Astro 7: Chap 10 - The Climates of Venus, and Mars, and why Mercury has no Atmosphere

Key Points: A7 Chap 10 - Atmospheres of Mercury, Venus, Mars

- Surface temperature and gravity determine how well you keep your atmosphere against leakage
- Loss mechanisms: Leakage of lighter molecules, impact cratering, ablation by solar wind if have only a weak magnetic field
- **Understand the greenhouse effect!**
- 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: rising temps add water in upper atmosphere, dissociated by solar UV, lost to space – this was Venus' fate
- Mars atmosphere has thinned progressively over 4.5B years due to no protection from solar wind (weak mag field).
- Mars and Venus both likely had moderate temperatures and oceans of water early in their history, rising solar luminosity drove Runaway Greenhouse on Venus, and loss of atmosphere via weak magnetic field drove away most of Mars atmosphere and water destruction
- **Mars climate over past millions of years: denser warmer atmosphere when axis tilt is high, cold thin atmosphere and "Ice Age" when tilt is small. Mars has no large moon to stabilize spin axis orientation**

The Common molecules and their atomic weight:

- ***Atmosphere*** – gas in the form of individual atoms or more typically, of molecules.
- --carbon dioxide CO_2 -> 12+2x16= **44**
- --Argon Ar (a noble gas) = **40**
- --nitrogen N_2 -> 2x14= **28**
- --water H_2O -> 16+2= **18**
- --methane CH_4 -> 12+4x1= **16**
- --hydrogen H_2 -> 2x1= **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:***

- $(½)m\langle v^2\rangle = (3/2)kT$
- 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…

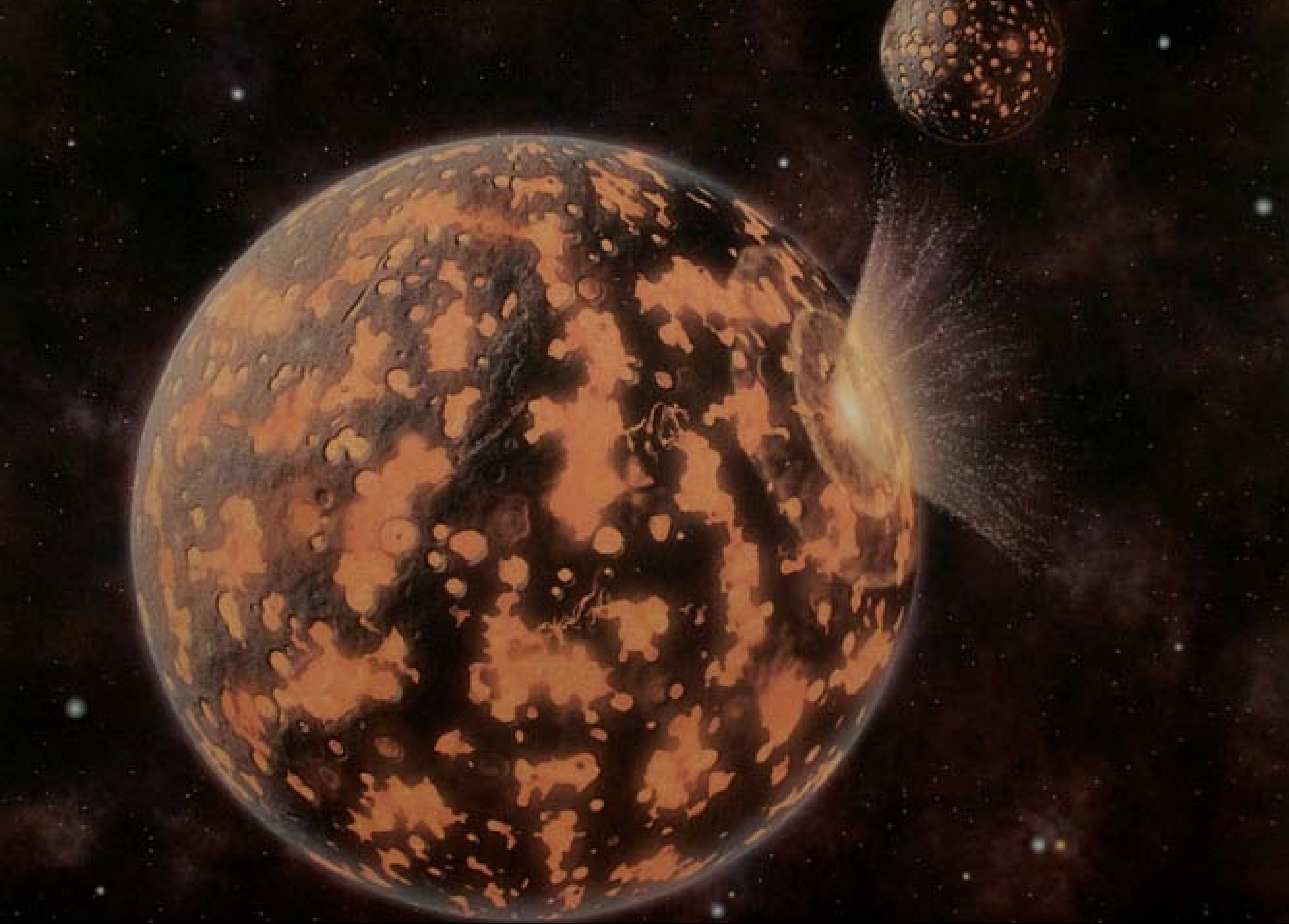
- ***Impact Cratering:*** Big asteroids or early protoplanets hitting the planet will deposit a lot of kinetic energy which becomes heat, blowing off a significant amount of atmosphere all at once.
- This is a significant issue only for the inner planets and only during the chaotic early epoch soon after formation, when the solar system still had large impactors in abundance.

The third way – A weak magnetic field leads to "Sandblasting" 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?

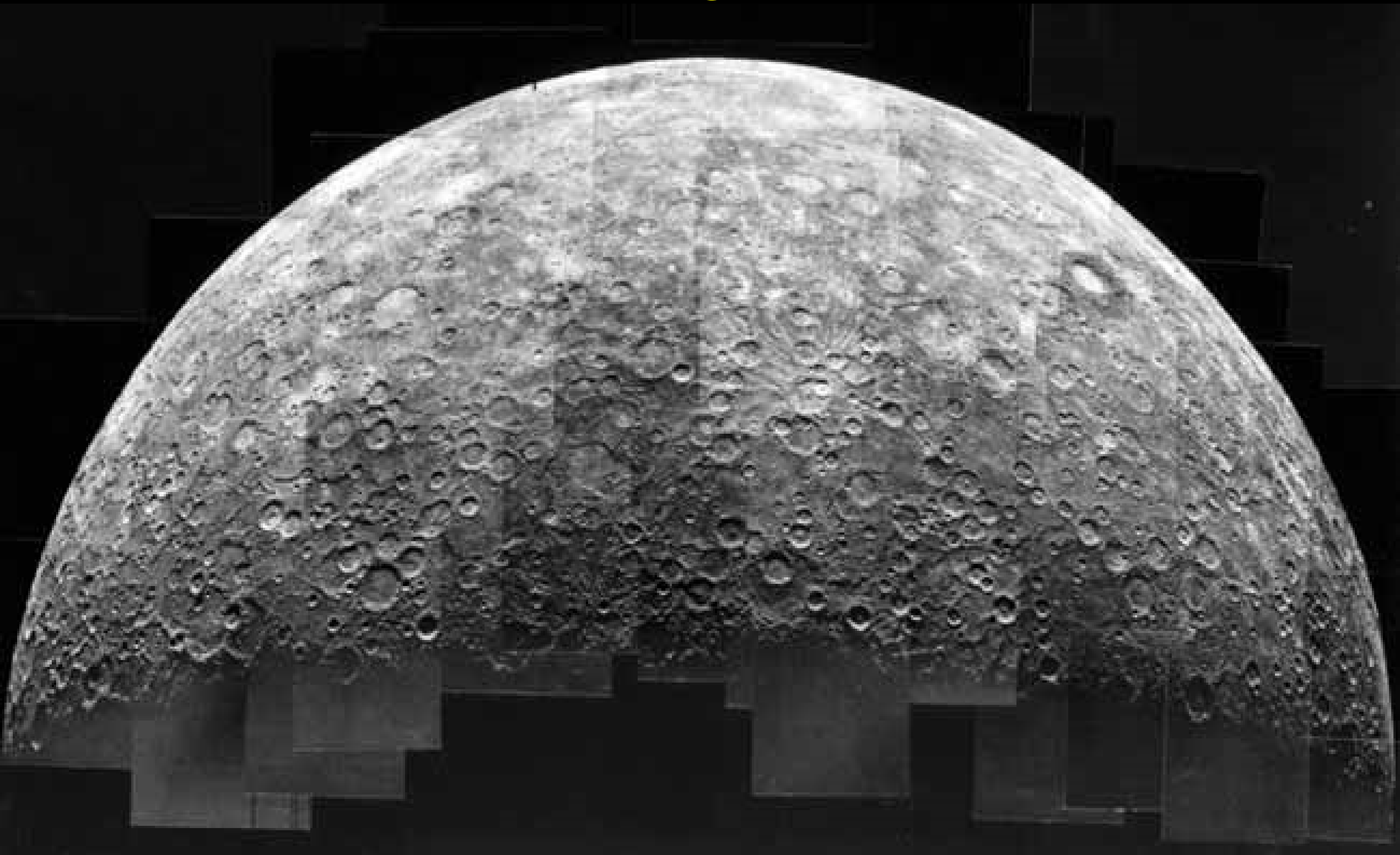
- It's hot close to the sun. So no ices. Only the rocky material (~3% of the solar nebula) could collect into self-gravitating objects. Not hydrogen and helium since escape velocities are too low; **these atoms are blown away; calculations indicate this is what halted planet formation,**
- Atmosphere 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.

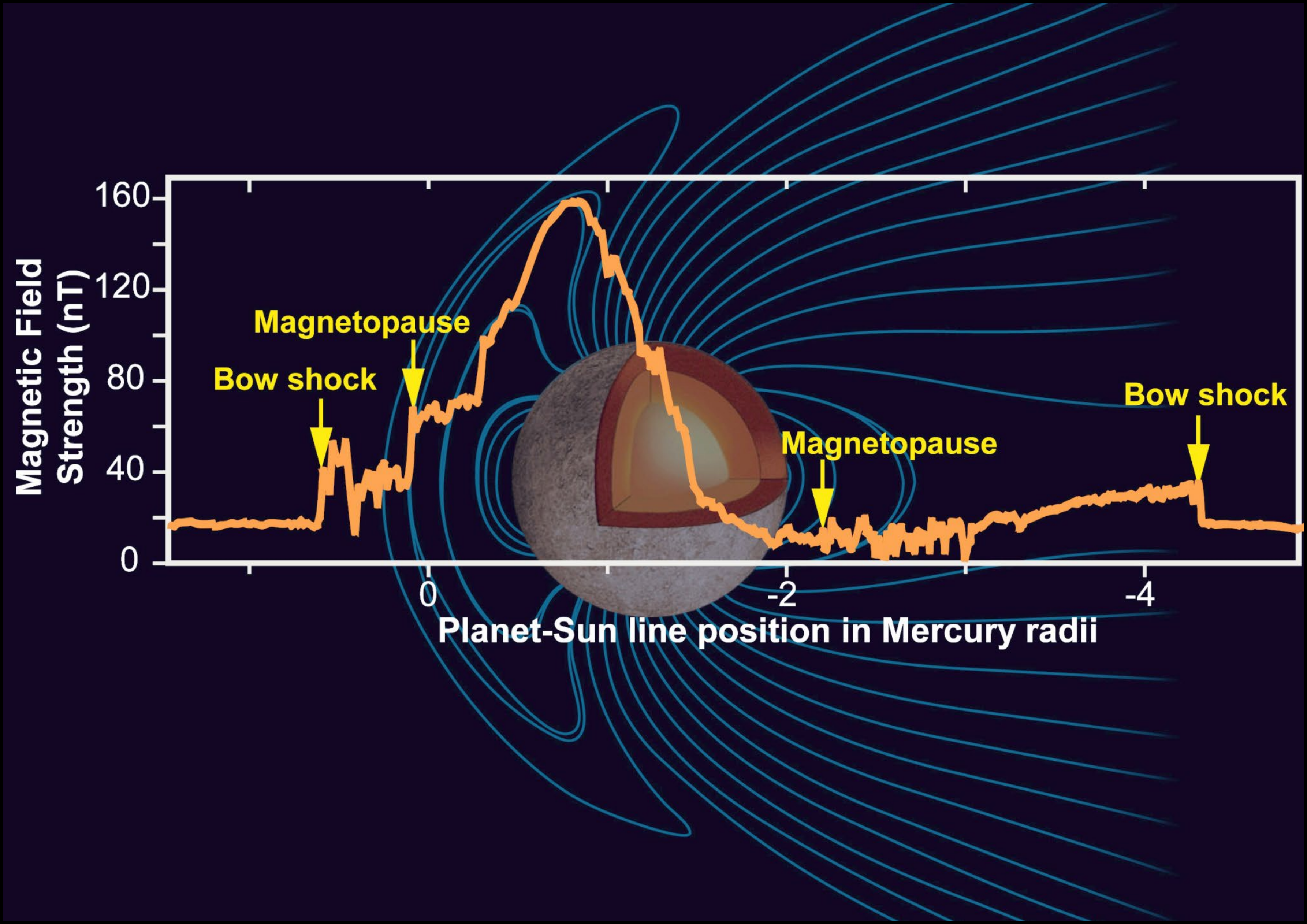
Mariner 10 flyby of Mercury in 1974



Much sharper cameras on the 2014 *Messenger* Mission to Mercury, gave images like this

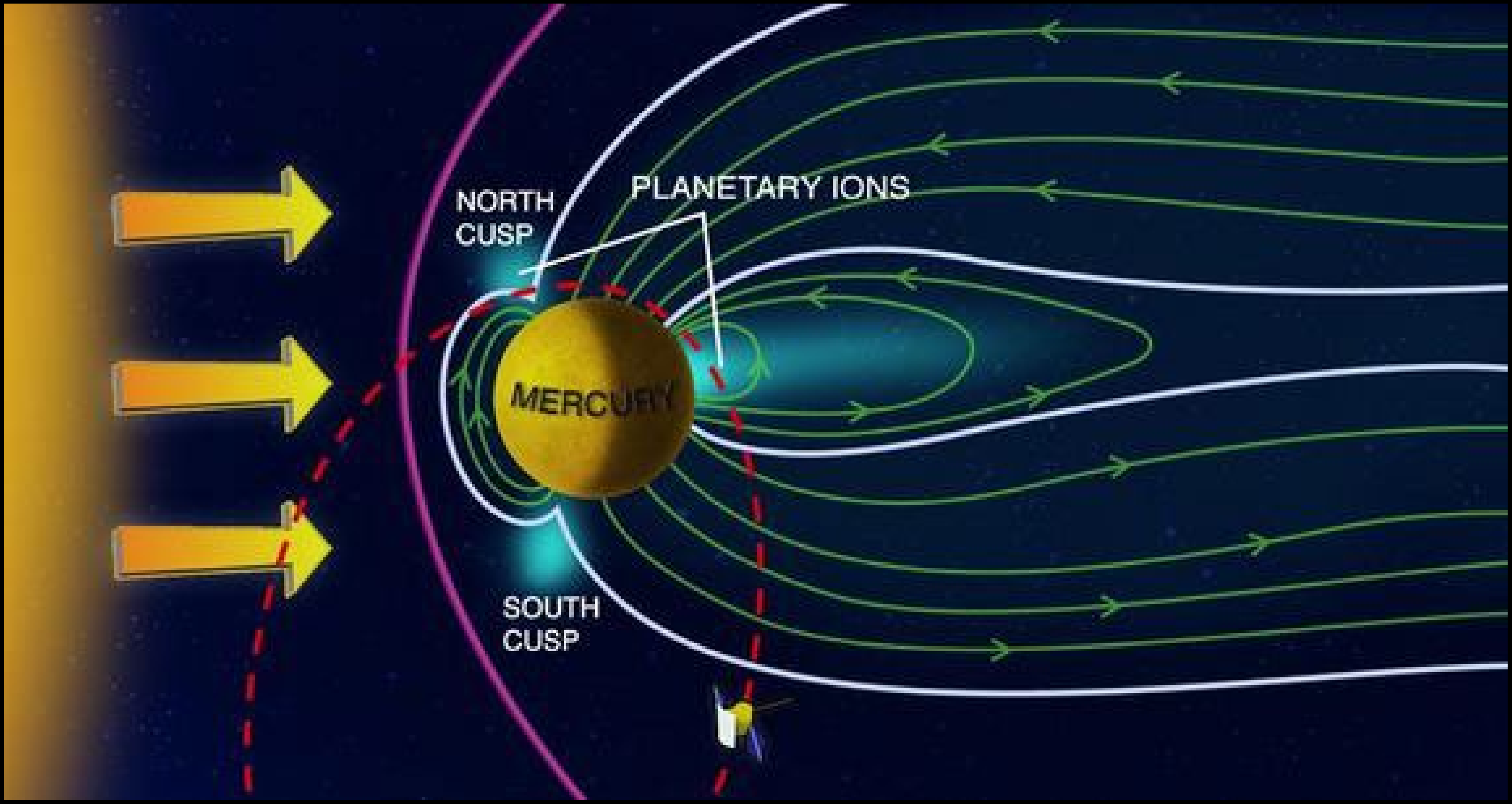
Mercury’s magnetic field: Only 1% as strong as Earth’s

- 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

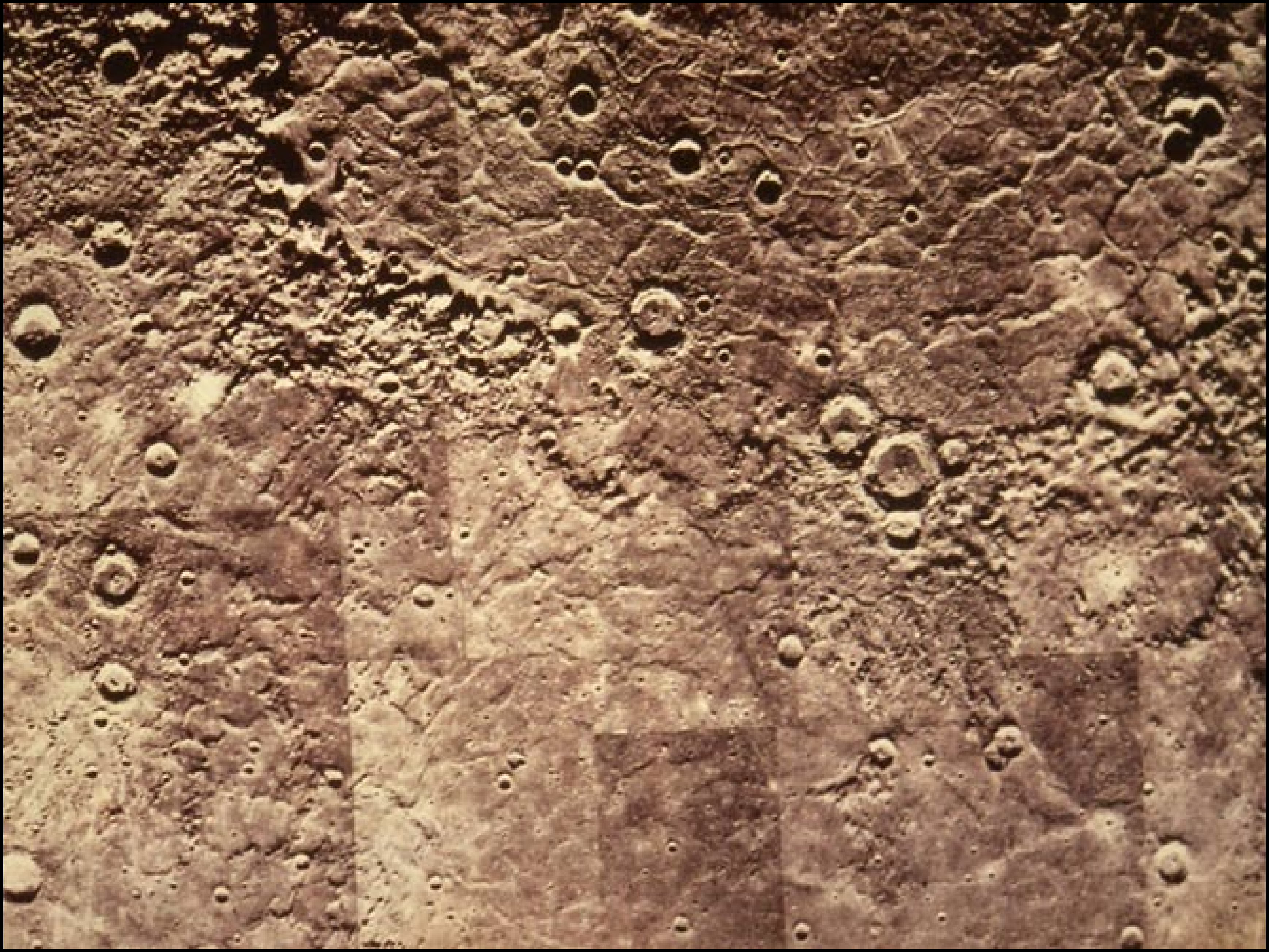


Magnetic Field Strength (nT)
160
120
80
40
0
Magnetopause
Bow shock
Magnetopause
Bow shock
0
-2
-4
Planet-Sun line position in Mercury radii

Mercury's Distorted Magnetopause and Weakened Magnetic Field



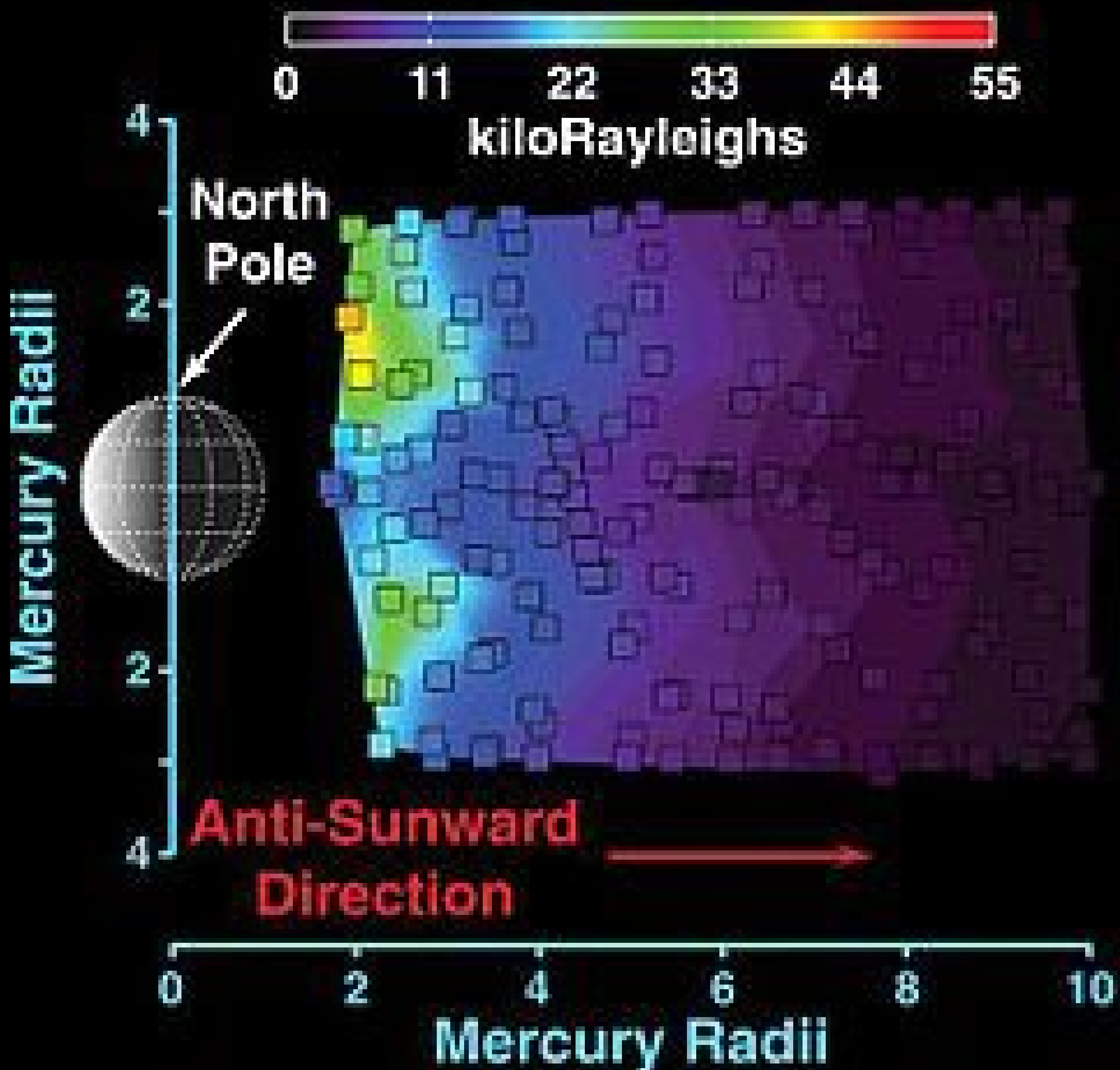
See Anything Interesting Here?



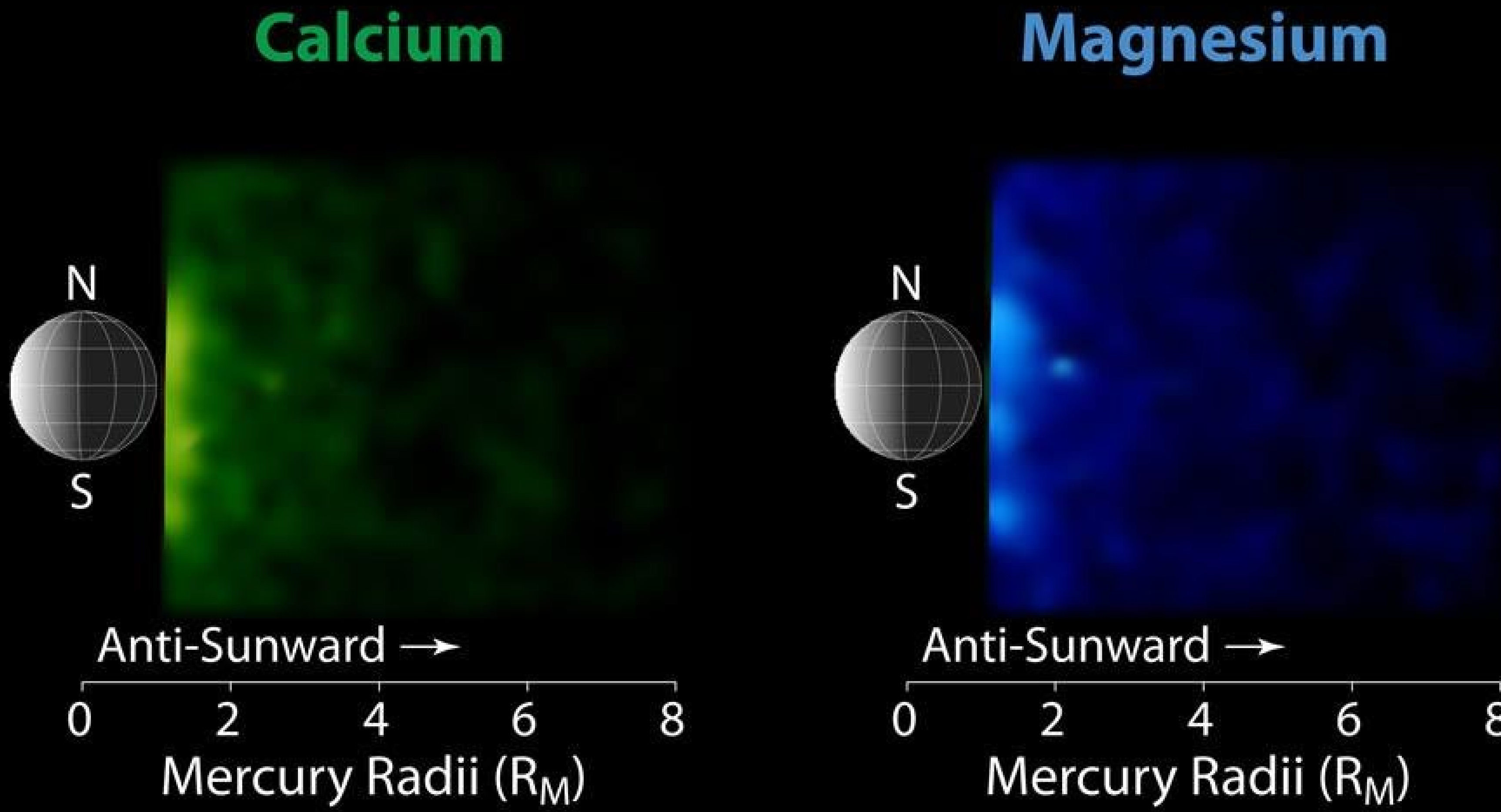
Evaporation Cracks

- Indicating early in Mercury's history, it had volatiles (water?) as part of its crust, which were baked out, lowing 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



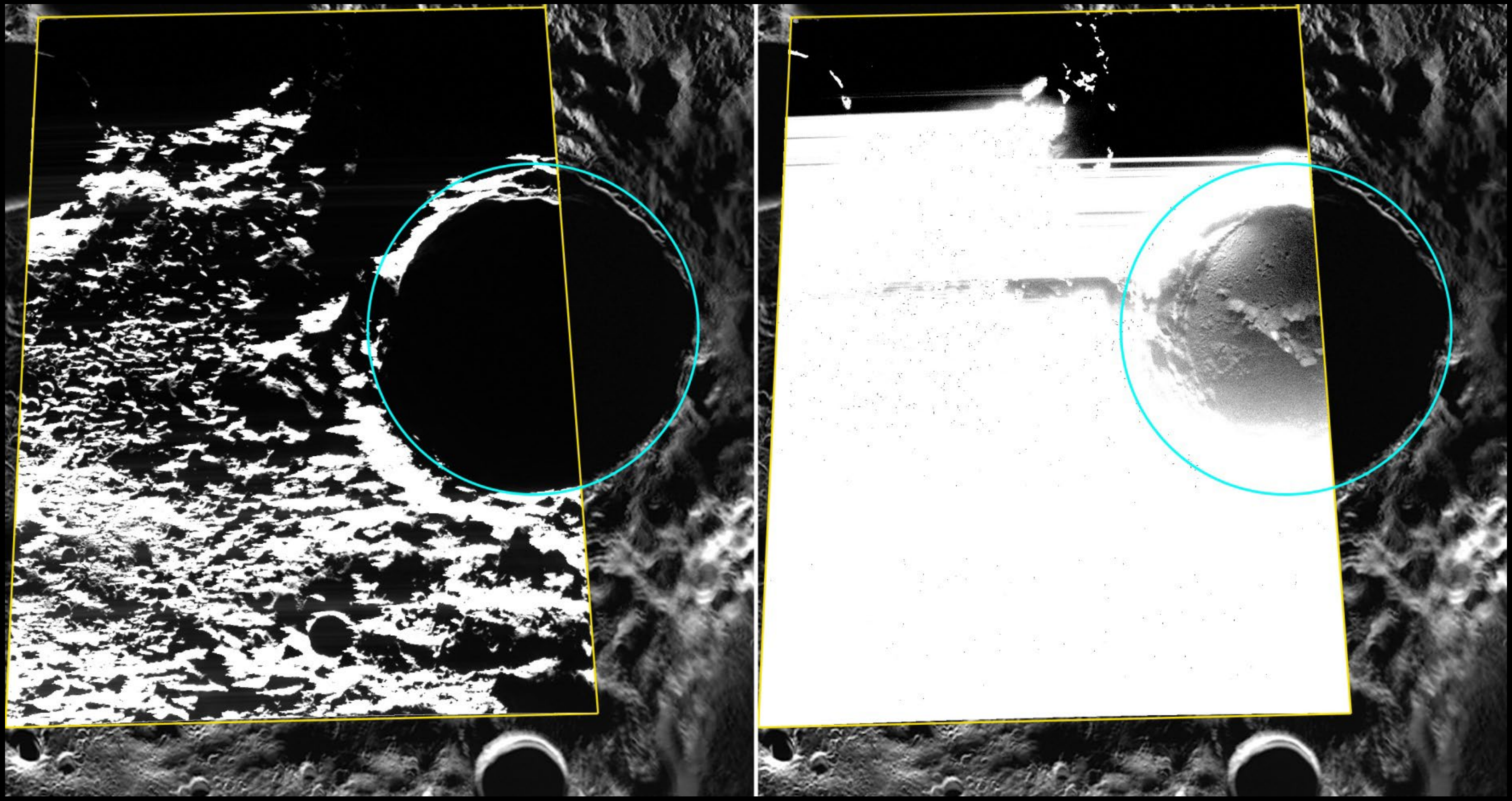
These Heavy Atoms Are Blasted off of Mercury's Surface

- …. By the solar wind
- Then blown away
- Very very low density
- Not properly called part of an "atmosphere"
- But, atoms in non-solid, non-liquid form, so worth mentioning just the same.

Without an atmosphere, Mercury's 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

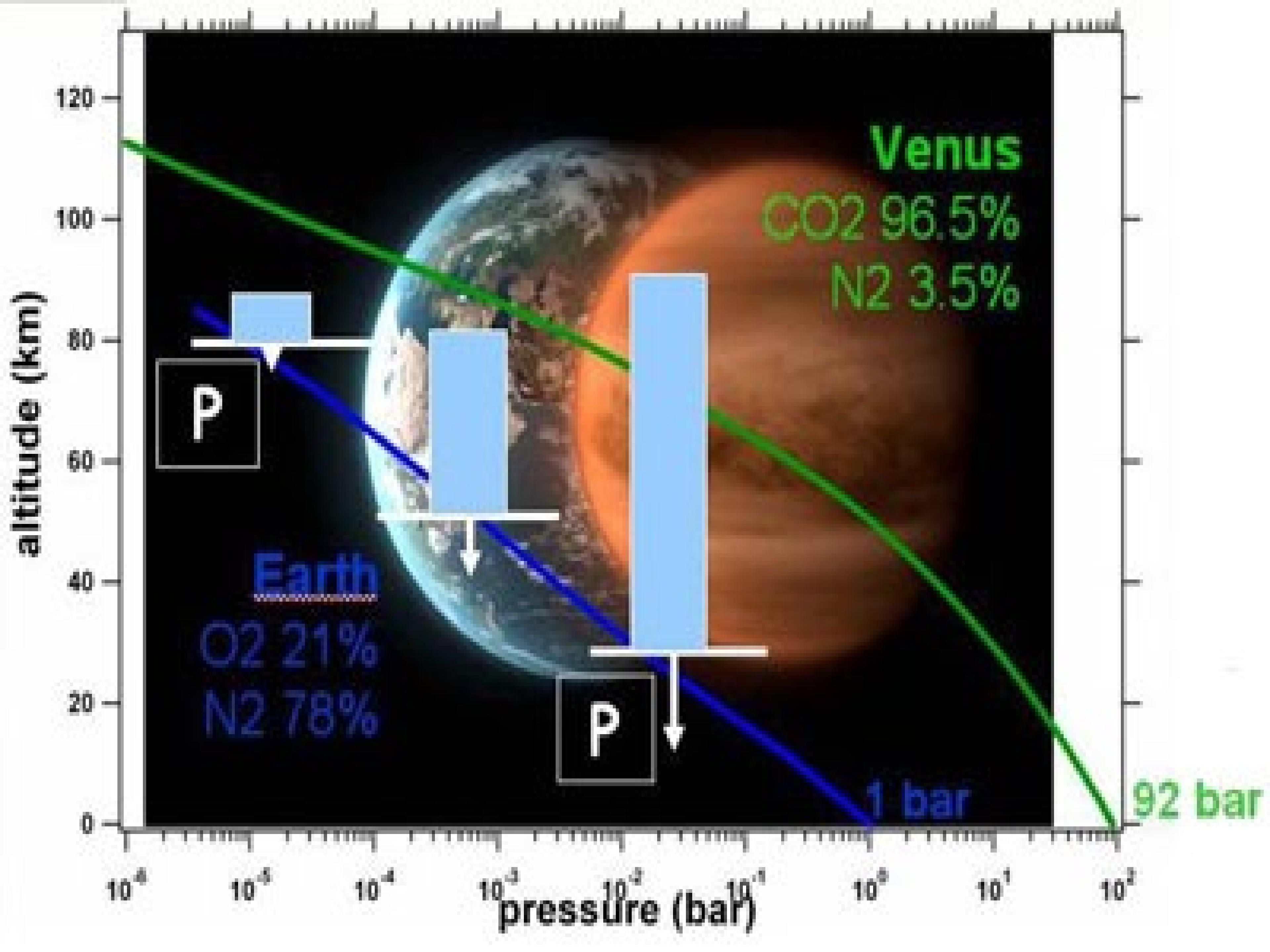
Icy crater at Mercury's pole which never sees the Sun. Caused by water-carrying micrometeorite impacts over the eons, is most consistent with models



Venus – Similar to Earth in Size and Surface Gravity

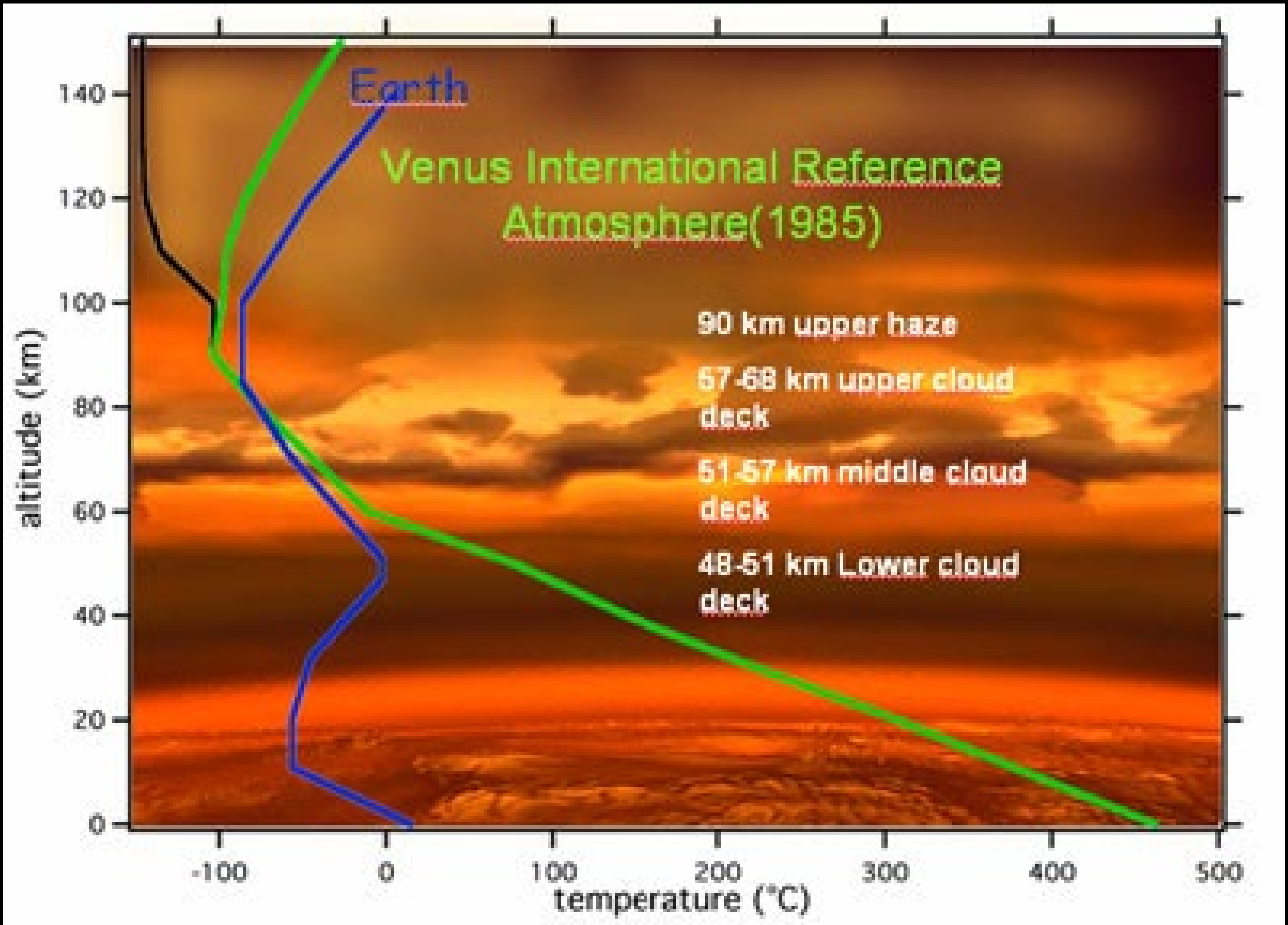
Early Venus

- 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 is almost pure CO2

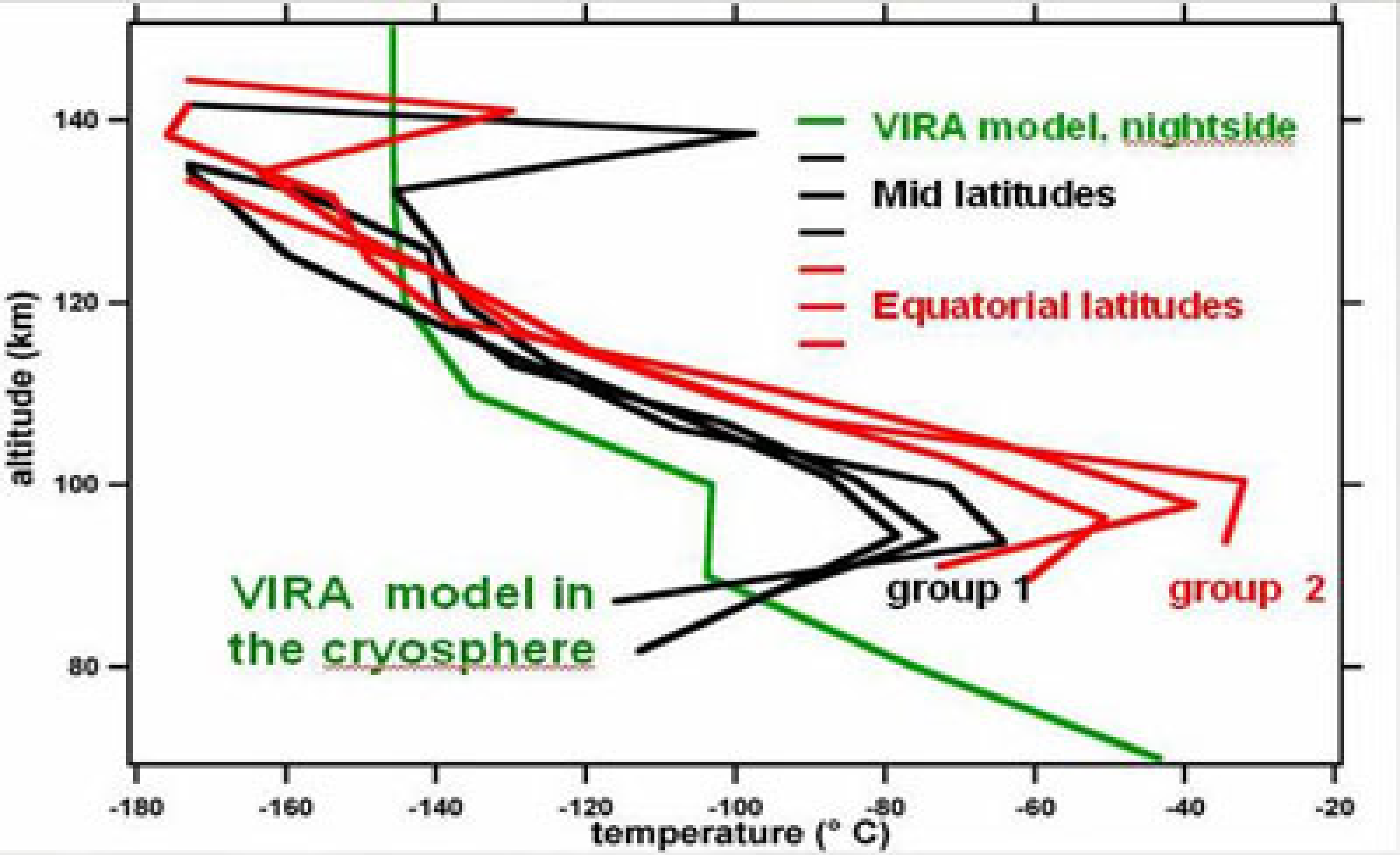


Venus
CO2 96.5%
N2 3.5%
Earth
O2 21%
N2 78%
P
P
1 bar
92 bar
altitude (km)
pressure (bar)

Before "Venus Express" – Best guess atmosphere profile…



After ESO's "Venus Express". Note this is only the very highest (>70,000 meters) coldest thinnest part of the atmosphere (below, opaque due to sulfuric acid droplets)



Key discovery of Venus Express…

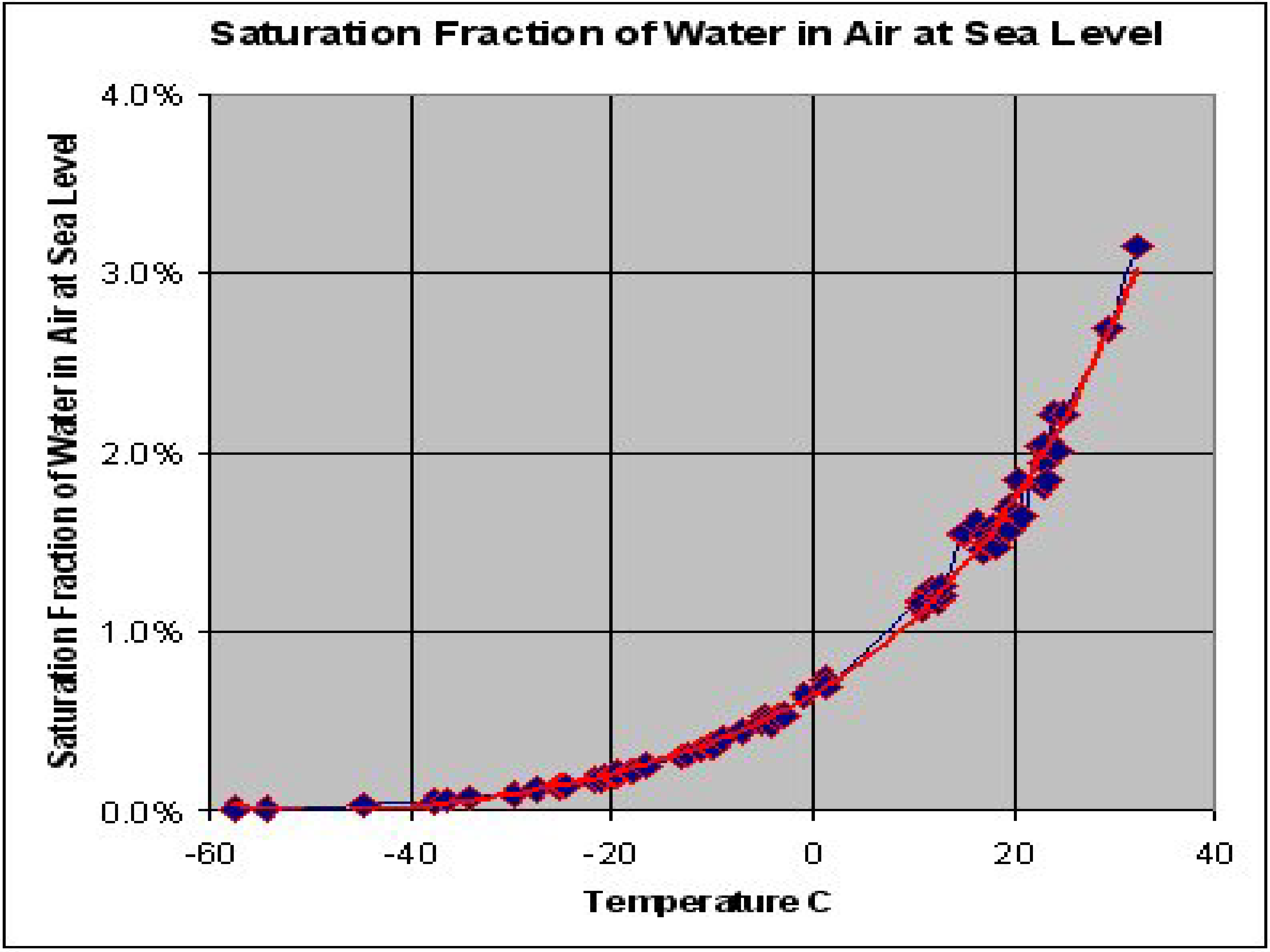
- Dry!!! The water vapor in the atmosphere at present, if condensed to liquid, would make a layer around the planet of only 3 cm deep (*vs.* ~500,000 cm for Earth)
- At top of atmosphere, solar UV breaks apart H_2O into H and O2. O2 combines with surface geology to make oxides, while the Hydrogen escapes 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 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…
- **An amplifying feedback cycle**
- **When the water vapor absorption becomes too effective, rising surface temperatures are unable to radiate through the opaque atmosphere, temperatures keep rising and the oceans continue to evaporate until the vapor pressure in the upper stratosphere reaches high levels**

Where does the Ocean Water Vapor go?

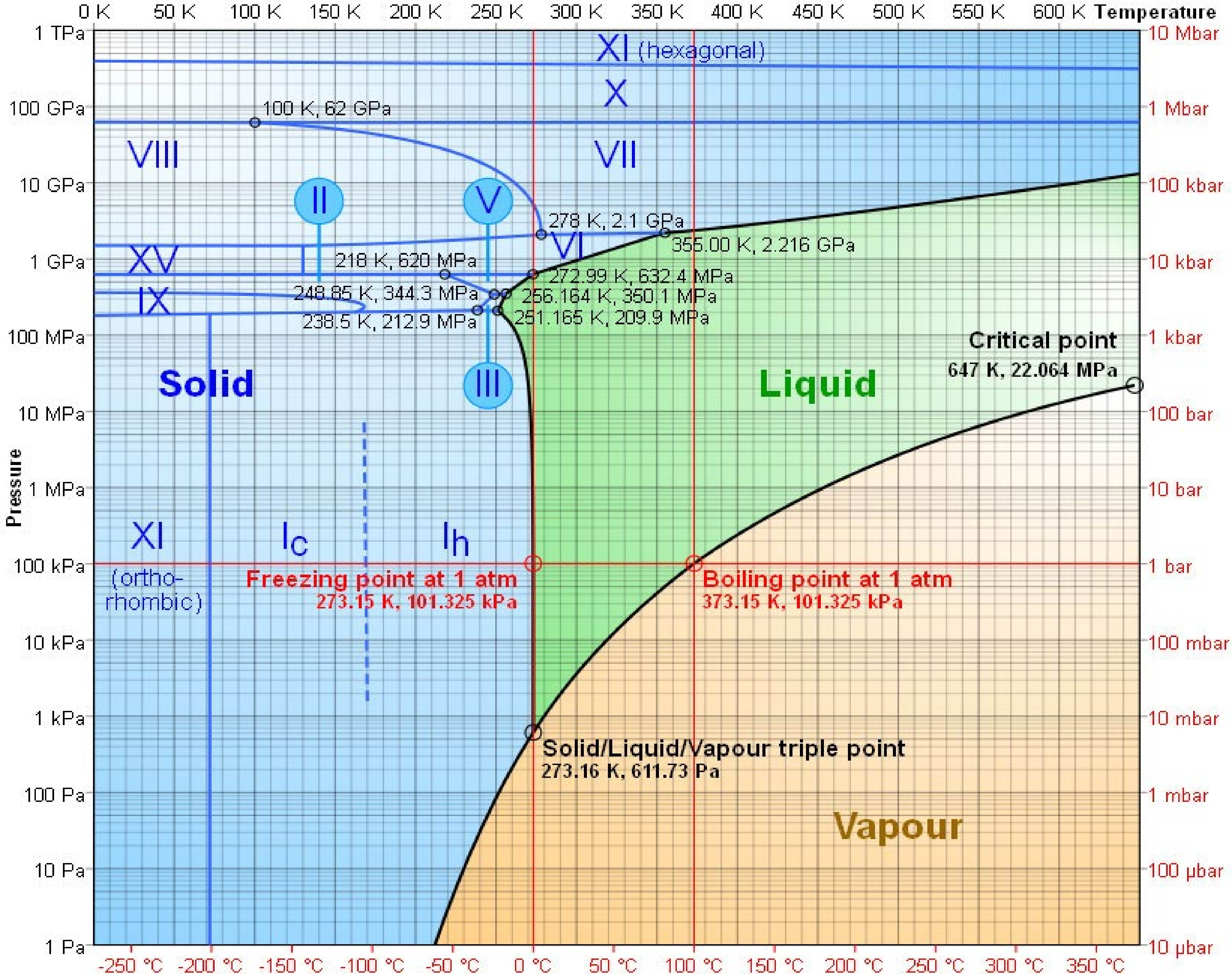
- Runaway starts when the solar UV in the upper stratosphere dissociates the H2O into O2 and H2 at a sufficiently high rate
- The hydrogen escapes to space, being very light weight and moving fast ("leakage"),while the oxygen eventually combines with elements at the surface. Both are lost from the atmosphere
- When the ocean has lost all of its liquid water, and dissociation continues in the stratosphere, eventually the planet turns bone dry, and then atmospheric temperatures cool somewhat, as outgoing IR absorption by water vapor decreases.
- But since CO2 is the major absorber, and it does not rain out, nor dissociate, the planet's fate is sealed.
- This was the fate of Venus



Saturation Fraction of Water in Air at Sea Level
4.0%
3.0%
2.0%
1.0%
0.0%
-60
-40
-20
0
20
40
Temperature C
Saturation Fraction of Water in Air at Sea Level

Notice: Saturation Humidity ***Accelerates*** Upward 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.

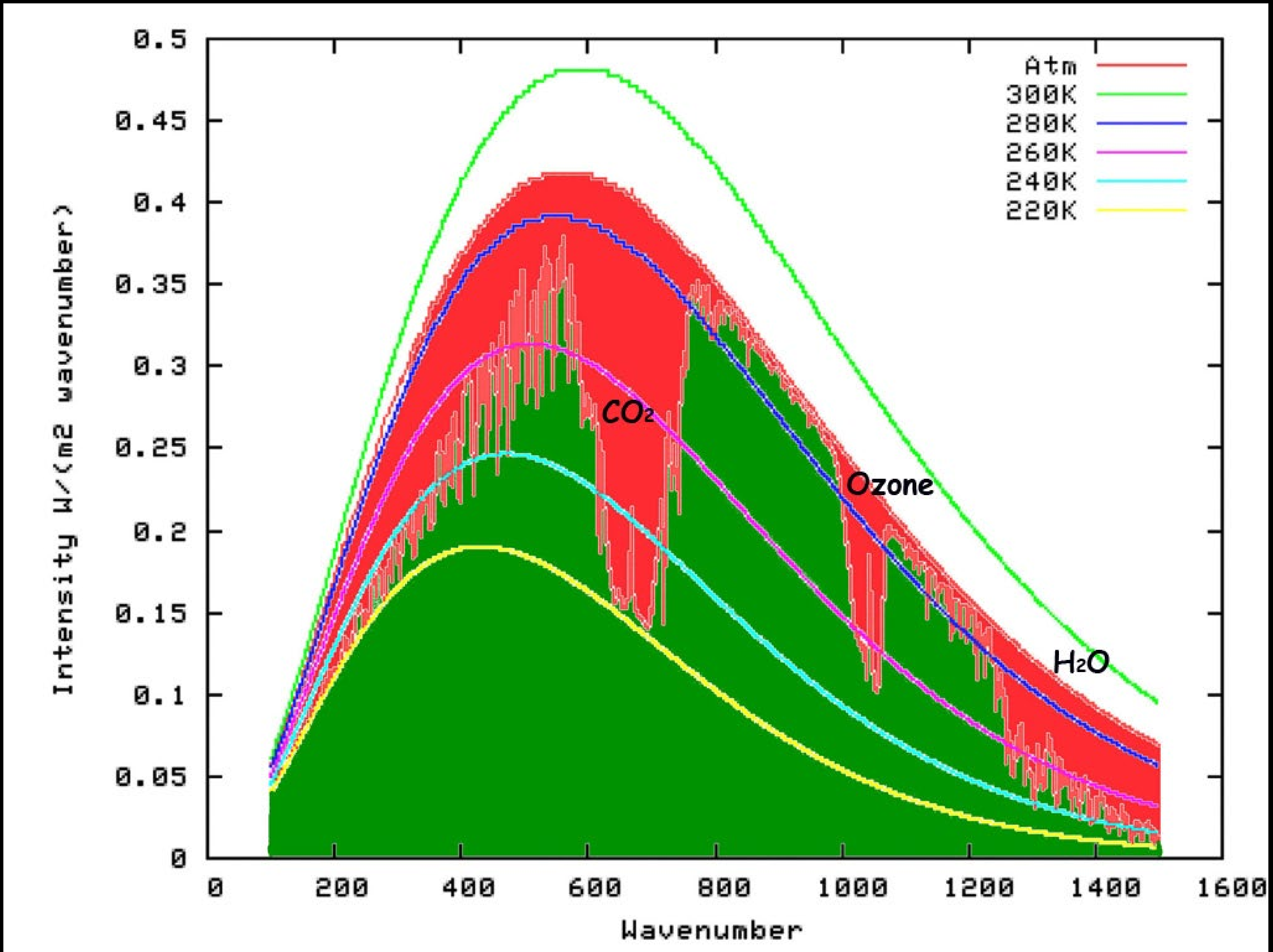


0 K
50 K
100 K
150 K
200 K
250 K
300 K
350 K
400 K
450 K
500 K
550 K
600 K
Temperature
1 TPa
100 GPa
10 GPa
1 GPa
100 MPa
10 MPa
1 MPa
100 kPa
10 kPa
1 kPa
100 Pa
10 Pa
1 Pa
Pressure
10 Mbar
1 Mbar
100 kbar
10 kbar
1 kbar
100 bar
10 bar
1 bar
100 mbar
10 mbar
1 mbar
100 µbar
10 µbar
XI (hexagonal)
X
100 K, 62 GPa
VIII
VII
II
V
278 K, 2.1 GPa
VI
355.00 K, 2.216 GPa
XV
218 K, 620 MPa
272.99 K, 632.4 MPa
IX
248.85 K, 344.3 MPa
256.164 K, 350.1 MPa
238.5 K, 212.9 MPa
251.165 K, 209.9 MPa
Critical point
647 K, 22.064 MPa
Solid
III
Liquid
XI
(ortho-
rhombic)
Ic
Ih
Freezing point at 1 atm
273.15 K, 101.325 kPa
Boiling point at 1 atm
373.15 K, 101.325 kPa
Solid/Liquid/Vapour triple point
273.16 K, 611.73 Pa
Vapour
-250 °C
-200 °C
-150 °C
-100 °C
-50 °C
0 °C
50 °C
100 °C
150 °C
200 °C
250 °C
300 °C
350 °C

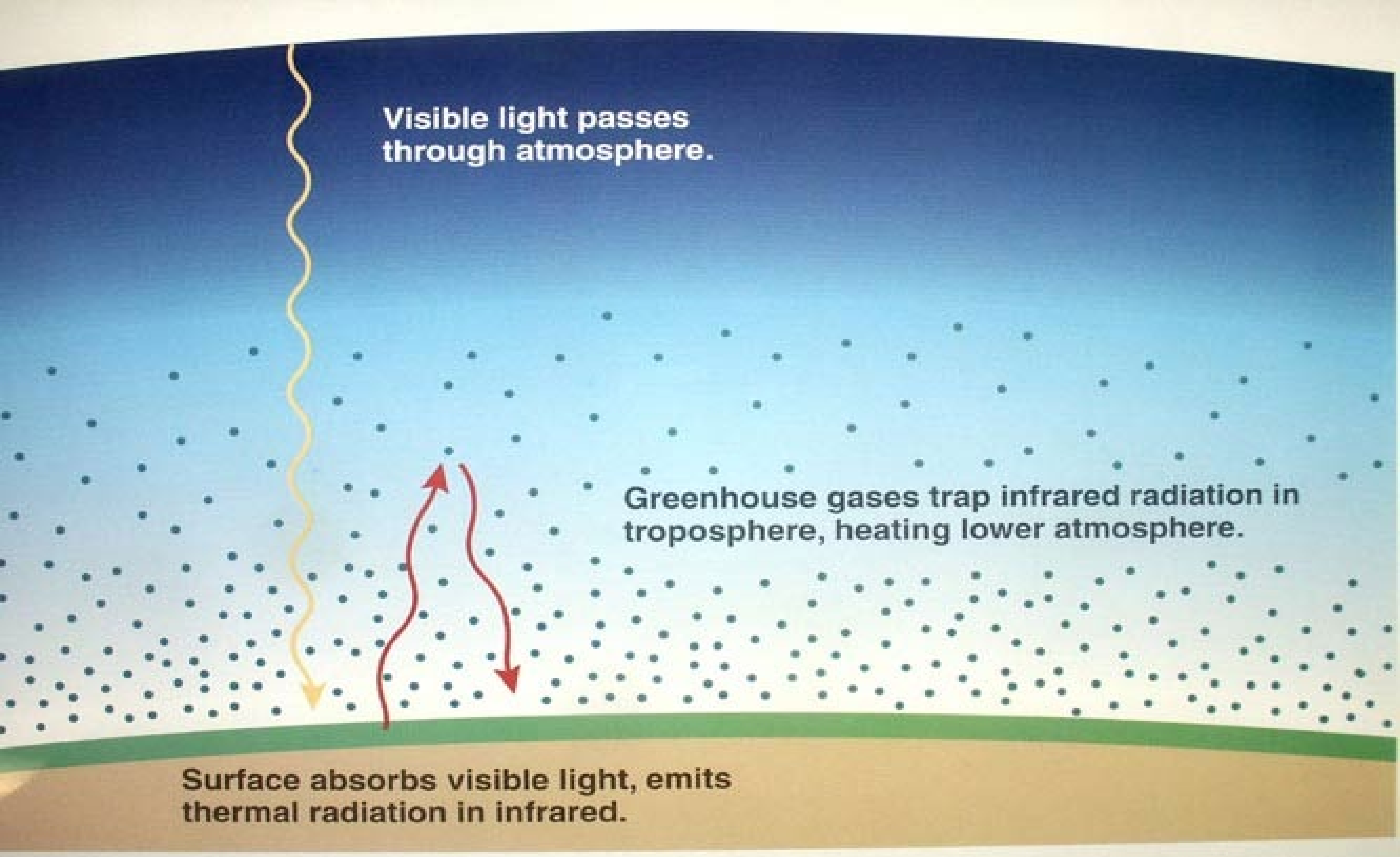
The Greenhouse Effect

- 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

Earth, at pre-industrial 280ppm CO2. the absorption bands of water vapor, ozone, and especially CO2 prevent a significant amount of Earth radiation from escaping. Water vapor absorption fraction is higher at higher temperatures



The Greenhouse effect



As the water vapor level rises…

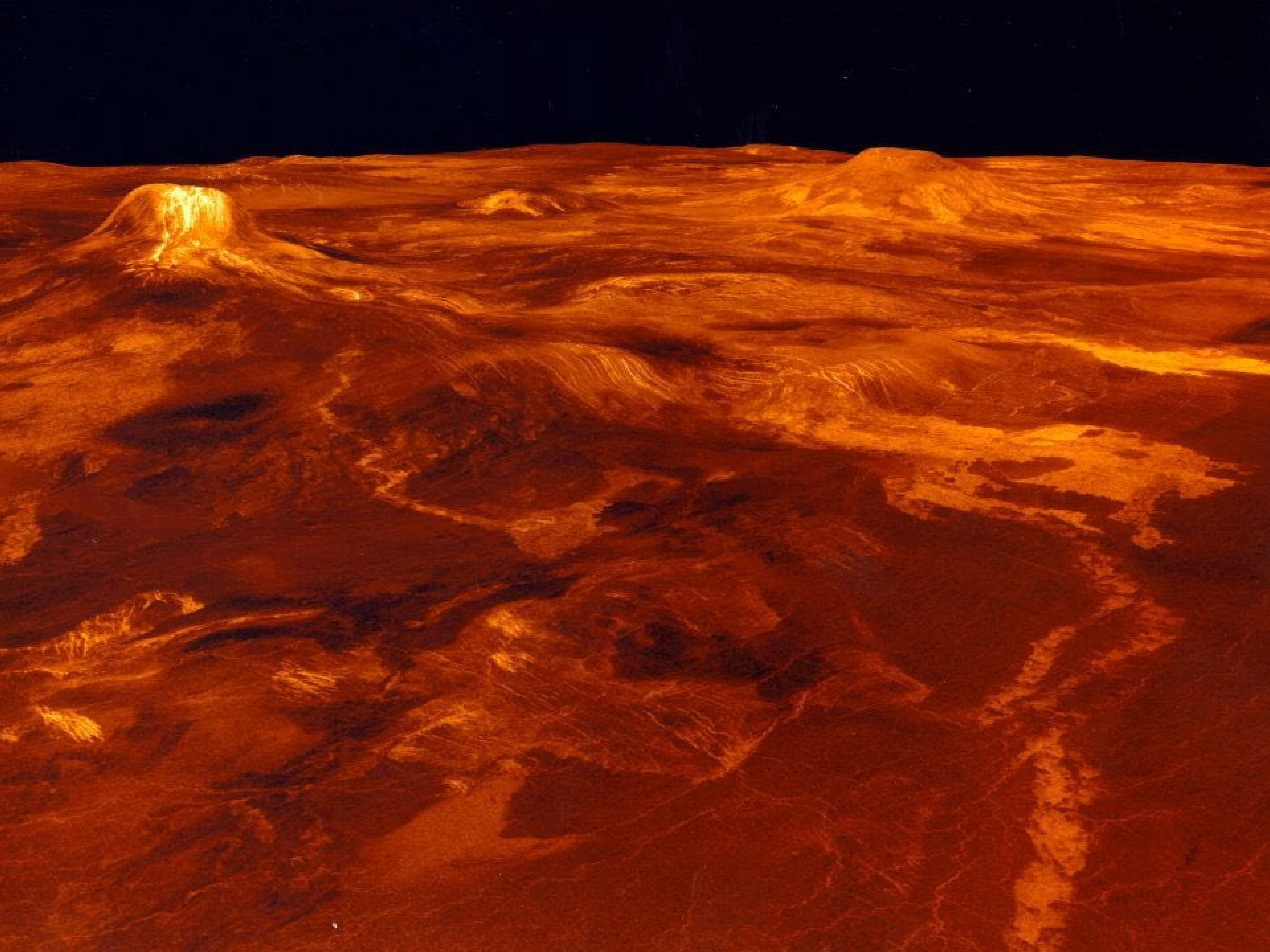
- Greenhouse heating rises, forcing more water vapor, forcing more heating…. An amplifying feedback which runs away!
- Until the oceans turn to vapor, which rises to the upper atmosphere, where…
- H_2O is split by solar UV into O_2 and H
- The O_2 combines with rocks to make oxides (e.g. iron oxide, aluminum oxide, etc)
- H, as we saw, will escape Venus' gravity into space
- The atmosphere is then left with CO_2, and little else.
- **But, Venus has no ability to make CO_2 into rock, no plate tectonics, and no carbon cycle like the Earth has (more on that later).**
- **That's bad….**

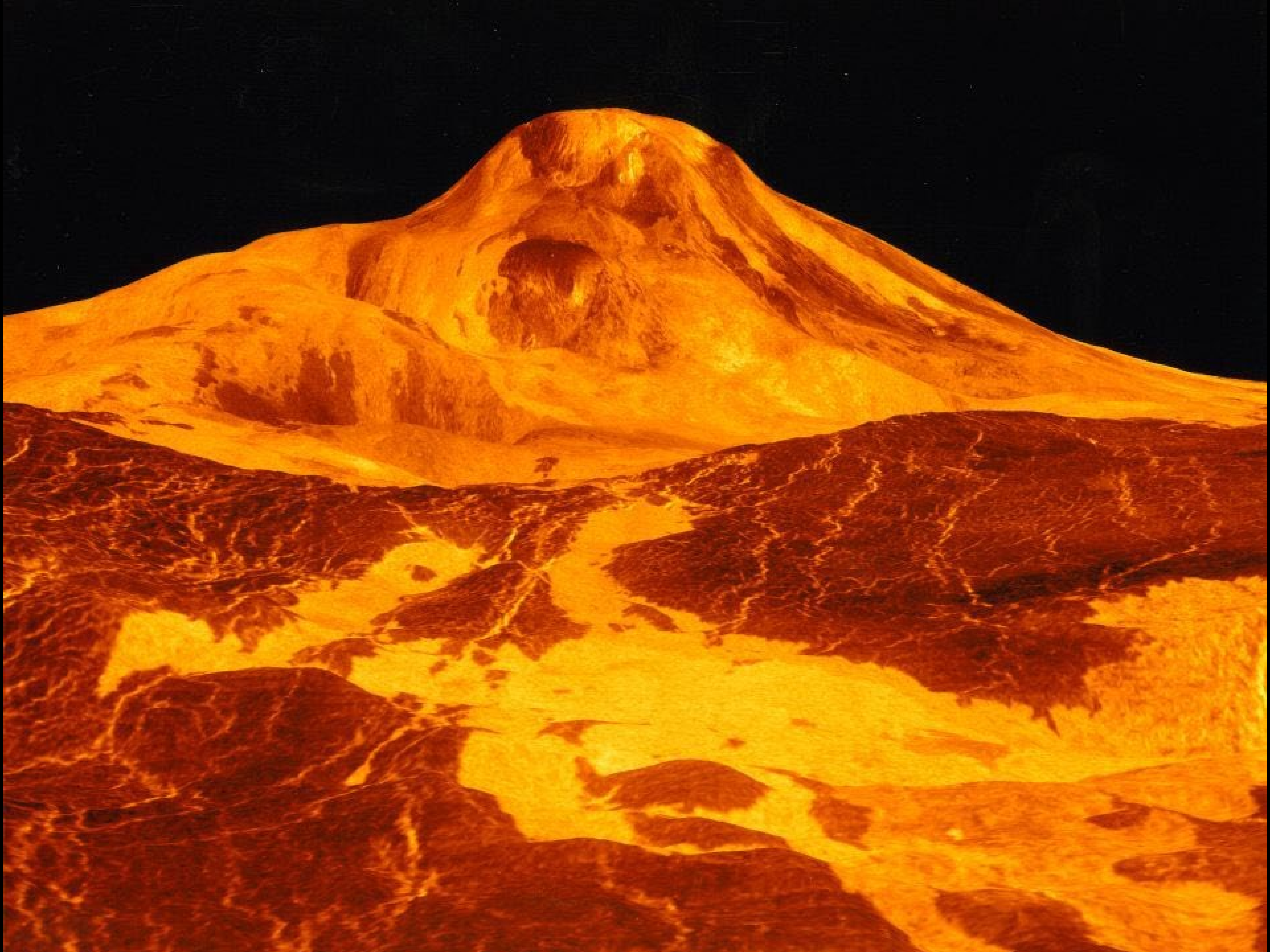
Why no plate tectonics?

- Need rapid spin rate 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

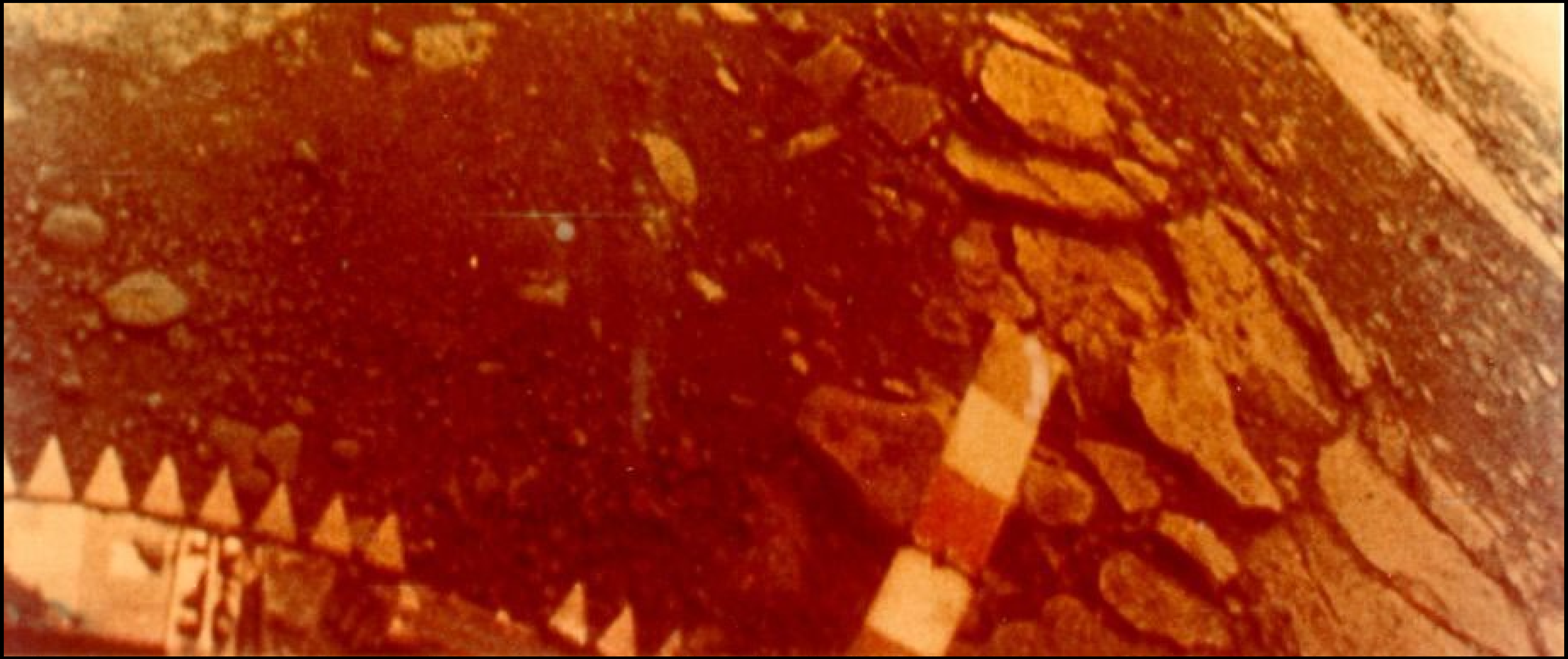
Net Result…

- 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.





Venera Lander, photo of Venus' Surface. Baked flat (ancient mud flat???) rocks. Fuels speculation of ancient ocean billions of years ago



Future of Venus Climate?

- More of the same, only worse
- Solar luminosity will slowly rise.
- Venus can’t get any drier
- Perhaps the volcanoes 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

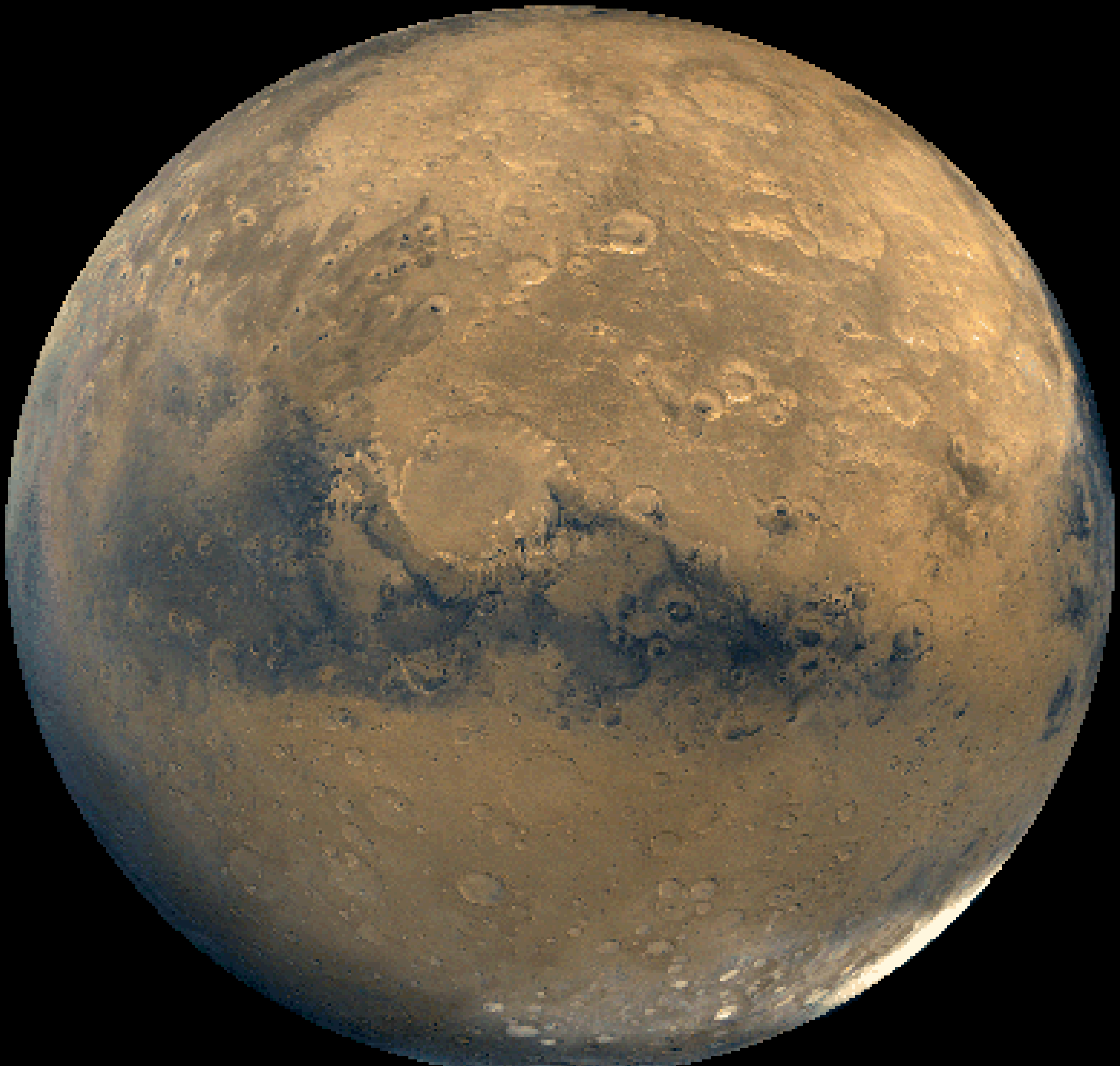
The Moon. It's geologically dead. No atmosphere, no hint of any early atmosphere. Atmospherically, it's aborted. Stillborn. Not alive now or ever. Origin of Moon see "Paleo Earth" powerpoint

Impacts broke through crust, show early bombardment period. Moon rocks show age 3.2-4.1B yrs for maria, up to 4.5B yrs for highlands. ‘late bombardment’?

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

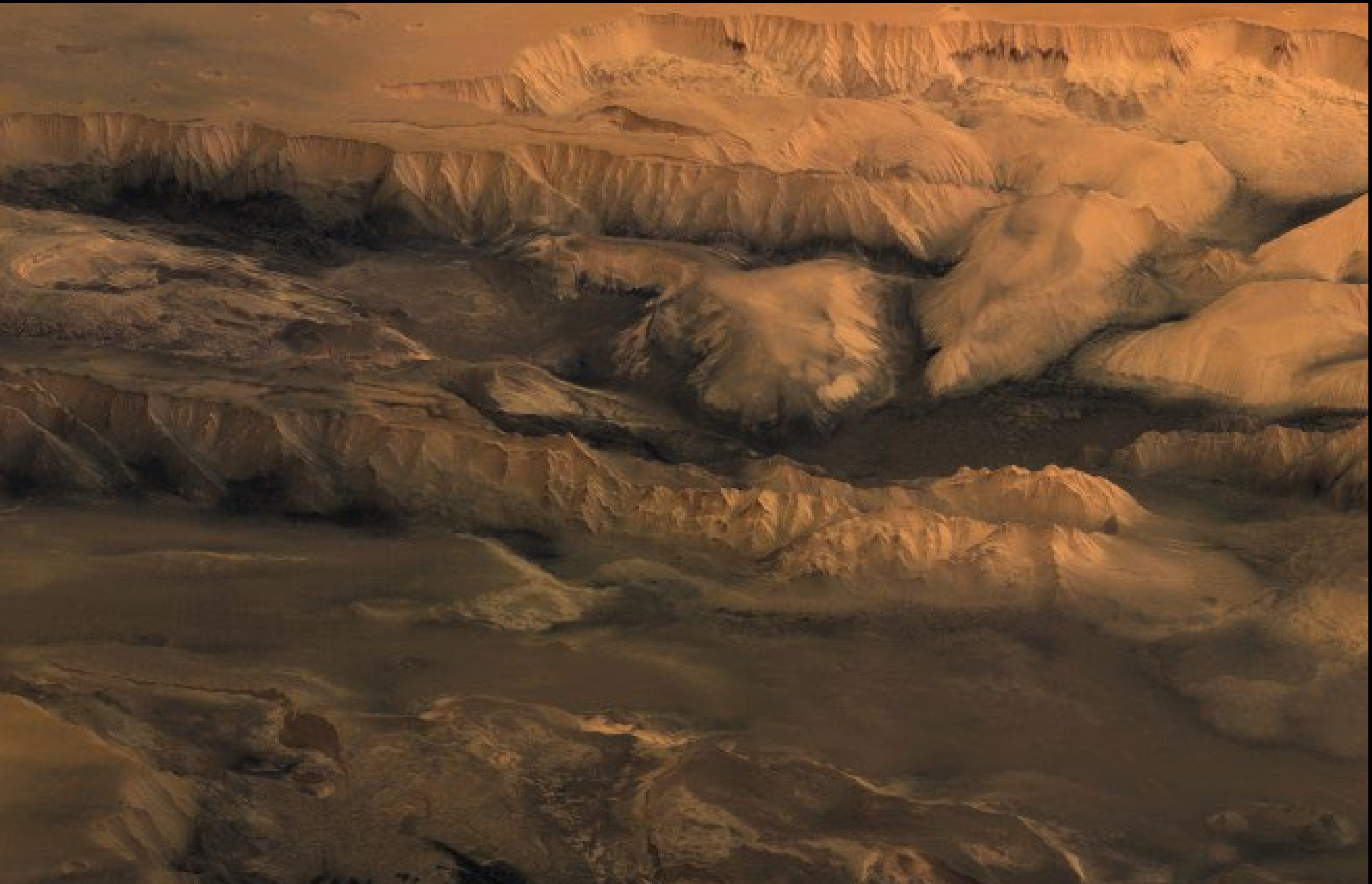
Mars – A pure CO_2 atmosphere

- …But not much of it. Only 1% of Earth's atmospheric pressure. Why so little?
- Mars shows limestone rock, so some of the CO_2 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 asteroids - can only do that if they lost some orbital energy, like impacting, or hitting ring material perhaps.

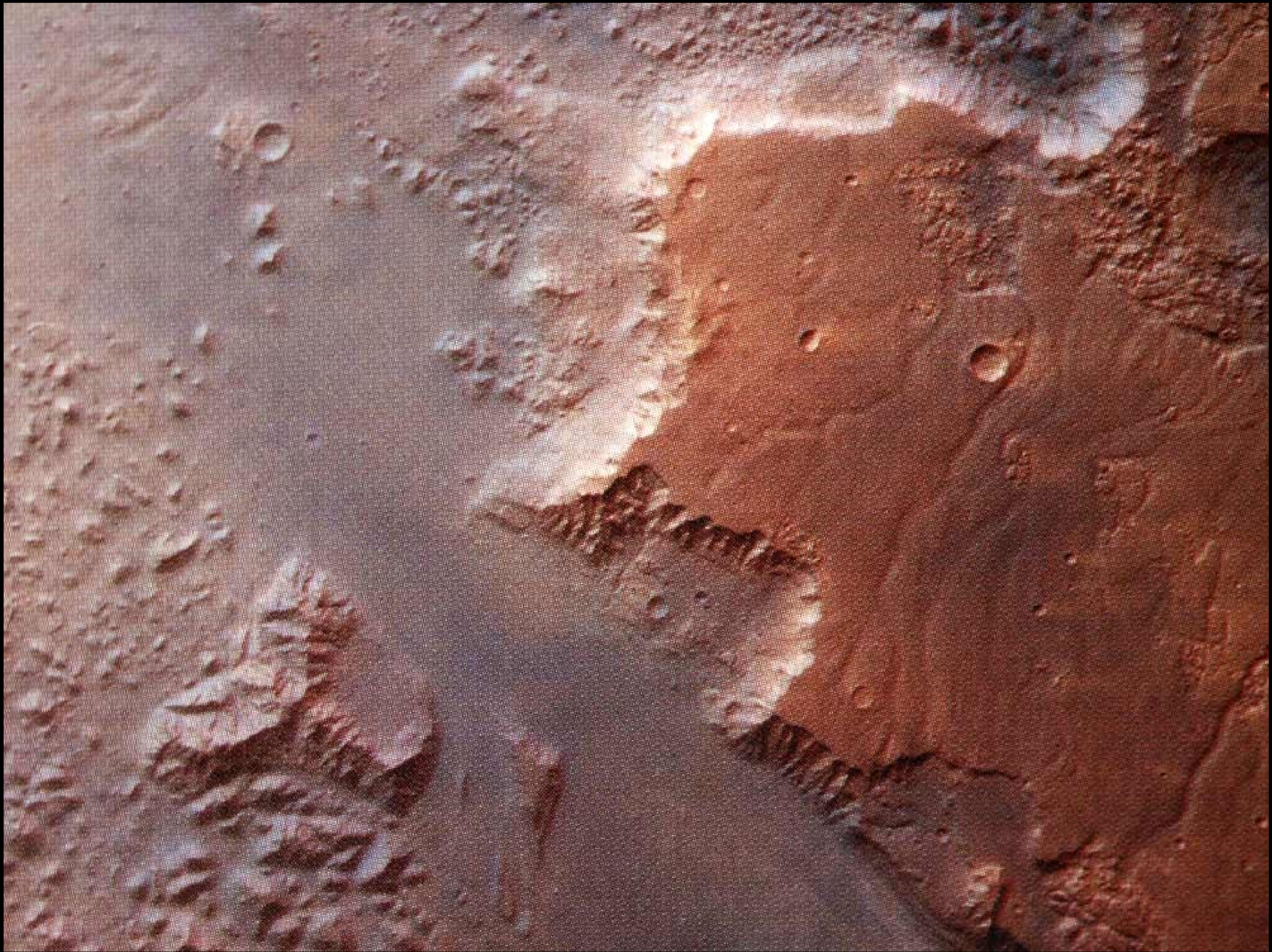


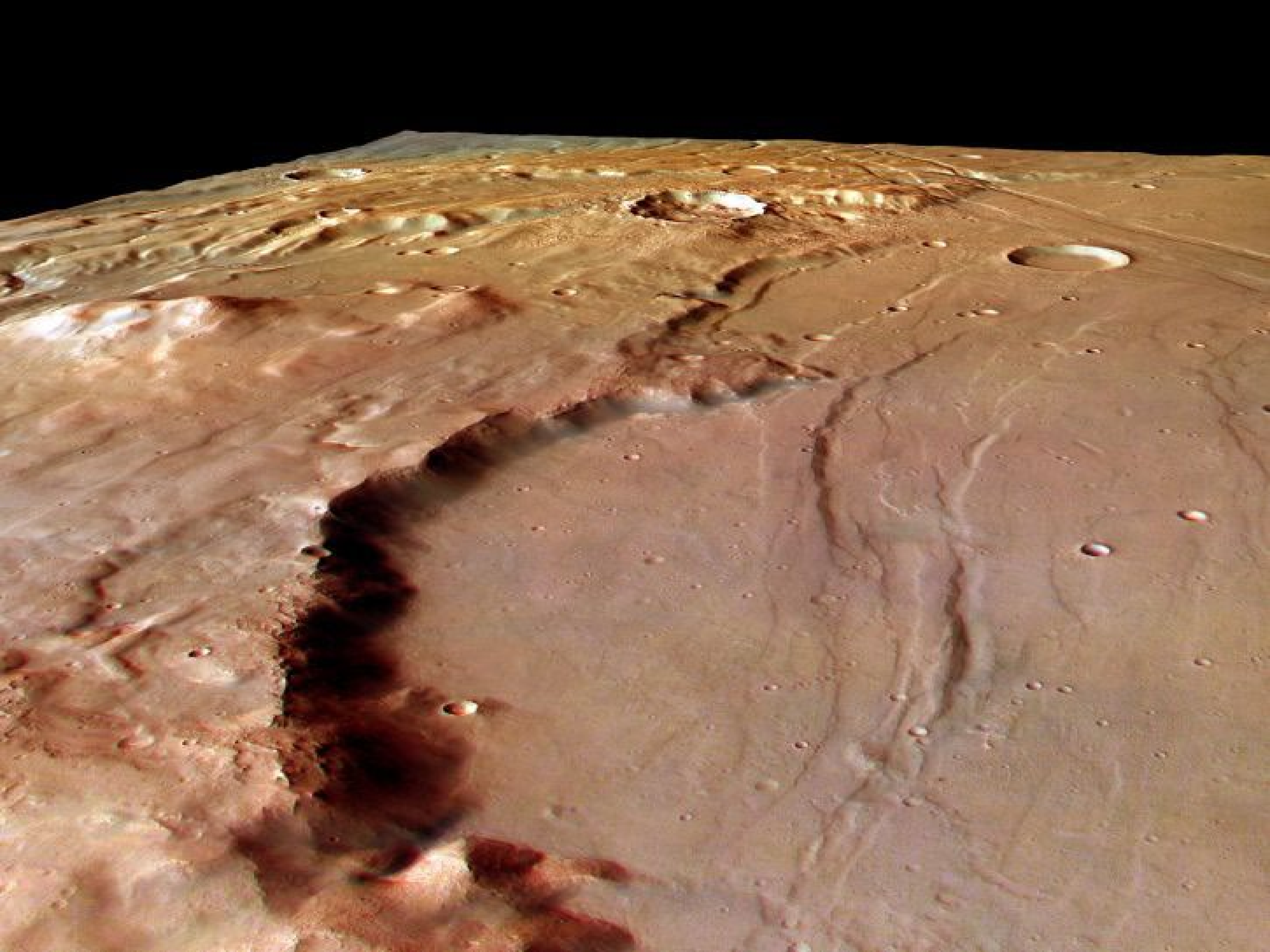
Olympic Mons: caldera

Mars: Valle Marinaris – huge erosional canyon from early era, when Mars had liquid water, cutting canyon from highlands down to polar ocean basin

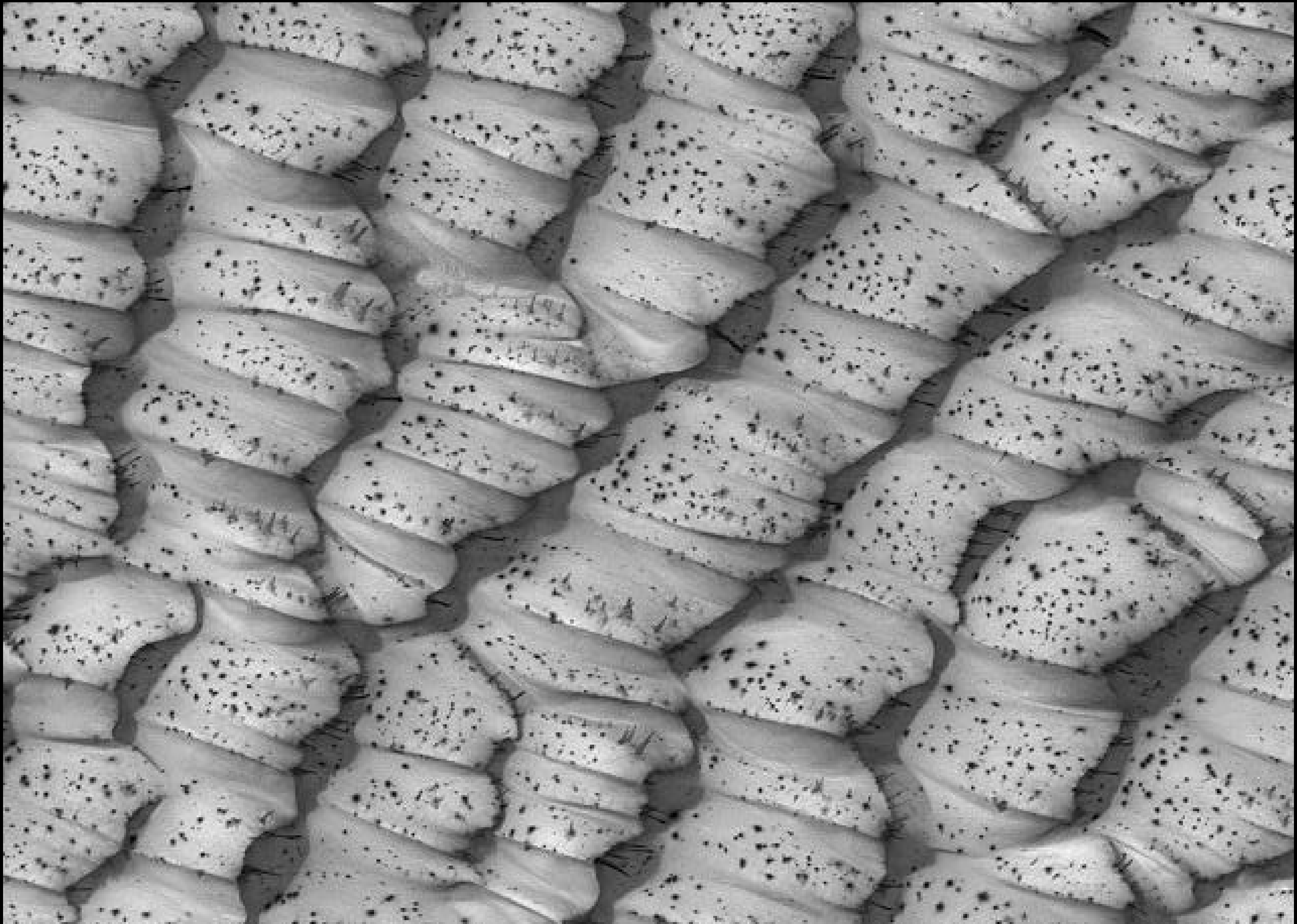


Continents and shorelines. Fractal dimension matches Earth's coastline fractal dimension

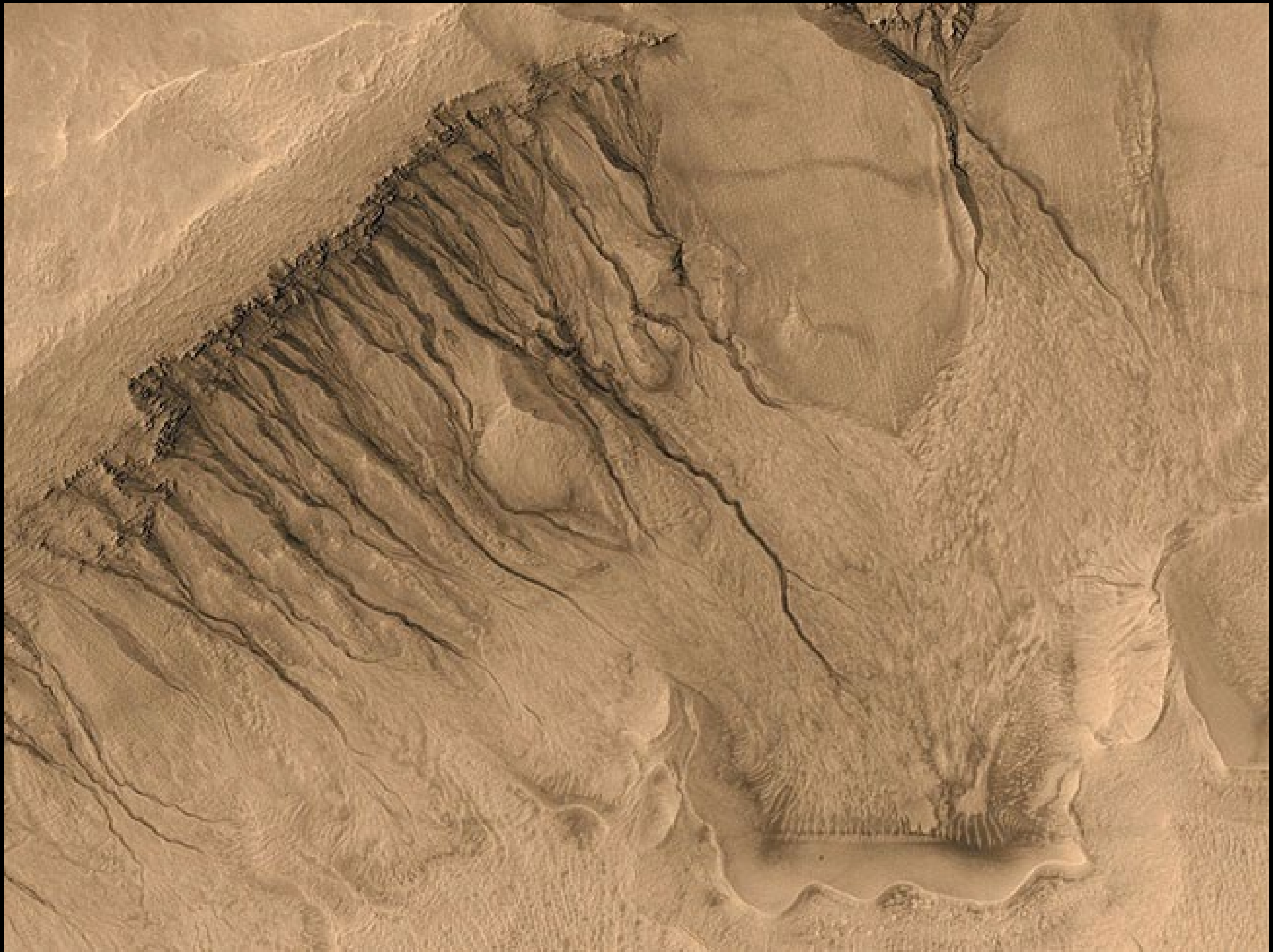




Martian sand dunes



Mysterious Gullies: Made by Powder? Sand? Water?



Made by Water?

- **Water? Pro**: briney residue claimed in recent reflection spectra, as if salty water had leaked out of ground and evaporated
- **Water? Con**: Only a few meters down, the soil is so deep as to be unaffected by the day/night or even the seasonal temperature cycle, and it remains therefore below freezing. If there’s any water source down there, it’s ice.
- Therefore, it would take only a few years to melt ALL of the shallow melt-able ice, and yet Mars has clearly had no significant surface water for billions of years. The atmospheric pressure it too low to permit liquid water. There’s no controversy about these facts.

A Better Theory?

- Scientists propose that sand, when cold enough, will allow frozen “dry ice” (CO2 from the atmosphere) to bind together the sand into a fragile solid
- Then when it gets sunny on those crater slopes, the CO2 turns to gas, and the sand, now filled with gas, flows like a liquid down the slopes, carving the channels

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.

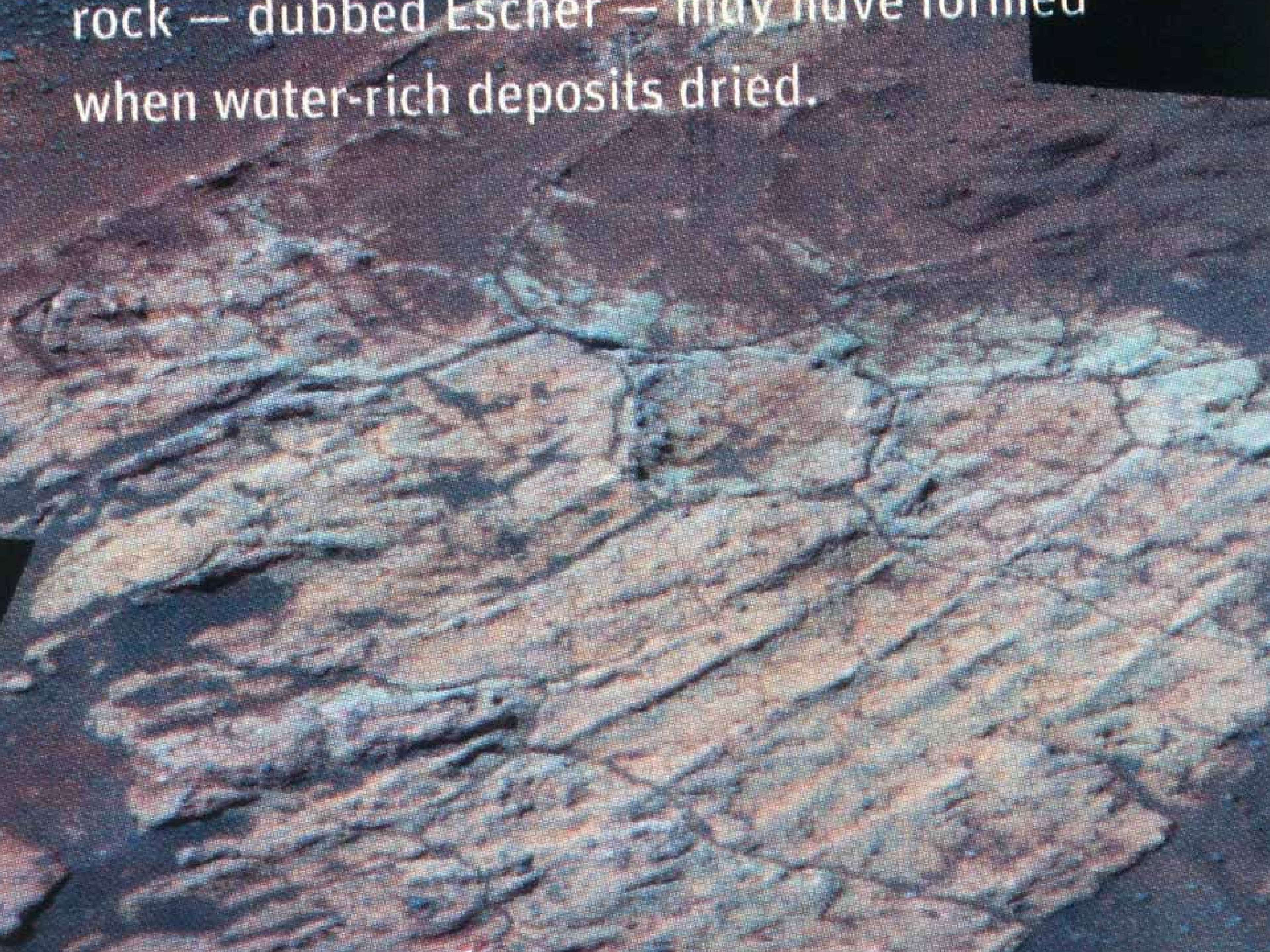
"Good," he replied. "I never hire any-

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

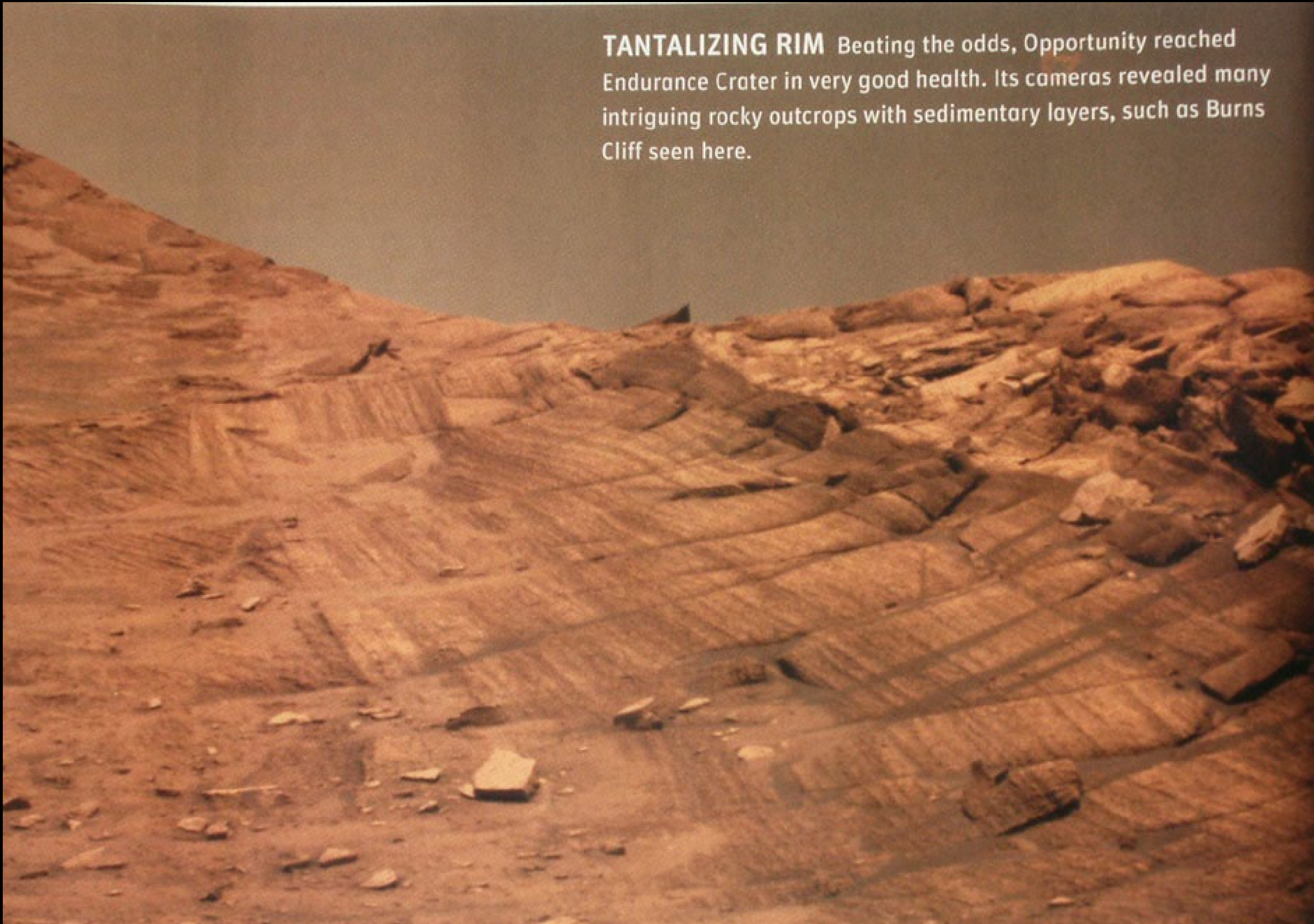
Italian, can mean artificial or natural channels). Lowell is portrayed as the passionate observer, always steadfast in his support of Martian canals and the civilizations, past or present, that must have

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

- **M**ars **A**tmospheric **E**volutio**n** 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

MAVEN and Mars: Atmosphere Loss via Solar Wind

- YouTube (1 min)

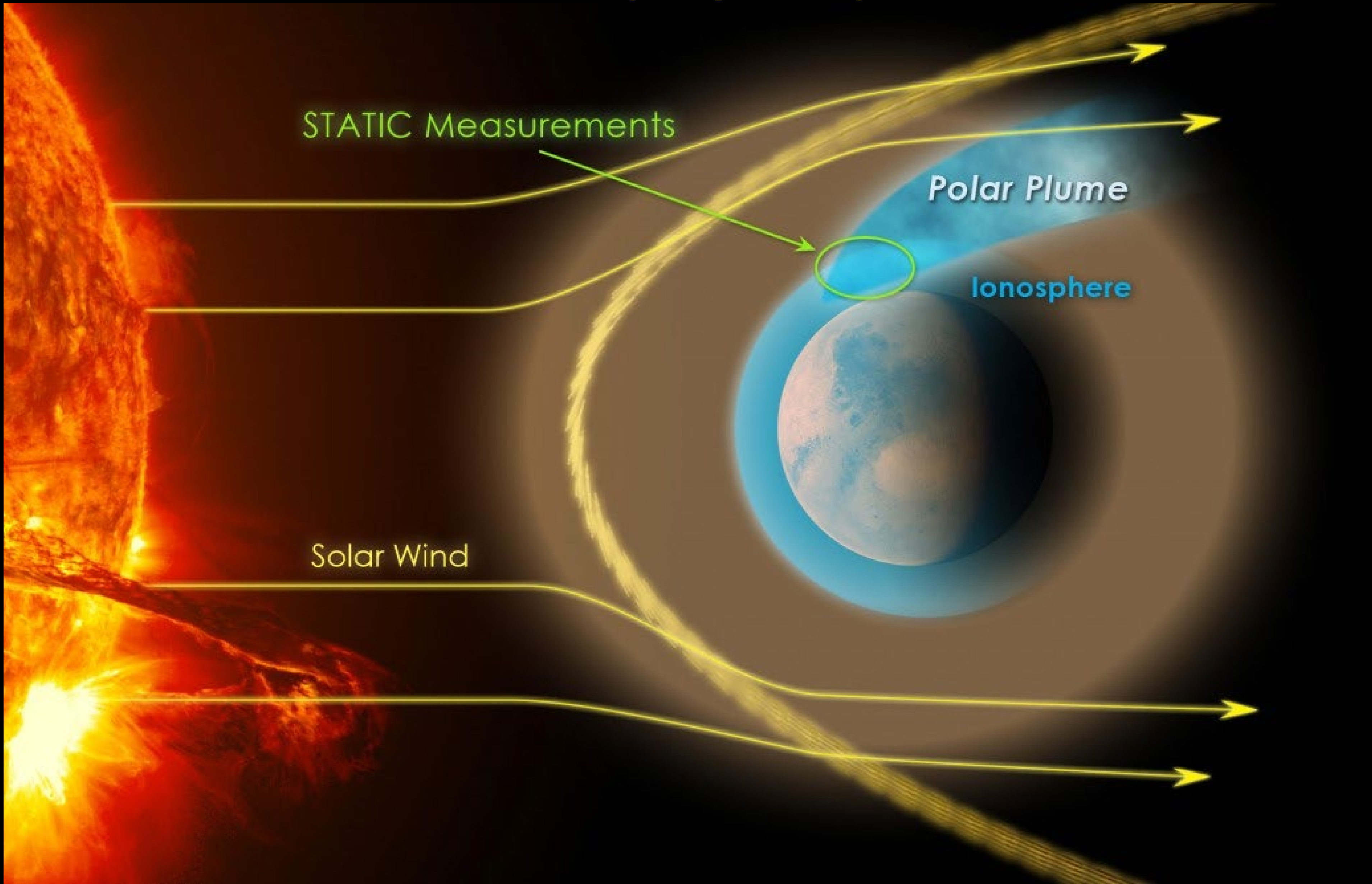
What can we say right now….?

- 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…

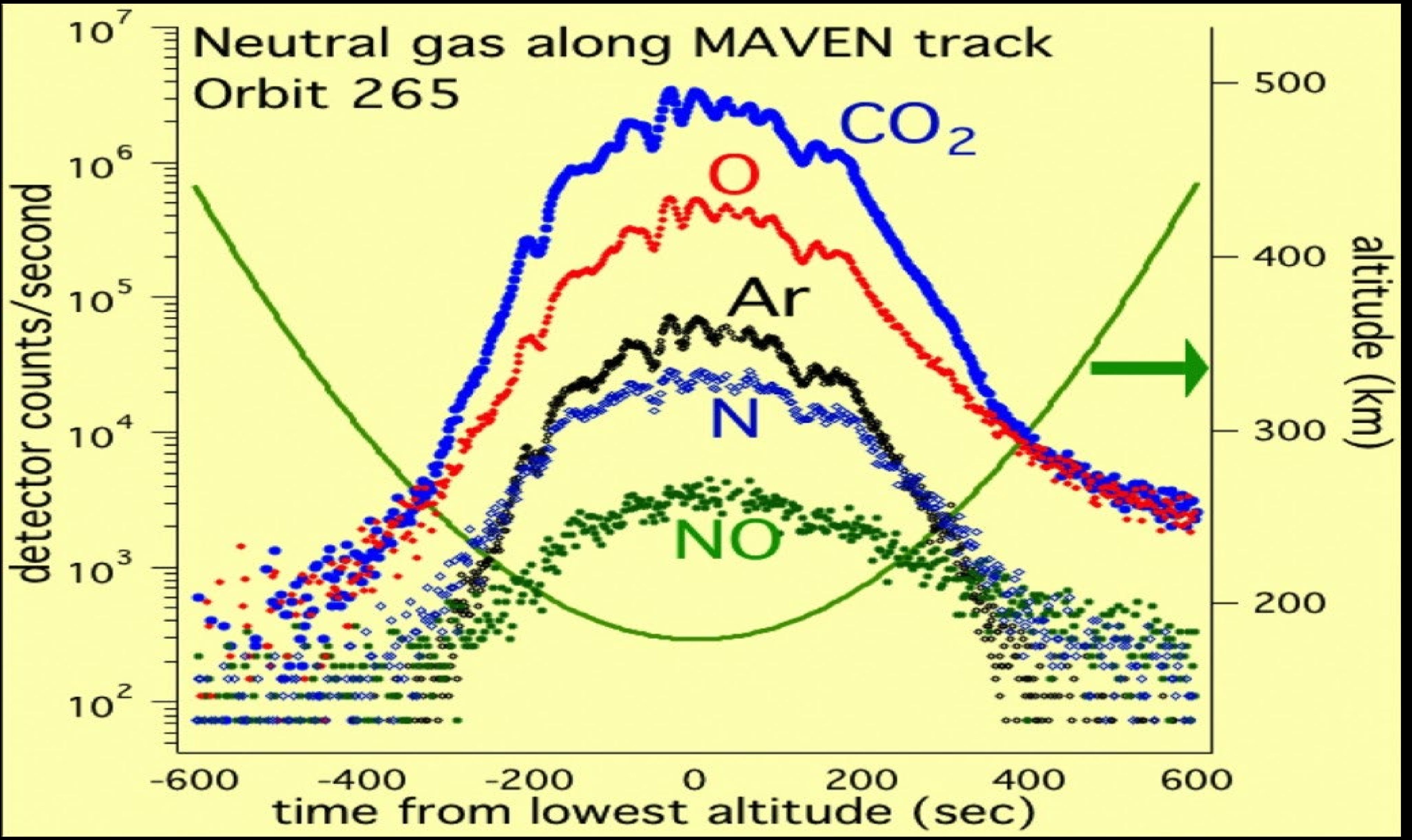
No magnetic field – BAD for your atmosphere

- 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.
- So, no water possible on Mars. Only ice, or a bit of vapor in the atmosphere

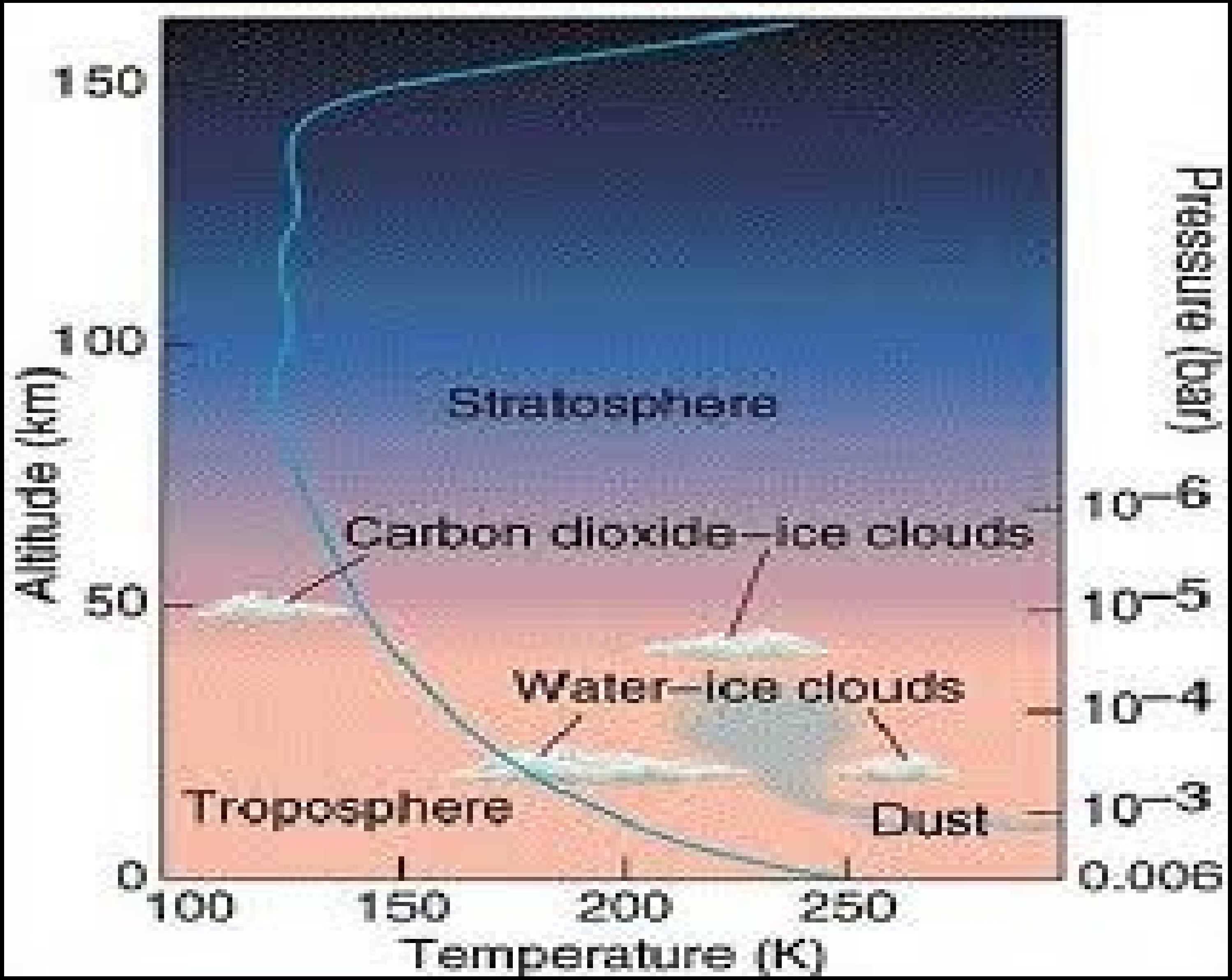
MAVEN finds solar wind can penetrate deep into atmosphere, carrying away molecules



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



General Structure of Mars Atmosphere Today



Mars Rover “Curiosity” Finds Clues…

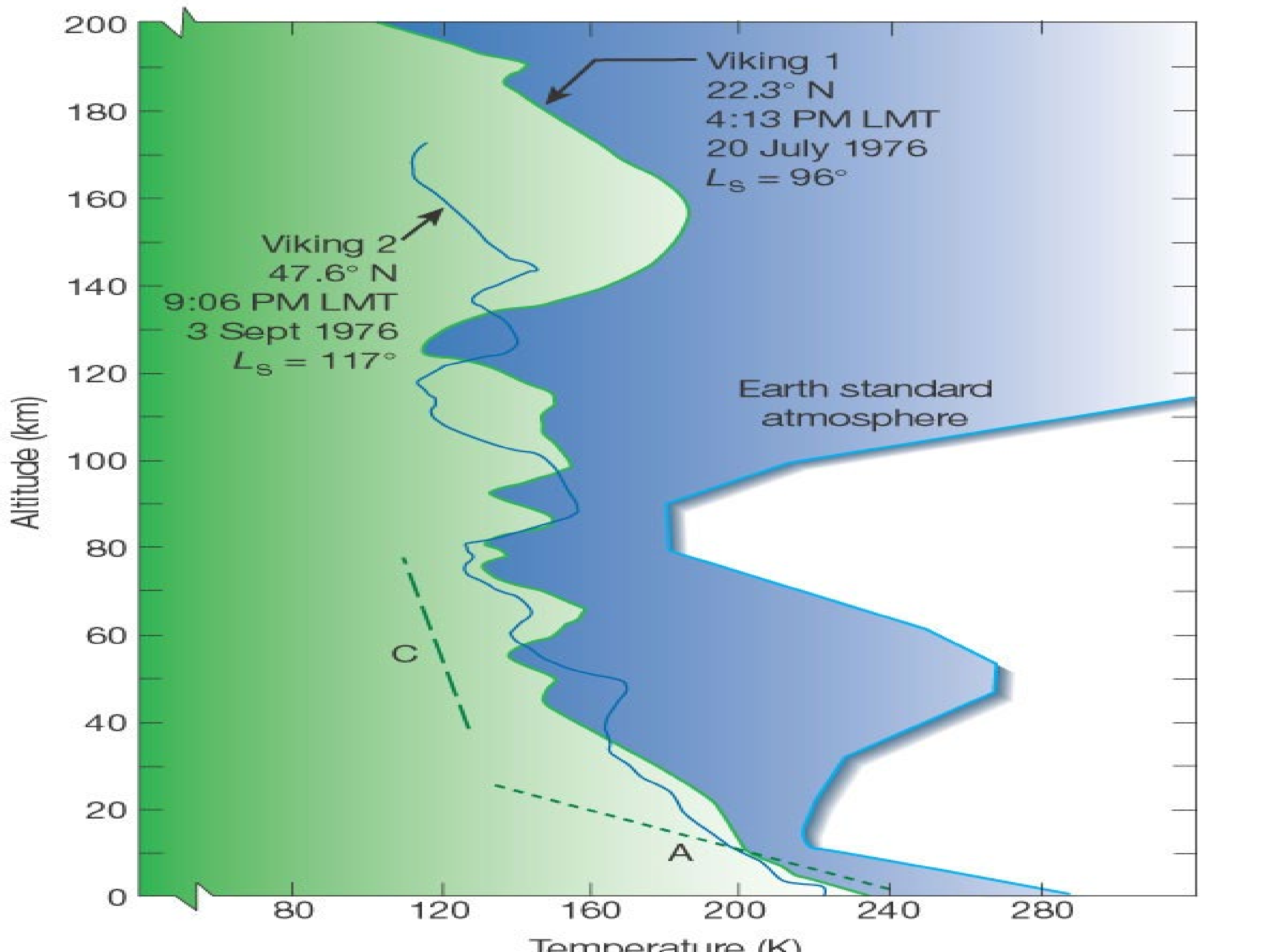
- …As to how Mars lost so much atmosphere – it finds the current atmosphere is much enriched in the heavy *vs* lighter isotopes for Argon and Carbon, vs. the abundances found in the older Martian rock found in Antarctica
- Lighter isotopes would be more easily lost to outer space by thermal leakage, 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

Ancient Martian Climate Has Some Twists, it Seems

- In Gale Crater, where Curiosity has been poking around, we find no evidence of carbonate rocks, limiting the amount of CO_2 the atmosphere may have had at the time the rocks were laid down.
- Yet the evidence for a liquid ocean billions of years ago is strong.
- We don't have a new theory which reconciles the evidence for low CO_2 (a few millibars worth of atmospheric CO_2, at most) and yet a warm enough climate billions of years ago when the sun was dimmer, to permit the very rocks which indicate low CO_2 to yet have been formed at the bottom of a liquid water lake.
- Interesting 2017 article on this 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 real Stratosphere because there is no heating via Ozone absorption of solar UV like there is on Earth.

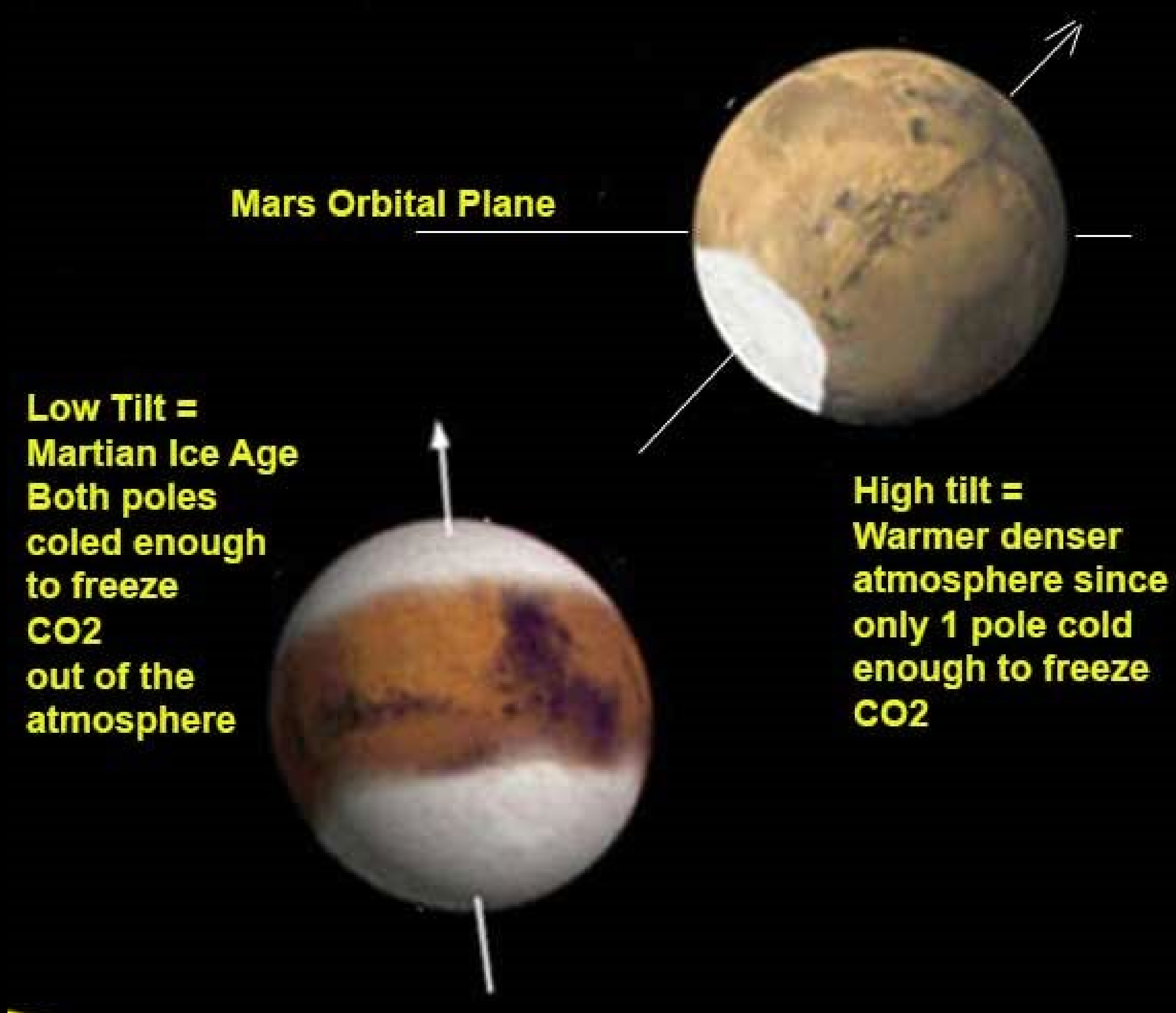


Viking 1
22.3° N
4:13 PM LMT
20 July 1976
Ls = 96°
Viking 2
47.6° N
9:06 PM LMT
3 Sept 1976
Ls = 117°
Earth standard atmosphere
C
A
Altitude (km)
Temperature (K)
0
20
40
60
80
100
120
140
160
180
200
80
120
160
200
240
280

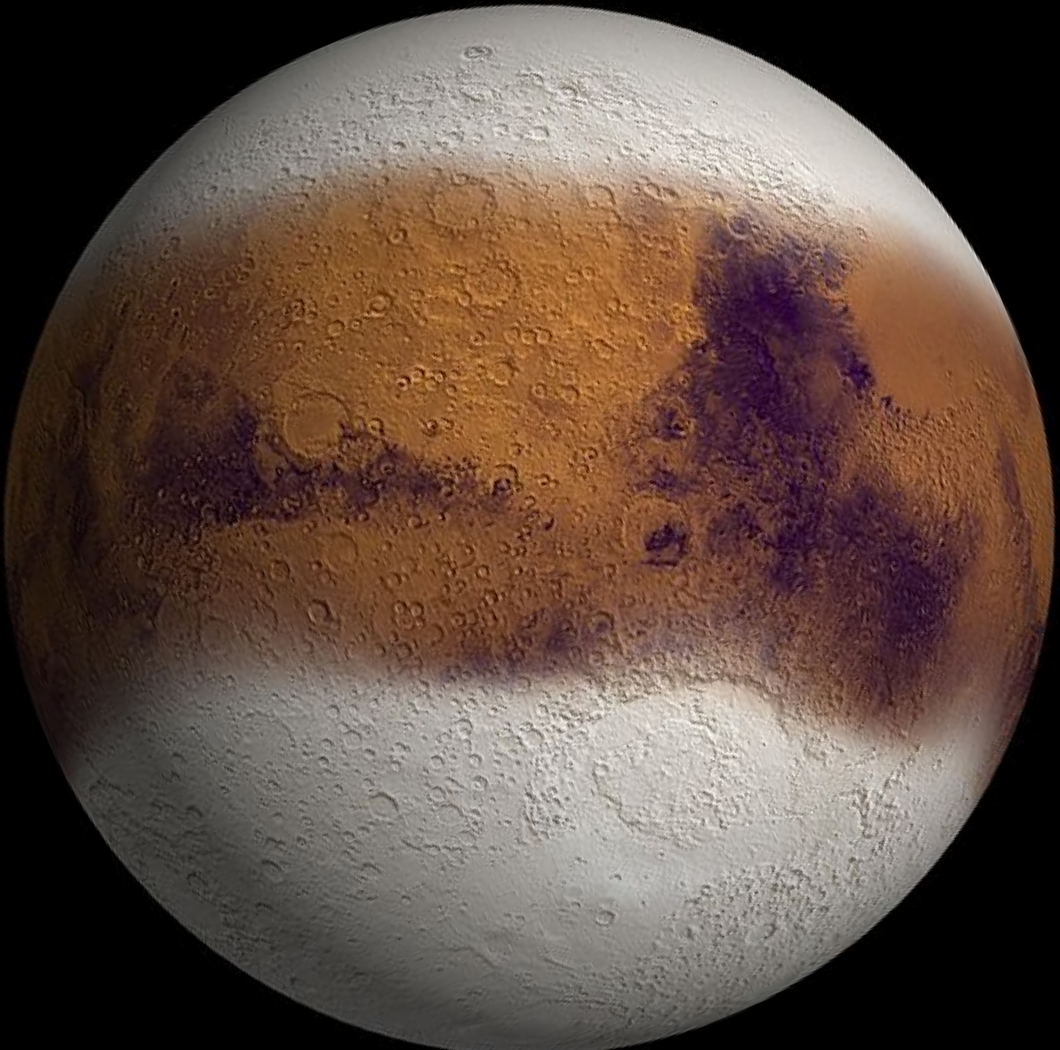
How Does Mars Atmosphere Change with Axis Tilt?

- Mars spin axis tilt varies from near zero to well over 45 degrees (~million year cycles) because not stabilized by a massive moon like we have
- 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.

At low tilt, both poles are cold enough to freeze CO_2 out of the atmosphere. When nearer ~45 degrees or more, one pole gets enough full day sunlight that all the CO_2 ice melts, and the CO_2 atmosphere gets thicker, warmer (both water and CO_2 are greenhouse gases)



Small Tilt = Martian Ice Age



Key Points: A7 Chap 10 - Atmospheres of Mercury, Venus, Mars

- Surface temperature and gravity determine how well you keep your atmosphere against leakage
- Loss mechanisms: Leakage of lighter molecules, impact cratering, ablation by solar wind if have only a weak magnetic field
- **Understand the greenhouse effect!**
- Mercury and our moon, too hot and too low gravity to retain any atmosphere, no mag fields didn't help either, for moon
- CO_2 dominates both Mars and Venus; heaviest common molecule
- Runaway greenhouse effect: rising temps add water in upper atmosphere, dissociated by solar UV, lost to space – this was Venus' fate
- Mars atmosphere has thinned progressively over 4.5B years due to no protection from solar wind (weak mag field).
- Mars and Venus both likely had moderate temperatures and oceans of water early in their history, rising solar luminosity drove Runaway Greenhouse on Venus, and loss of atmosphere via weak magnetic field drove away most of Mars atmosphere and water destruction
- **Mars climate over past millions of years: denser warmer atmosphere when axis tilt is high, cold thin atmosphere and "Ice Age" when tilt is small. Mars has no large moon to stabilize spin axis orientation**