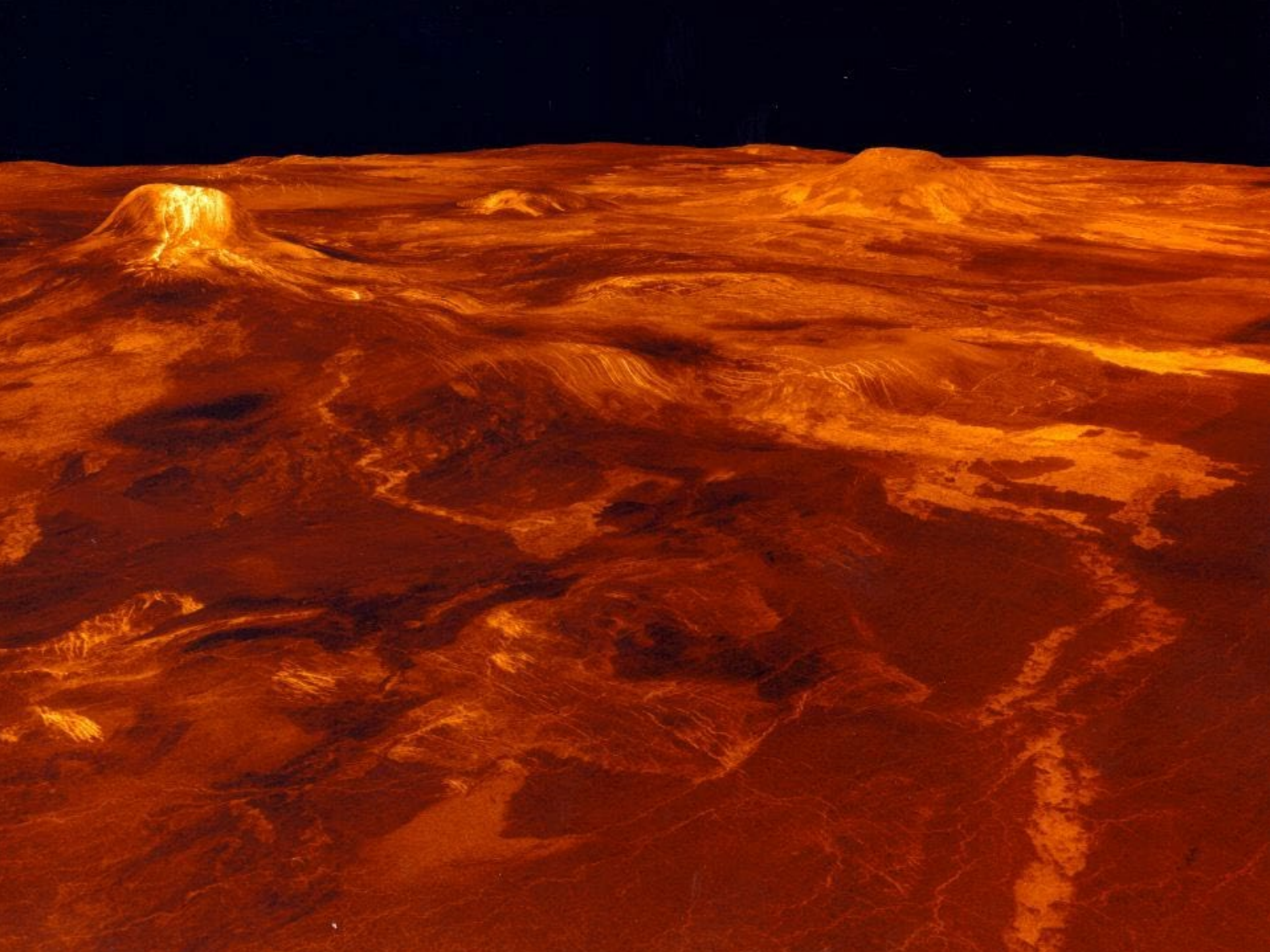
- Greenhouse heating rises, forcing more water vapor, forcing more heating.... An amplifying feedback which runs away...
- Until the oceans reach the vaporization point and water vapor is so dense it rises significantly into the upper atmosphere where...
- H₂O is split by solar UV into O and H
- The O₂ combines with rocks to make oxides (e.g. iron oxide, aluminum oxide, etc)
- H, as we saw, will escape Venus' gravity into space
- The atmosphere is then left with CO₂, and little else.
- **But, Venus has no ability to make CO₂ into rock, no plate tectonics, and no carbon cycle like the Earth has (more on that later).**
- **So the CO₂ stays in the atmosphere, forever.**
- **That's bad....**

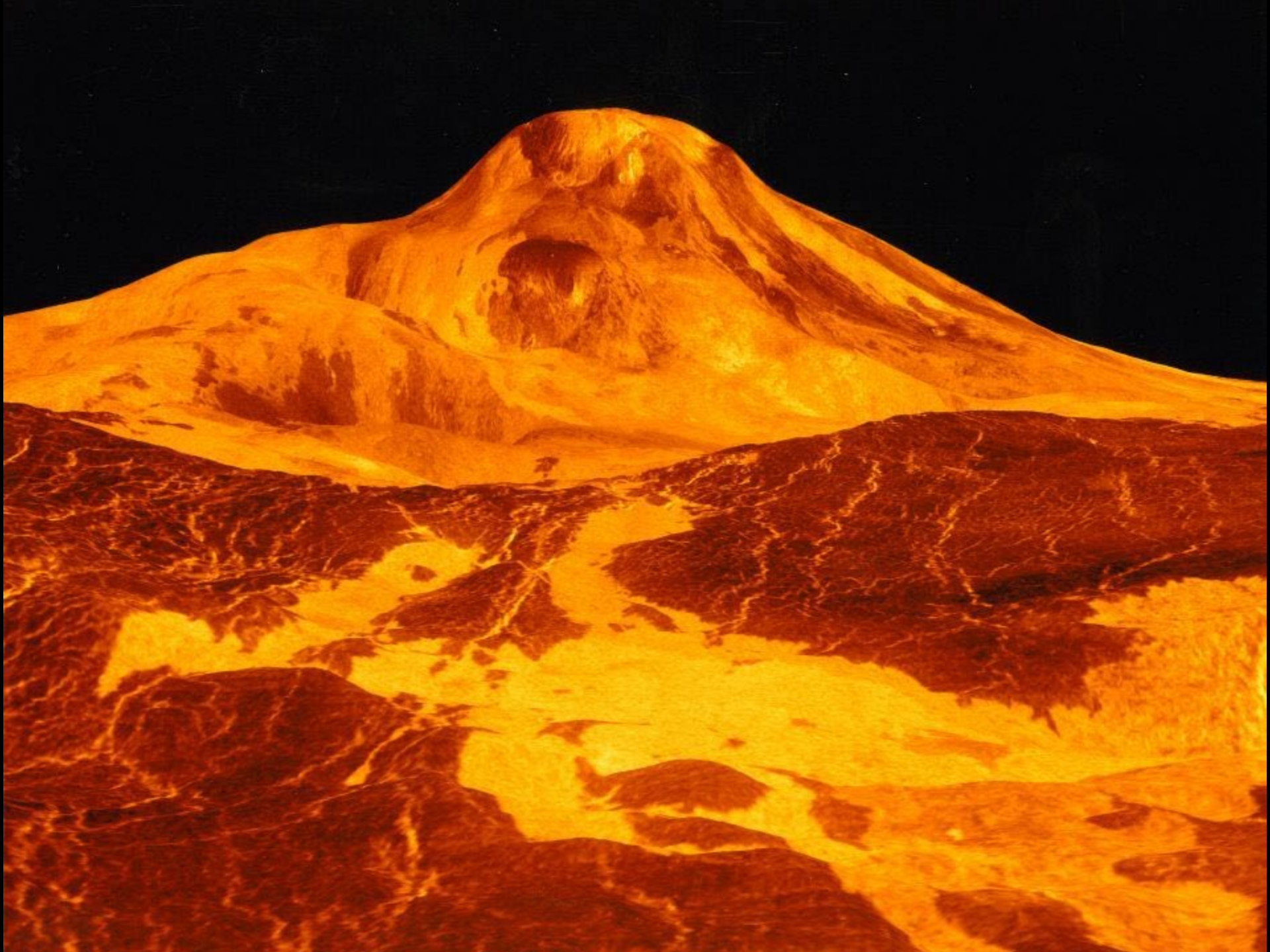
Why no plate tectonics?

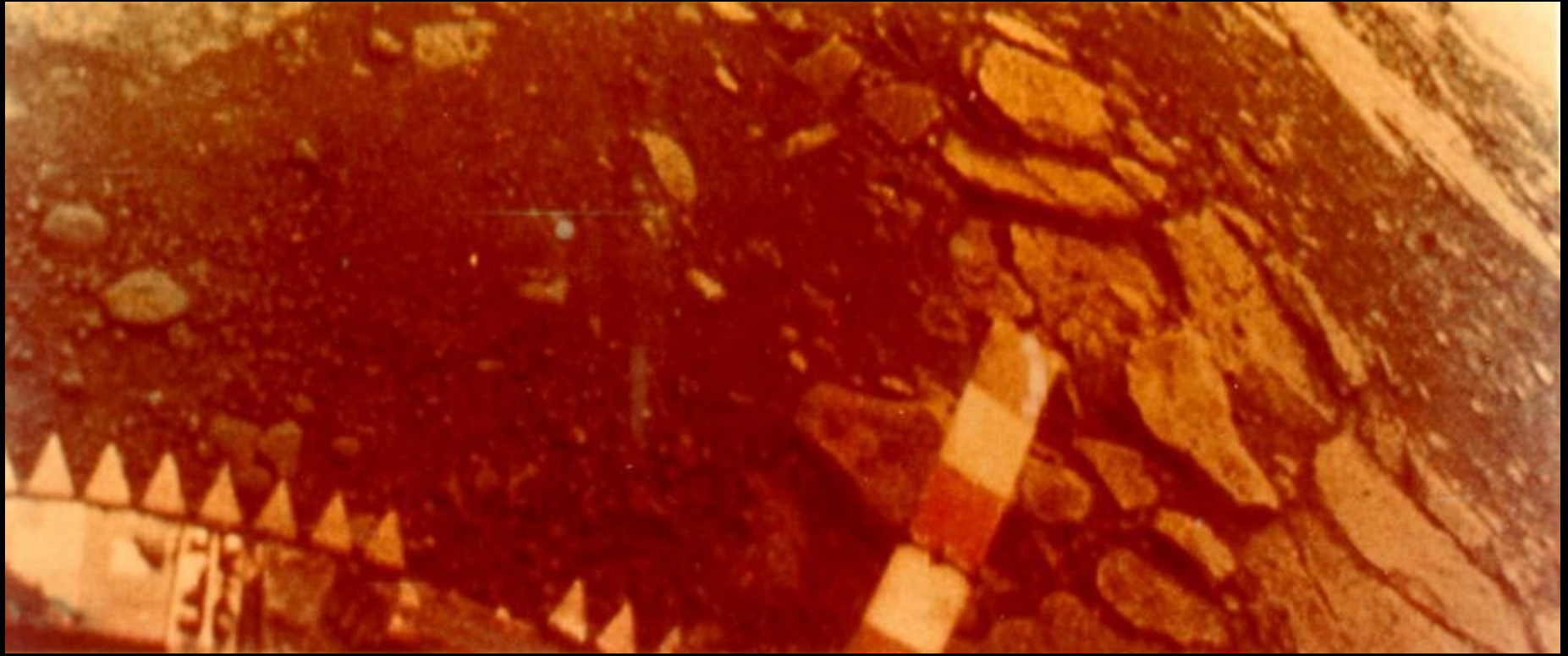
- Rapid spin rate helps to drive plate tectonics, but Venus rotates only once in 243 days (and backwards relative to most planets)
- Early collision took away ~all of its rotation?
- Venus year is 224 Earth days
- It has estimated ~100,000 volcanoes, but not driven by tectonics like on Earth. Probably just a very thin crust.
- 60 km up, is a layer of thick opaque sulfuric acid droplets – sulfur from volcanoes?
- These are very reflective – that's one reason Venus is so bright in our evening sky
- These keep temperatures from being EVEN hotter on Venus

Net Result...

- A ~pure CO₂ atmosphere, with a bit of Nitrogen.
- Surface temperatures of 735K ~ 900F
- Atmospheric pressure 100x that of Earth.
- The high density effectively heats the night side almost as much as the day side.
- And poles too.







Future of Venus Climate?

- More of the same, only worse
- Solar luminosity will slowly rise.
- Venus can't get any drier
- Perhaps the volcanos may slowly diminish, since the crust may thicken (slowly) with time. This may reduce sulfuric acid content, which would probably reduce the albedo, absorbing more incoming solar radiation
- Hot and getting hotter, likely forecast

The Moon. What can one say? It's dead. No atmosphere, no hint of any early atmosphere. Atmospherically, it's aborted.

Stillborn. Not alive now or ever.



Impacts broke through crust, show early bombardment period. Moon rocks show age 3.2B yrs for maria, 4.5B yrs for highlands



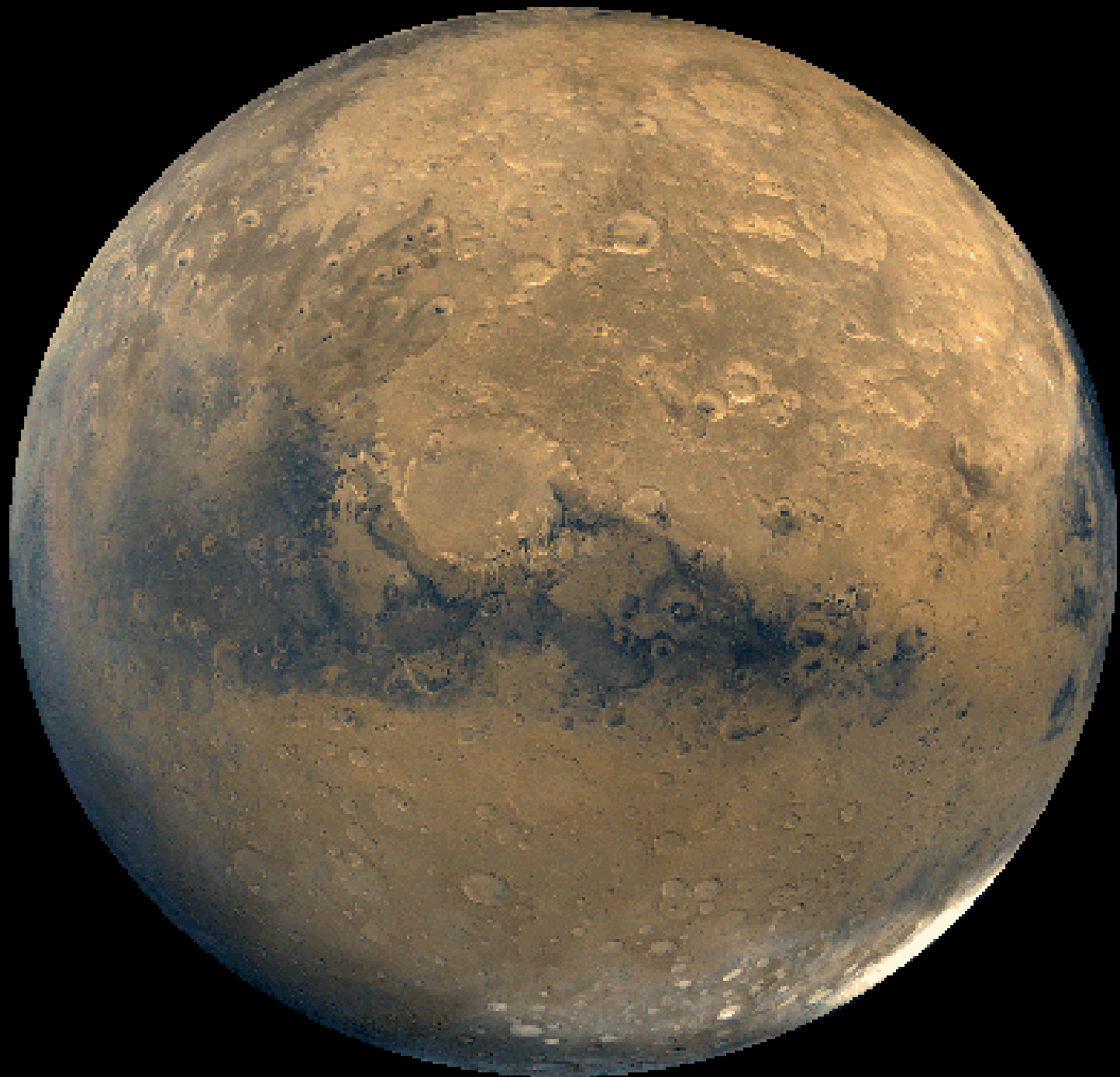
Craters on top of craters – sign of an ancient surface.
Lunar highlands here almost as old as the solar system
– 4.5 Billion Years.



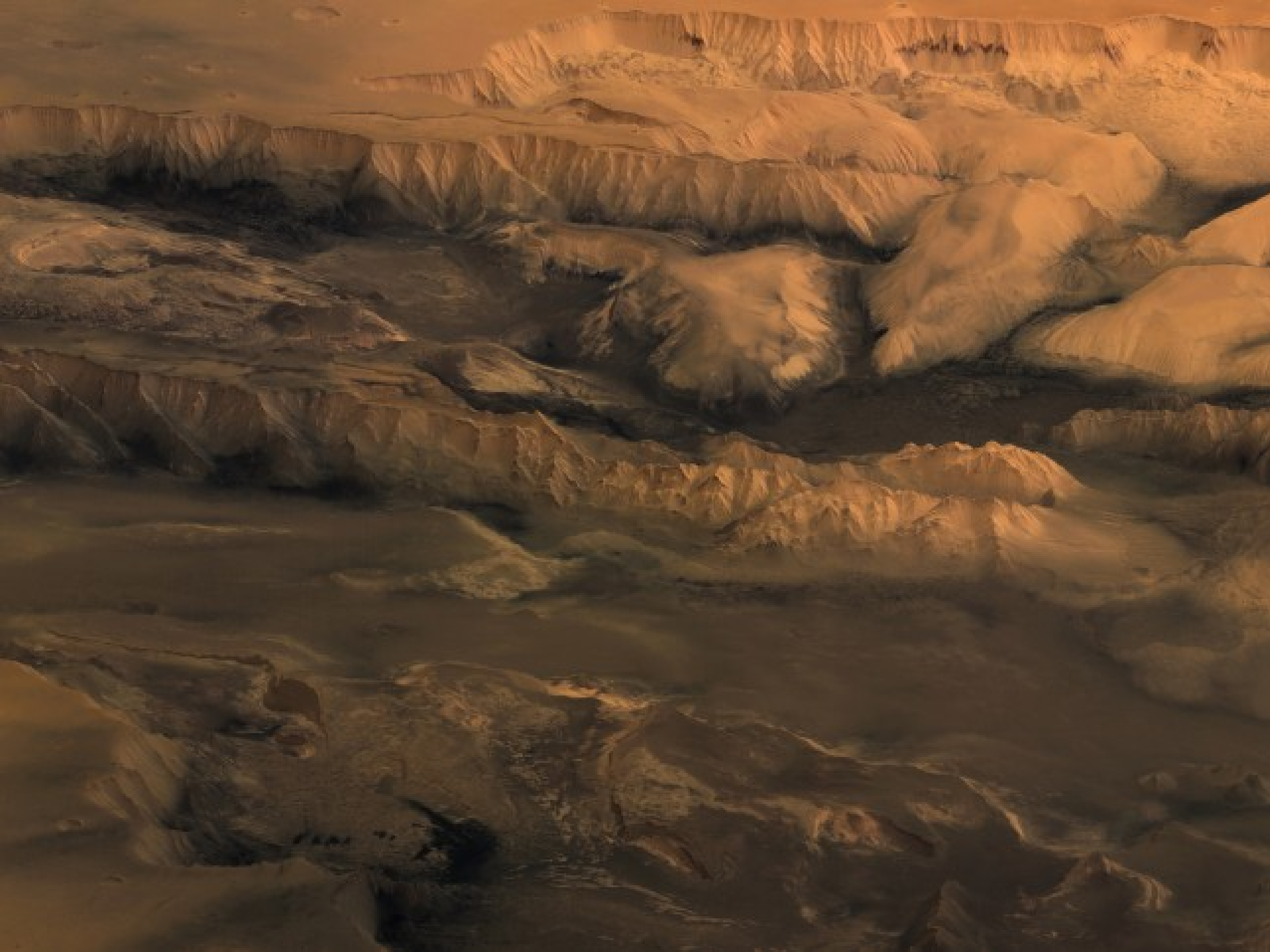
Mars – A pure CO₂ atmosphere

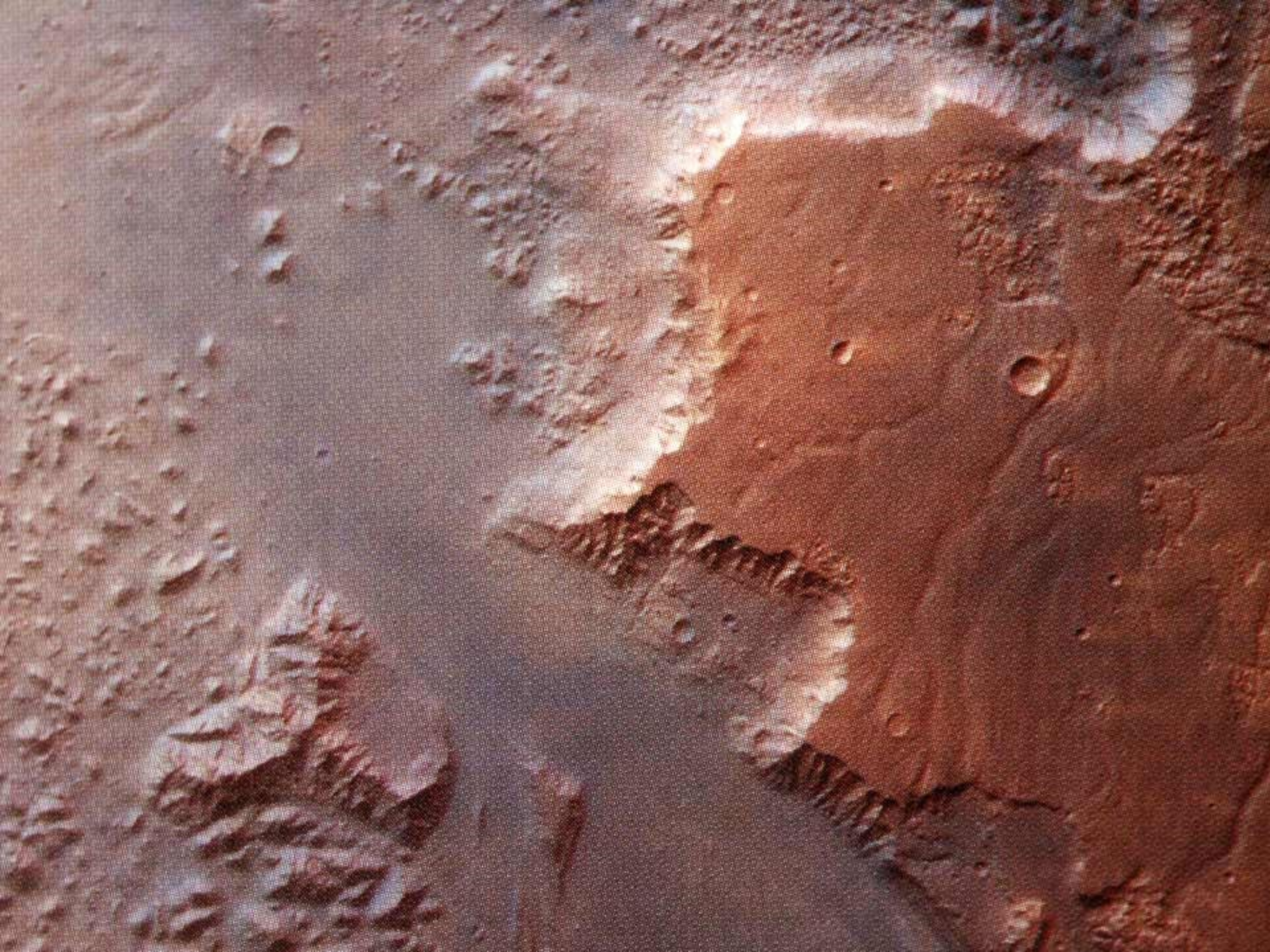
- ...But not much of it. Only 1% of Earth's atmospheric pressure. Why so little?
- Mars shows limestone rock, so some of the CO₂ got turned into rock in the ancient oceans
- Impact cratering – Mars is close to the asteroid belt, and likely gets hit more than the Earth. And, it has already captured 2 asteroid - can only do that if they lost some orbital energy, like impacting, or hitting ring material?

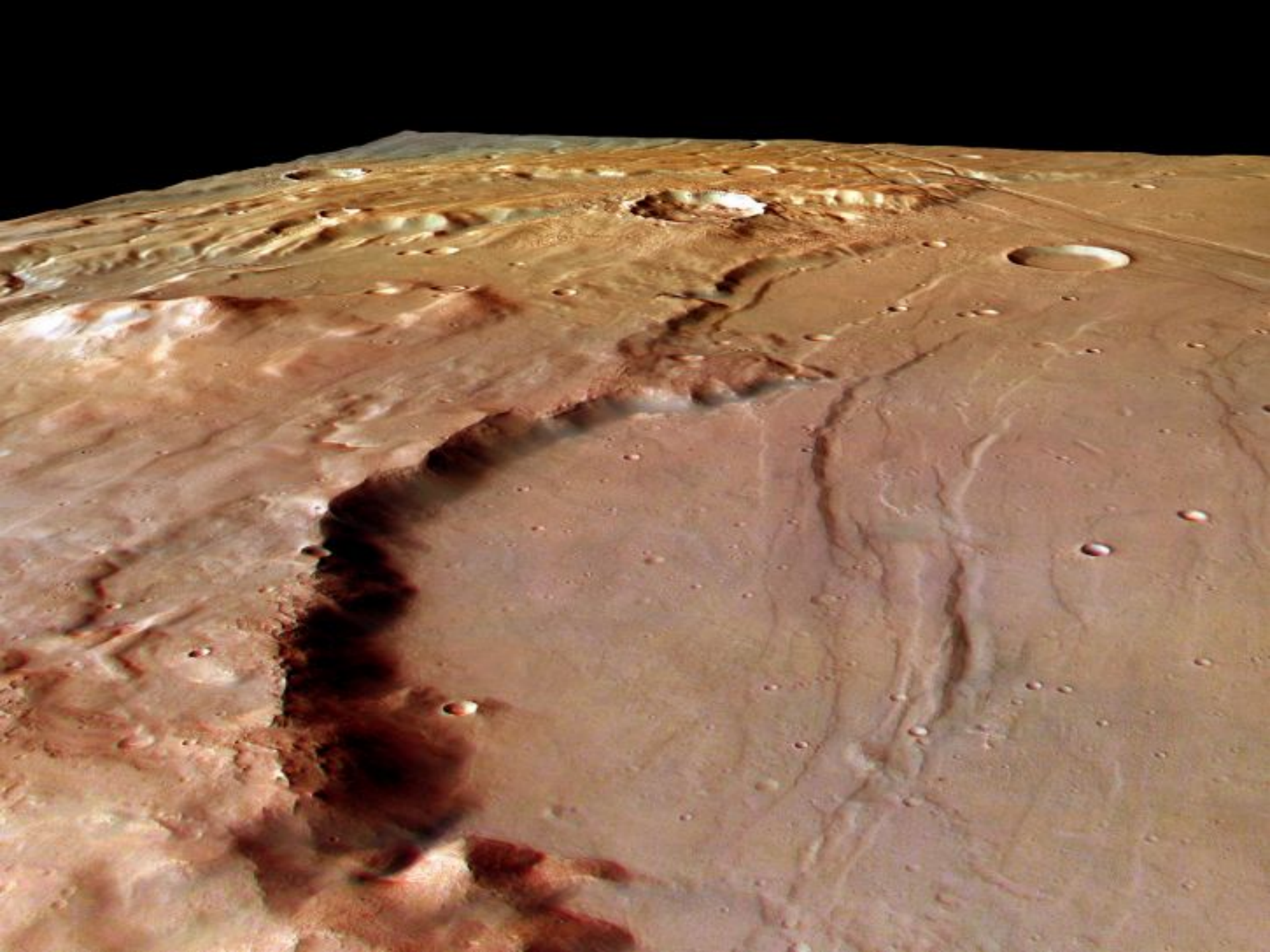




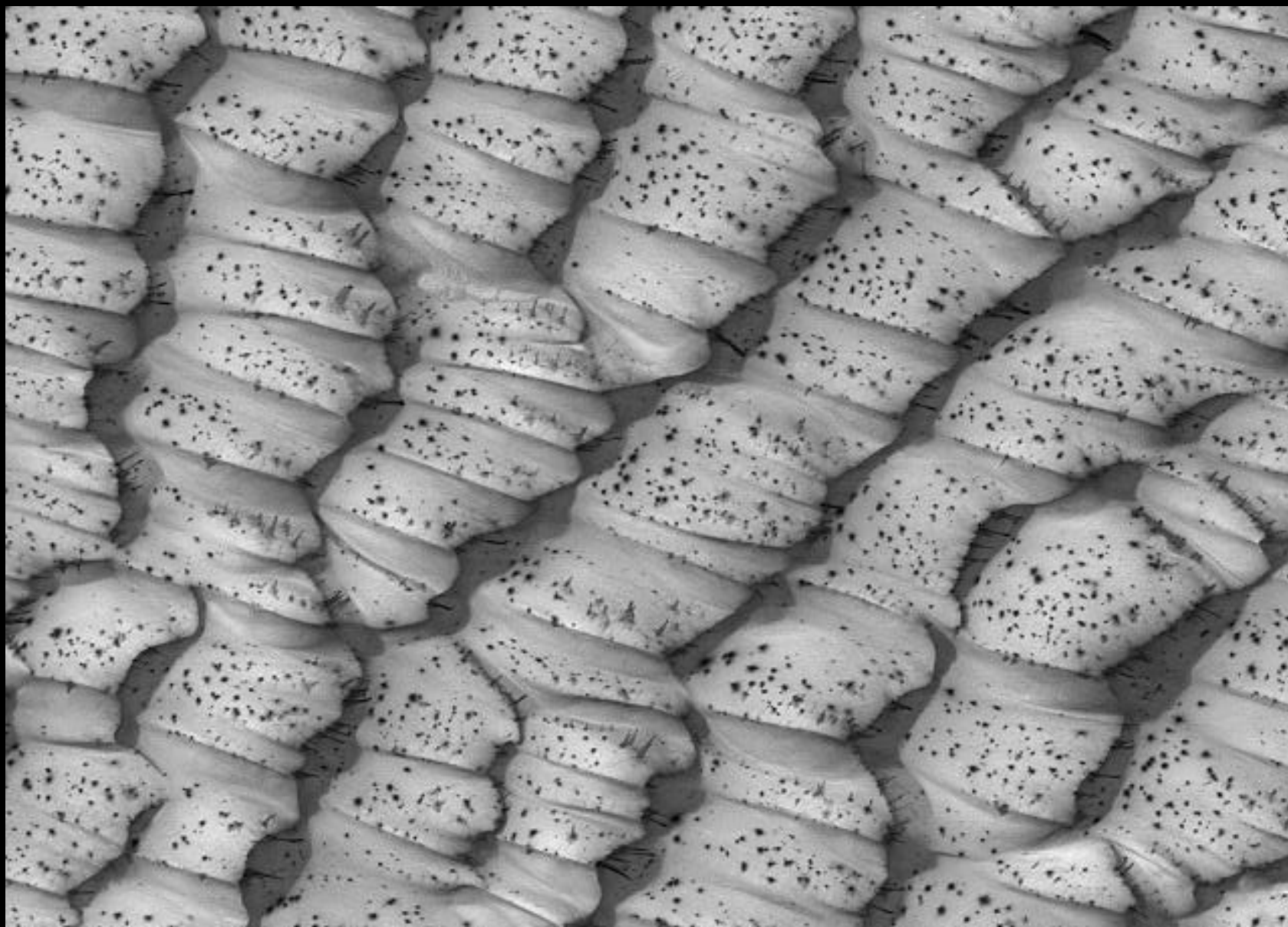




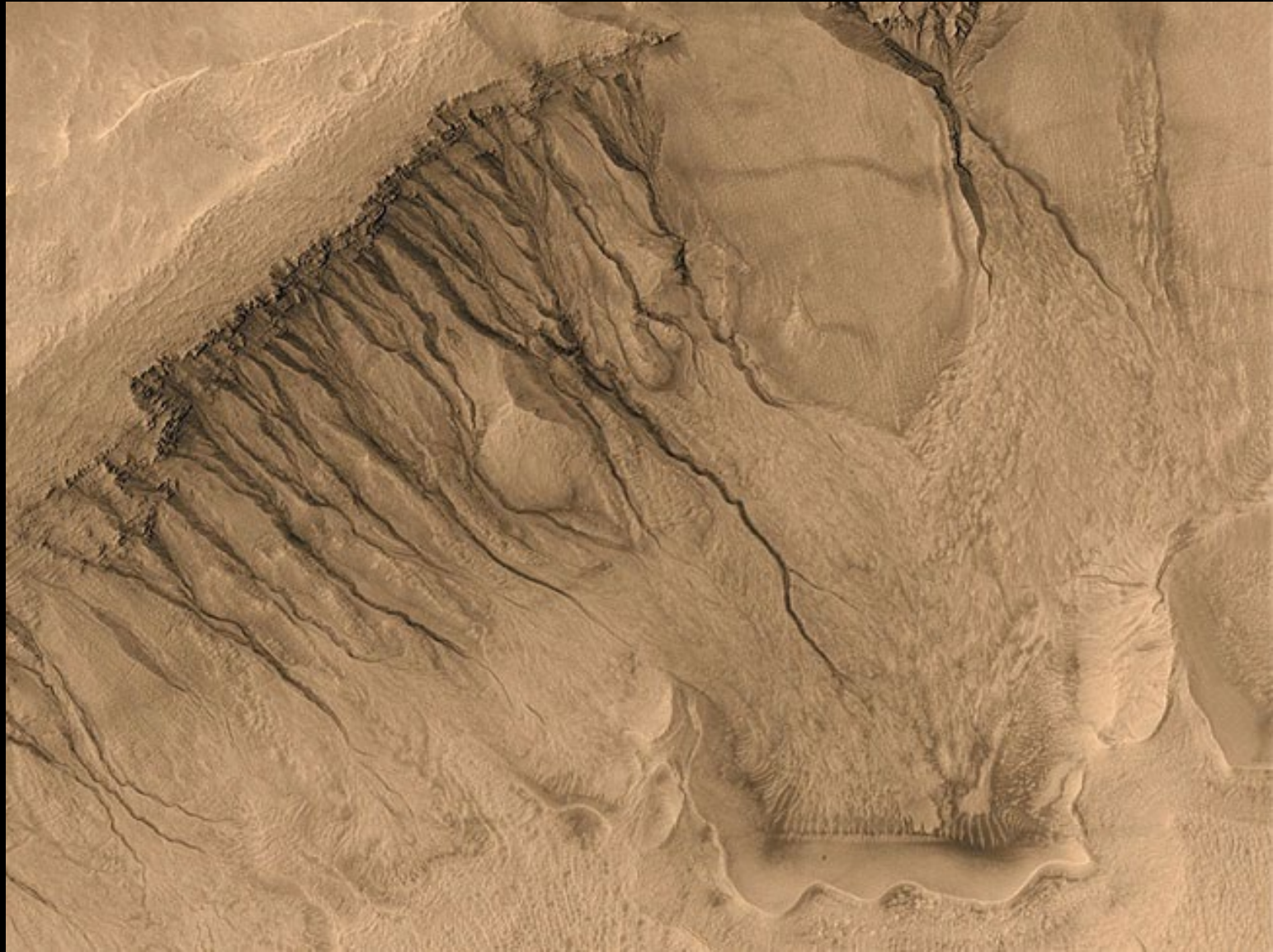




Martian sand dunes



Mysterious Gullies: Made by Powder? Sand? Water?



WHILE AN UNDERGRADUATE planetary-science student, I applied for a research position with a professor on campus. During my interview the professor looked at me and asked plainly, "What's your favorite planet?"

I was startled by the question but promptly answered that my favorite was not really a planet — I was fascinated by the planetary wannabes that make up the asteroid belt and the Kuiper Belt.

"Good," he replied. "I never hire any-

With the advent of the telescope came Earth's first Martians — those who dedicate their lives to understanding the red planet. In 1644 the first Martian surface features were recorded. By 1659 Christiaan Huygens had identified a prominent feature — now known as Syrtis Major — in a sketch. From that point on, Mars observers abound. No perihelic opposition (closest approach to Earth) came without a legion of Martians, armed with powerful telescopes, observing the red orb.

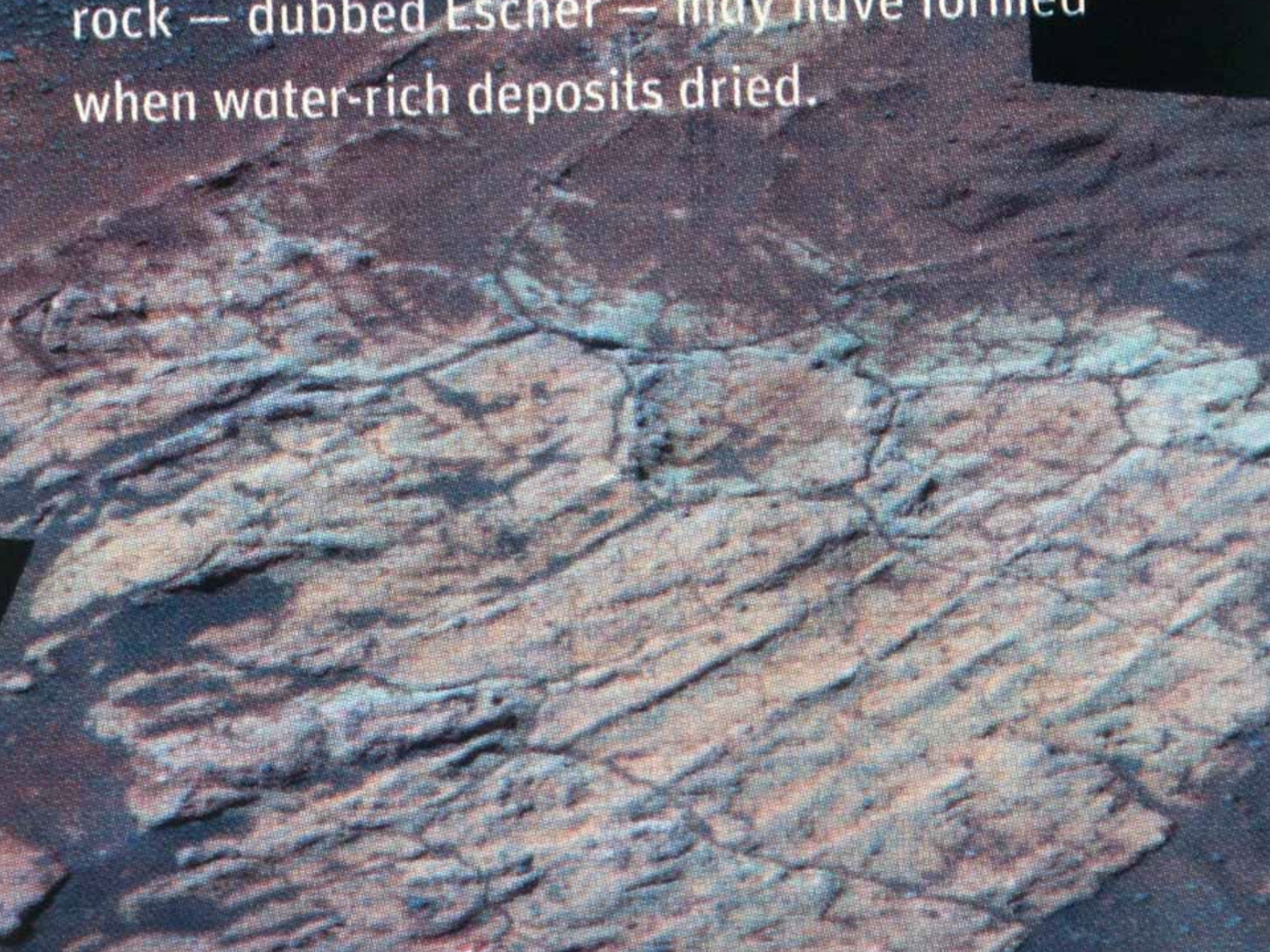
As telescopic technology advanced, so too did our understanding of Mars. The

Italian, can mean artificial or natural channels). Lowell is portrayed as the passionate observer, always steadfast in his support of Martian canals and the civilizations, past or present, that must have

Two decades after the Viking spacecraft went to Mars, another lander finally snapped images of the planet's surface on July 4, 1997. The Mars Pathfinder mission was deemed a tremendous success; however, two subsequent missions failed. This Mars-scape was assembled from a mosaic of images from Pathfinder's camera. Courtesy NASA/JPL.



rock — dubbed Escher — may have formed
when water-rich deposits dried.



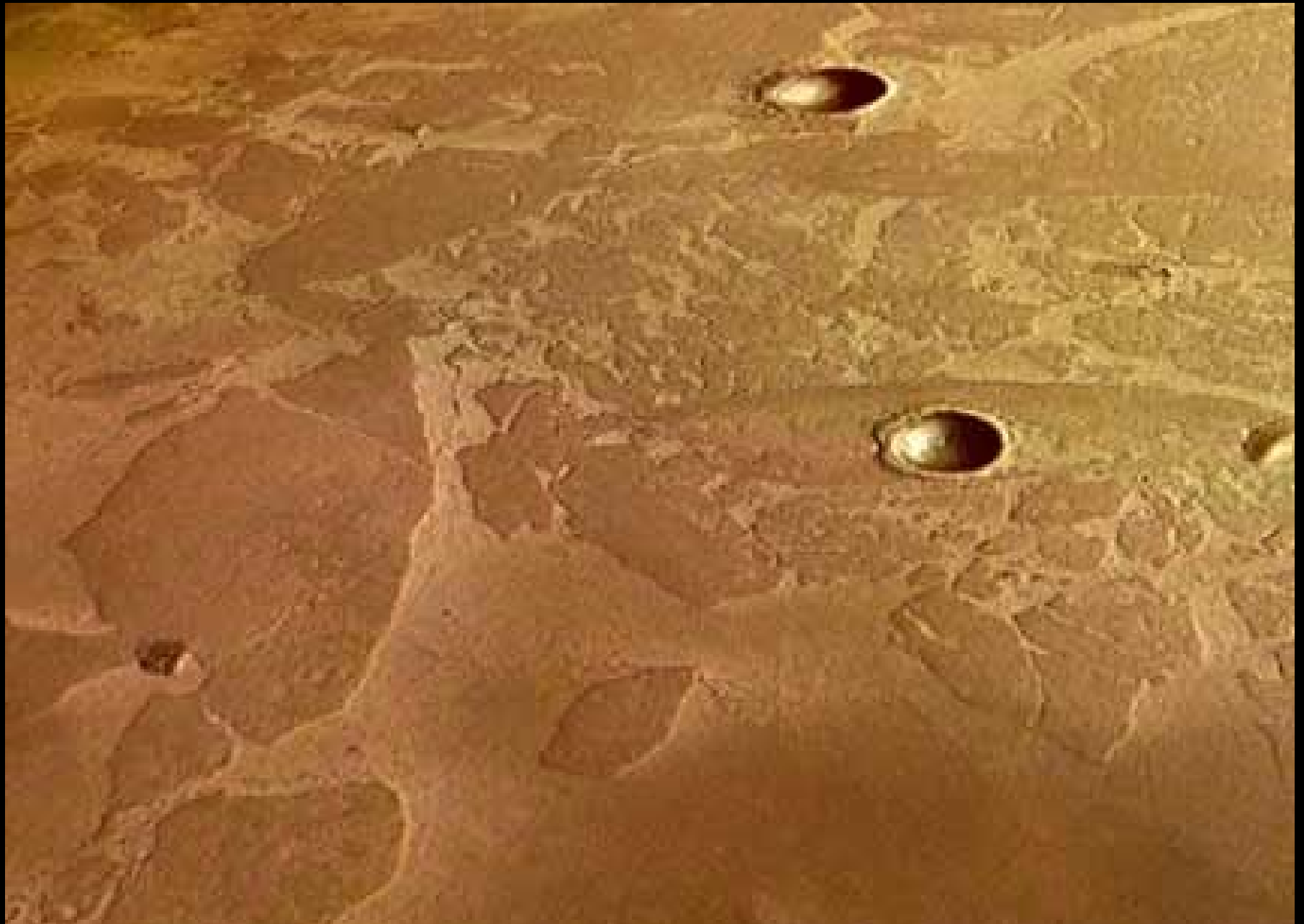
**Closeup of sedimentary rock with “blueberries”
of Iron-rich minerals formed in water**



TANTALIZING RIM Beating the odds, Opportunity reached Endurance Crater in very good health. Its cameras revealed many intriguing rocky outcrops with sedimentary layers, such as Burns Cliff seen here.



Dust-covered frozen lakes?



The MAVEN mission in 2014

- **Mars Atmospheric Evolution** mission – goal will be to determine loss rates of many molecular species from the upper atmosphere, and temperature and pressure profiles
- With known solar history and solar wind and Mars very weak magnetic field,
- This should constrain modelling of the general history of Mars atmosphere

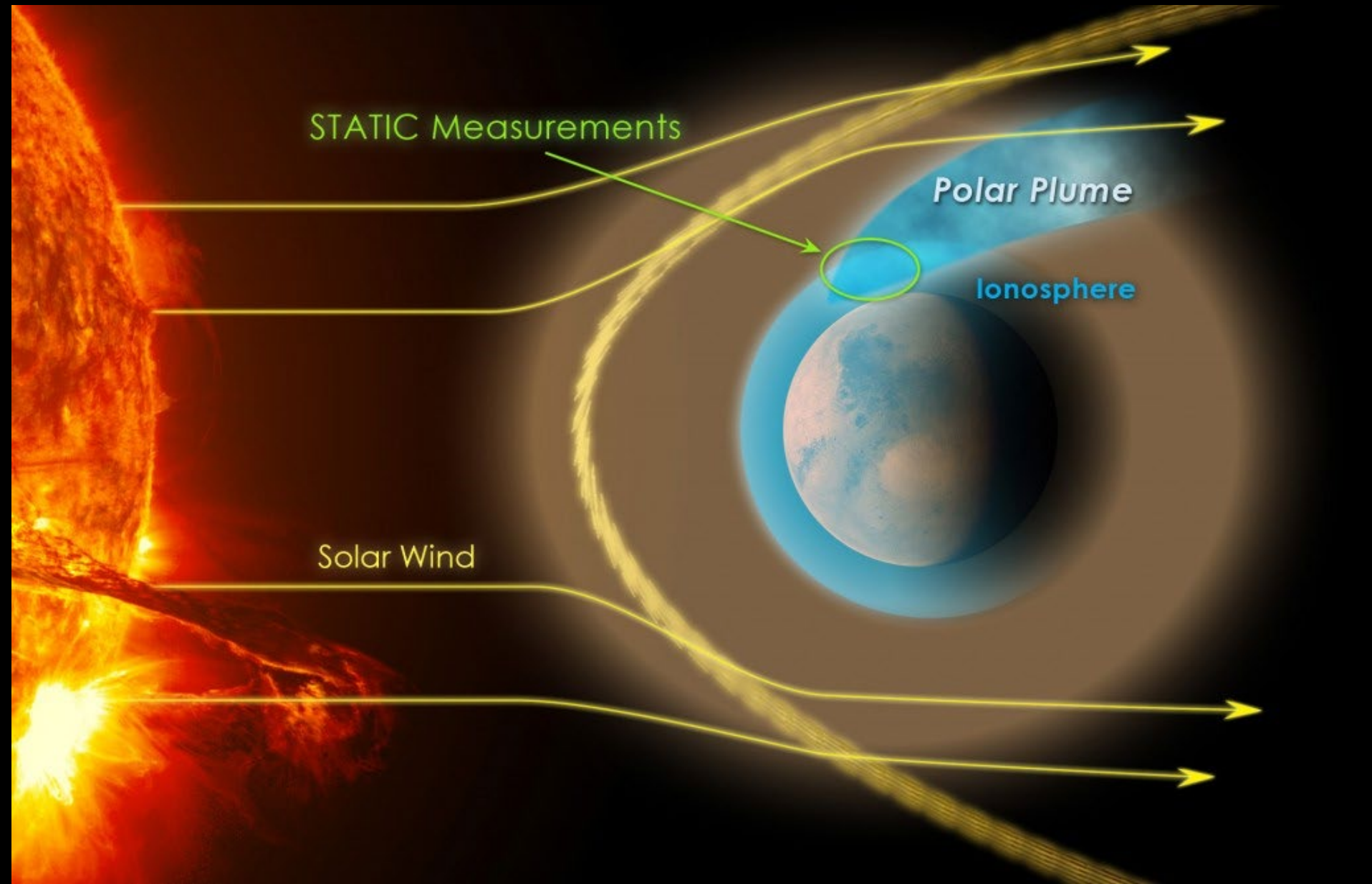
What can we say so far....?

- Impact cratering likely took away most of early atmosphere and dominated escape mechanisms in the first few hundred million years
- Volcanoes and comet impacts would have replaced this early atmosphere with water vapor, CO₂, some ammonia
- Good evidence for an early ocean, fractal fossil coastline just like seen on Earth, as greenhouse warming would allow warm enough temperatures for liquid water over much of Mars.
- Mars has only a weak magnetic field, even though it rotates as rapidly as Earth. Reason is not well understood, but...

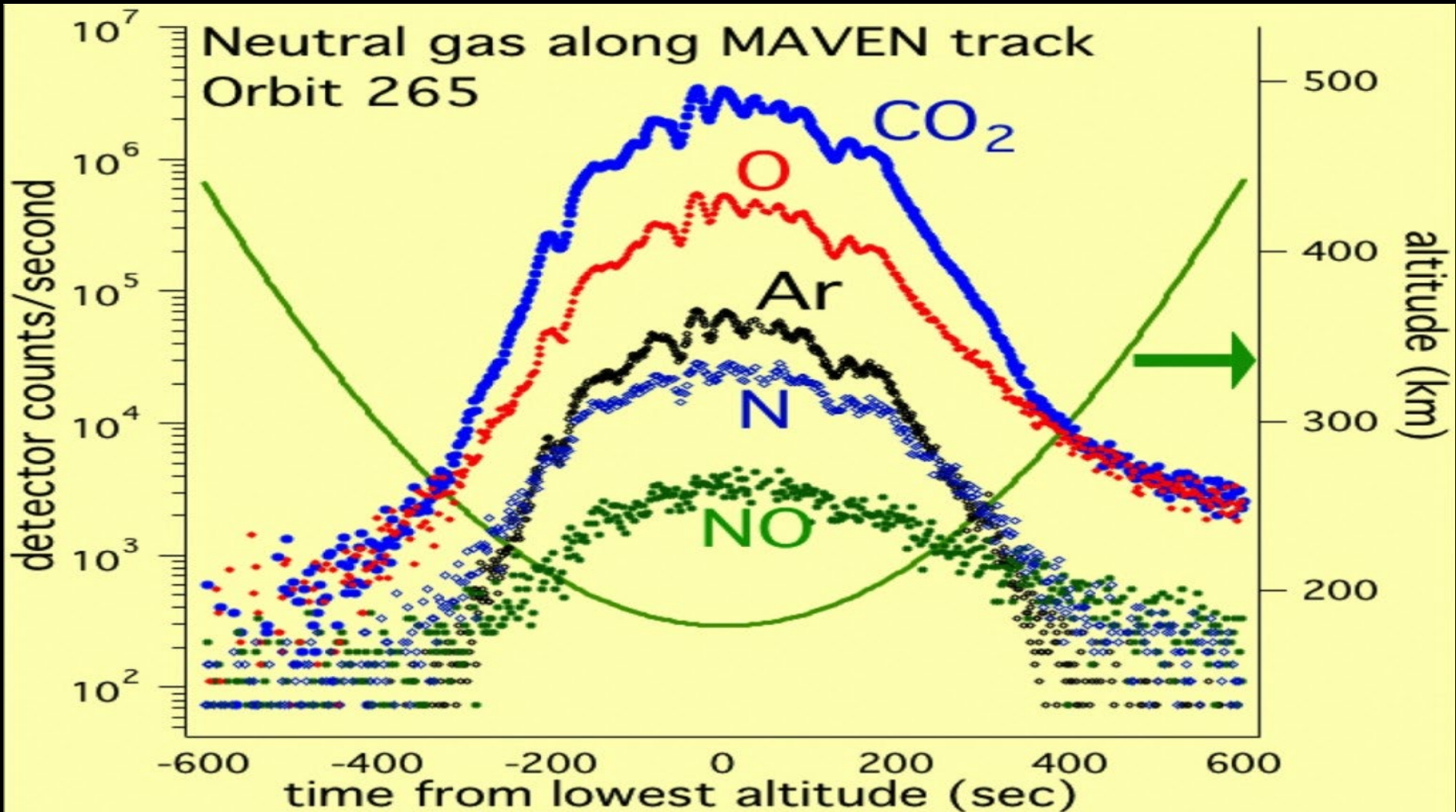
No magnetic field – BAD for your atmosphere

- With no magnetosphere, the solar wind (particles going hundreds of km/sec) would “sandblast” away the atmosphere slowly over time.
- Especially since Mars has only 40% of the Earth’s surface gravity and so escape is easier
- The heaviest molecule would leak the slowest – that’s CO₂. That’s what indeed remains.
- As atmosphere is stripped away, greenhouse effect weakens, temperatures drop, but so does the boiling point of water, right down to the freezing point where it is today. However, the triple point (see slide ~#31) where water can exist as ice, water, and vapor) is not far from the conditions at the bottom of Valle Marinaris where air pressure is highest.
- So, no water possible on Mars. Only ice, or a bit of vapor in the atmosphere

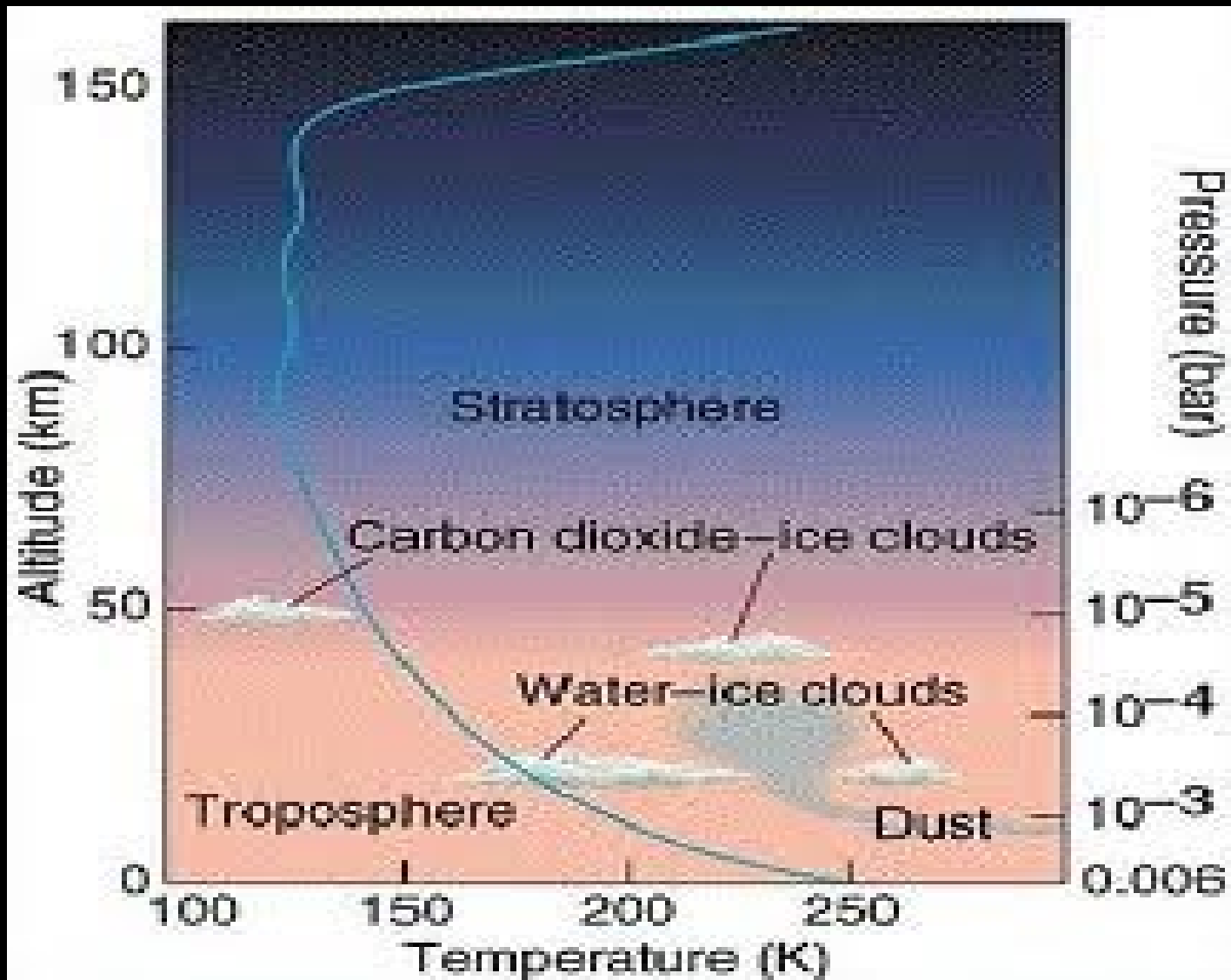
MAVEN finds solar wind can penetrate deep into atmosphere, carrying away molecules



MAVEN: Neutral gas is: CO₂, O, Ar, N, NO. CO₂ especially dominates at the lower altitudes (center of graph)



General Structure of Mars Atmosphere Today

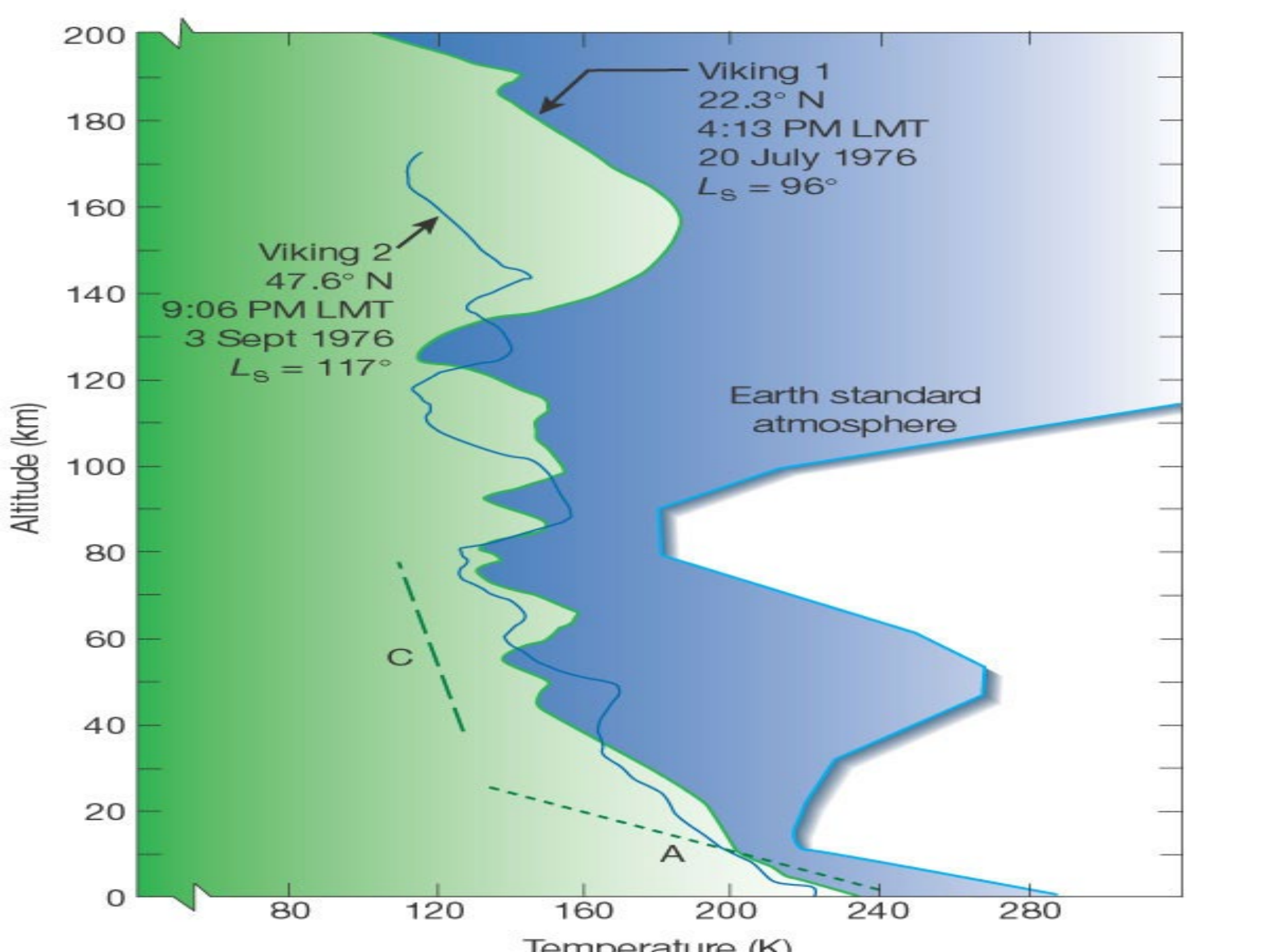


Mars Rover “Curiosity” Finds Clues...

- ...As to how Mars lost so much atmosphere – it finds the current atmosphere is much enriched in the heavy vs lighter isotopes for Argon and Carbon, vs. the abundances found in the older Martian rock found in Antarctica
- Lighter isotopes would be more easily lost to outer space by thermal leakage, as at a given temperature, they move faster.
- Thus, leakage to outer space over long periods of time (vs. all at once, in Impact Cratering) has played an important role
- This supports indirectly the solar wind – weak magnetic field theory for atmosphere lost, as this would be a mechanism for enhanced loss to outer space
- See [announcement here](#)

Mars Atmosphere Layers: Not Like Earth's

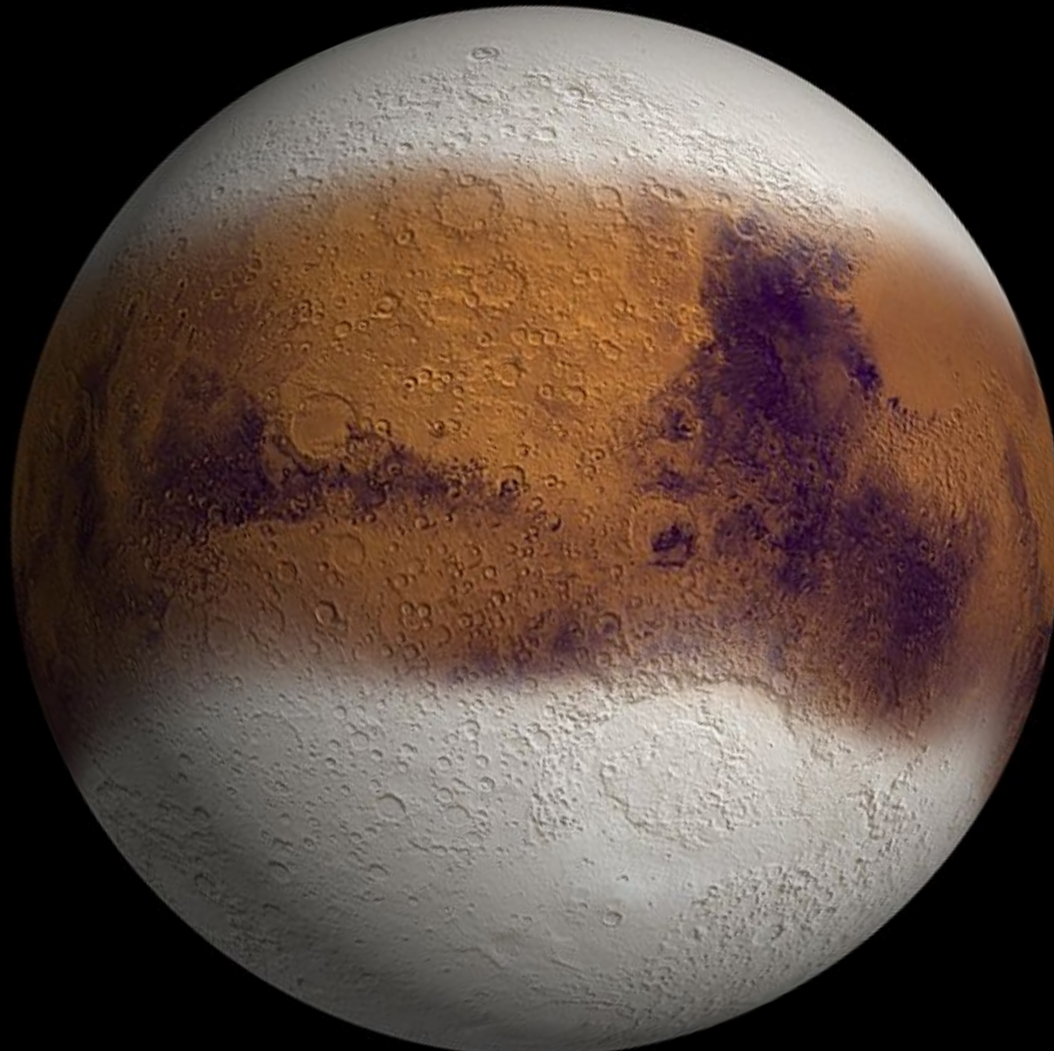
- Viking mission in mid 70's found Mars atmosphere generally cools consistently with increasing altitude, although data shows smaller scale noise or perhaps true temperature variations (see next image).
- There is no Stratosphere because there is no heating via Ozone absorption of solar UV like there is on Earth.



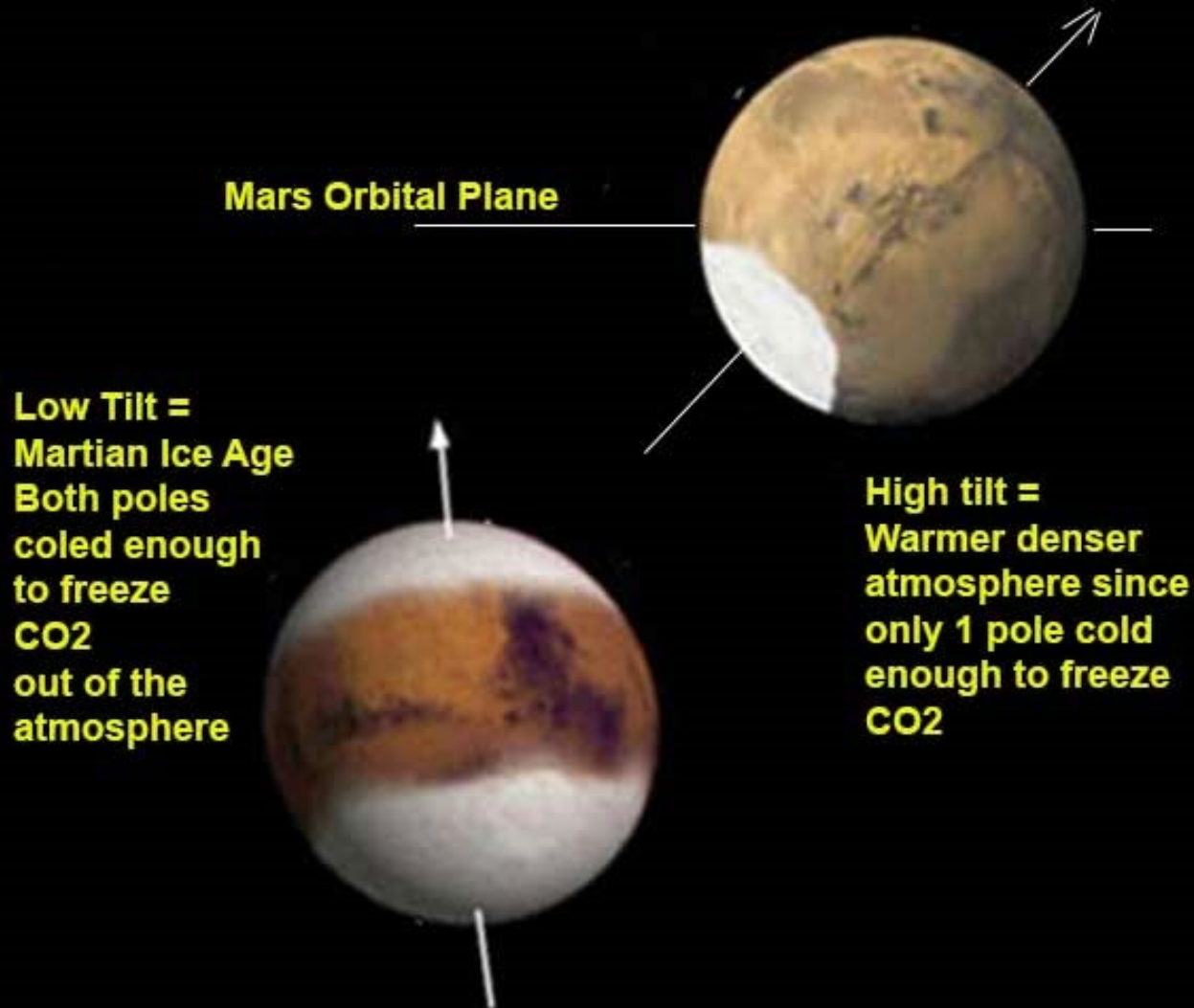
How Does Mars Atmosphere Change with Axis Tilt?

- Mars spin axis tilt varies from near zero to well over 45 degrees (!) because not stabilized by a massive moon like we have (10^5 - 10^6 year cycles).
- When near zero tilt, neither pole gets enough heat to ever thaw, and we get a Martian Ice Age, with atmospheric CO₂ freezing out and onto both poles extensively, so - thinner atmosphere, colder
- **Large tilt corresponds to thicker, warmer atmosphere ([study source: Laskar 2002](#))**
- Today, near 23 degrees, poles alternate, getting icy with the seasons, and an intermediate climate.

Small Tilt = Martian Ice Age



When nearer ~45 degrees or more, one pole gets enough full day sunlight that all the CO2 ice melts, and the CO2 atmosphere gets thicker, warmer (both water, CO2 are greenhouse gases)



Key Points: Chap 10 - Atmospheres of the Inner Planets (except Earth, which has separate PowerPoint)

- Surface temperature and gravity determine how well you keep your atmosphere
- Loss mechanisms: Leakage of lighter molecules, impact cratering, ablation by solar wind aided by weak magnetic field
- **Understand the greenhouse effect!**
- Venus suffered the Runaway Greenhouse Effect, so is bone dry.
- Mercury and our moon, too hot and too low gravity to retain any atmosphere, no mag fields didn't help either, for moon
- CO₂ dominates both Mars and Venus; heaviest common molecule
- Runaway greenhouse effect: water vapor in upper atmosphere dissociated by solar UV, lost to space
- Mars atmosphere has thinned progressively over 4.5B years due to no protection from solar wind (weak mag field).
- Mars and Venus likely had water oceans early in their history
- **Mars climate: denser warmer atmosphere when axis tilt is high, cold thin atmosphere when tilt is small**