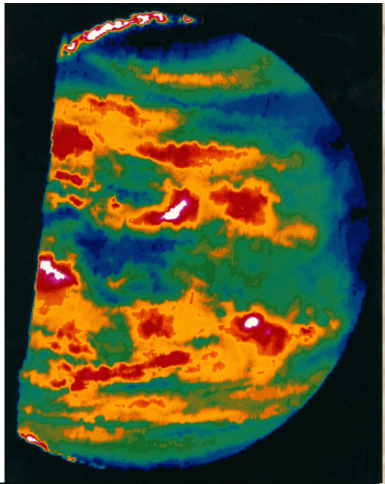
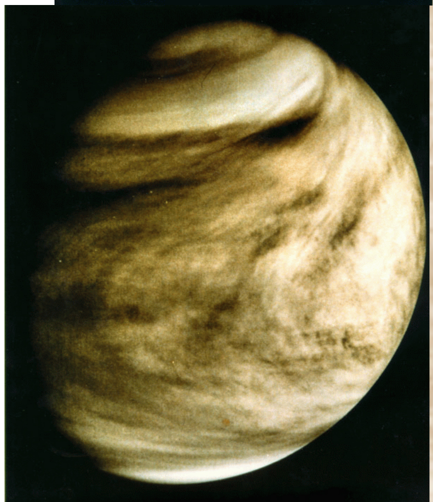


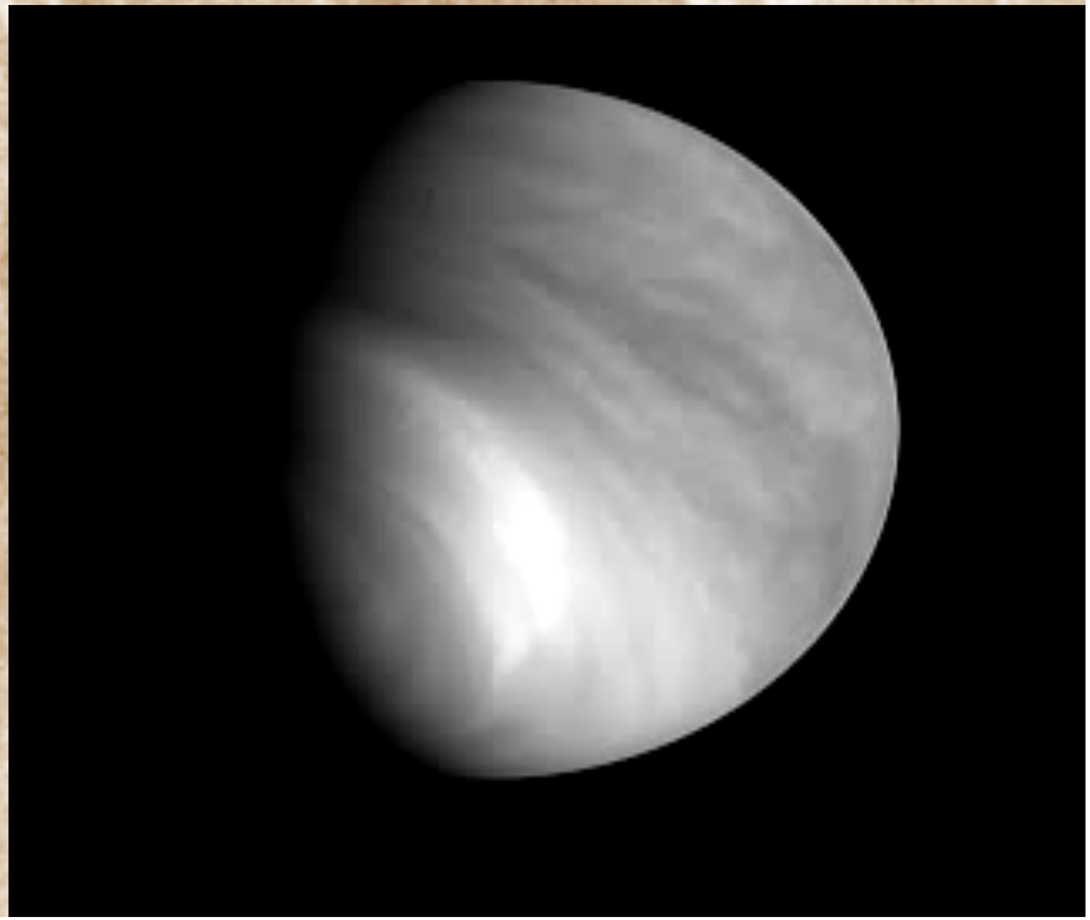


The Atmosphere of Venus

David Grinspoon
Denver Museum of Nature & Science

Exeter ExoClimes

9/7/2010



New York Times 11/16/1928

SAYS LIFE MAY BE ON VENUS

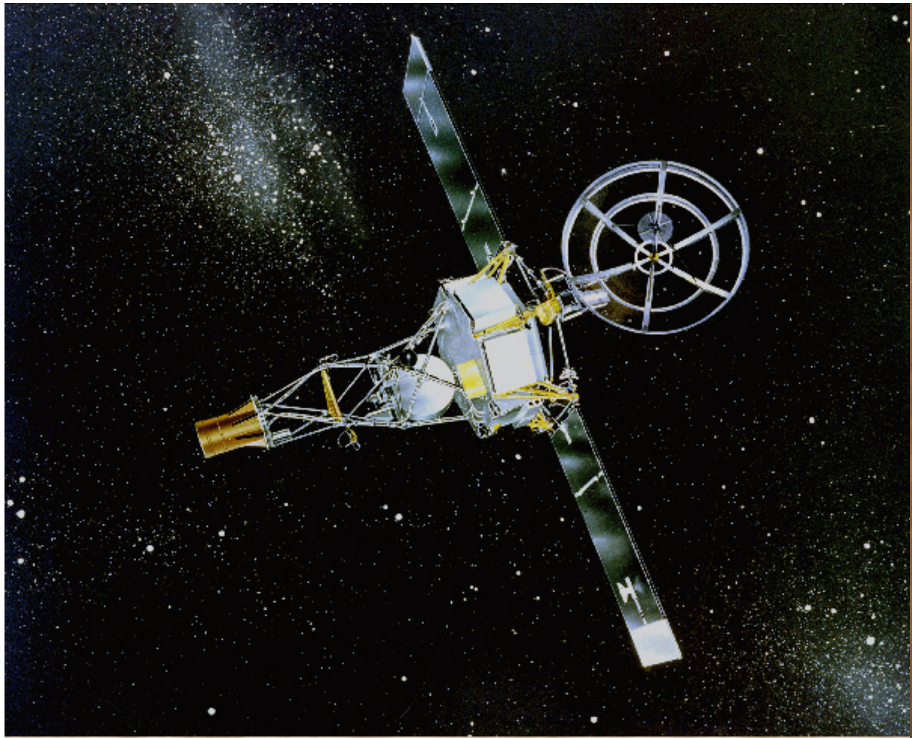
Cambridge Savant Believes Mars Also Has Essentials for Existence.

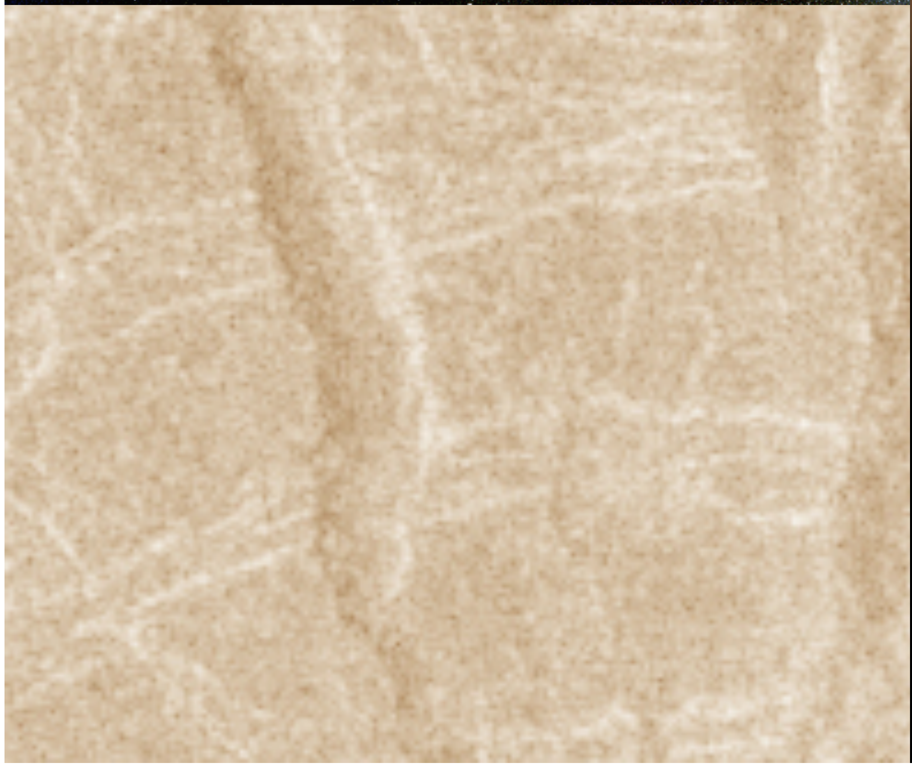
Special Cable to THE NEW YORK TIMES.

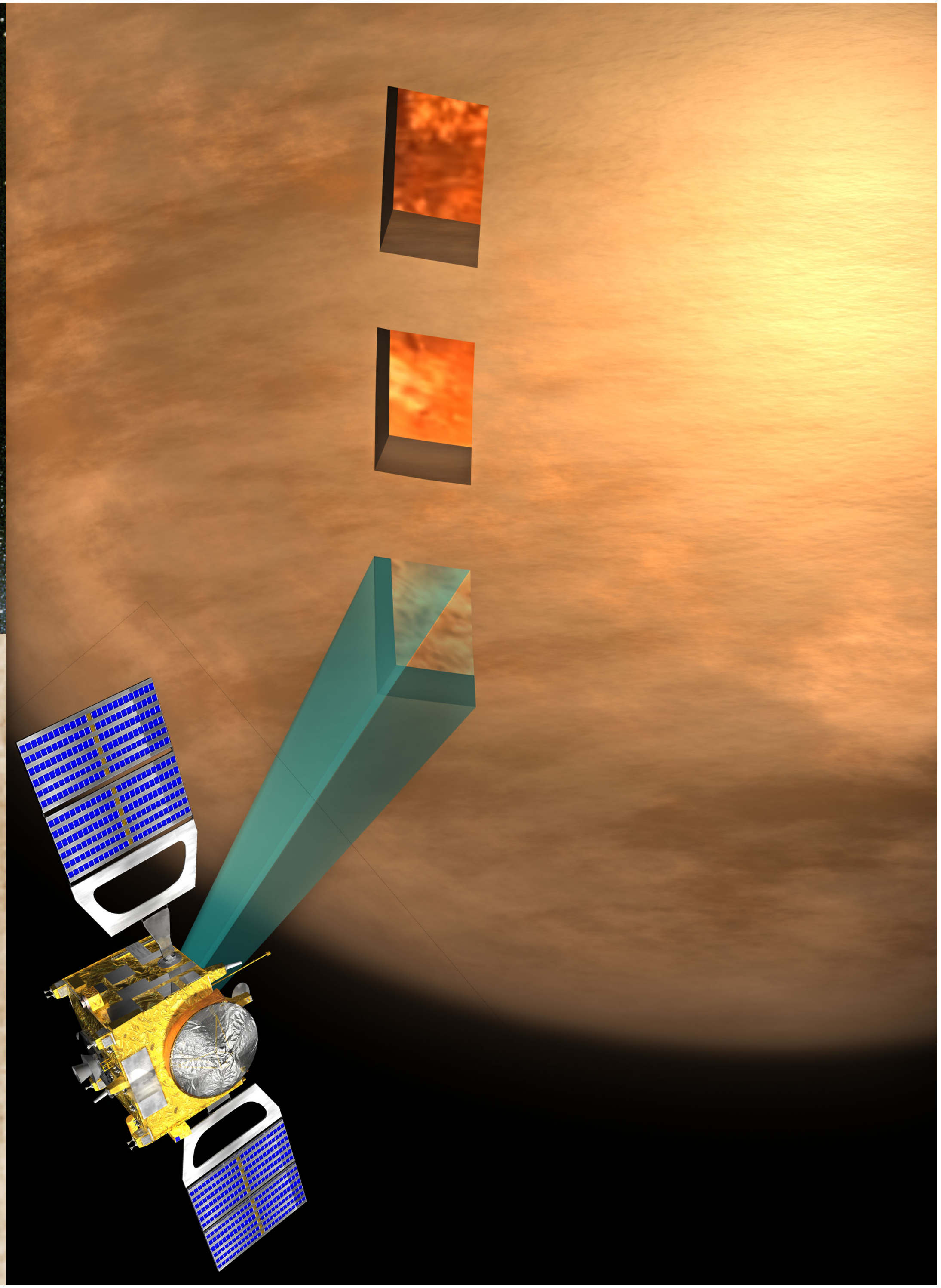
LONDON, Nov. 15.—That life may exist on both Venus and Mars is the conclusion reached by Dr. A. S. Eddington, professor of astronomy at Cambridge. In a book to be published tomorrow he says that Venus, so far as is known, would bewell adapted for life similar to ours. The planet is about the same size as the earth, nearer the sun but probably not warmer, and possesses an atmosphere of satisfactory density.

As regards Mars, Professor Eddington says that the two essentials, air and water, are both present but scanty. The Martian atmosphere is thinner than ours, but perhaps adequate. It has been proved to contain oxygen.

If animal life exists on that mysterious planet, he says, it probably is a different form of life from ours, as "Mars has every appearance of being a planet long past its prime."







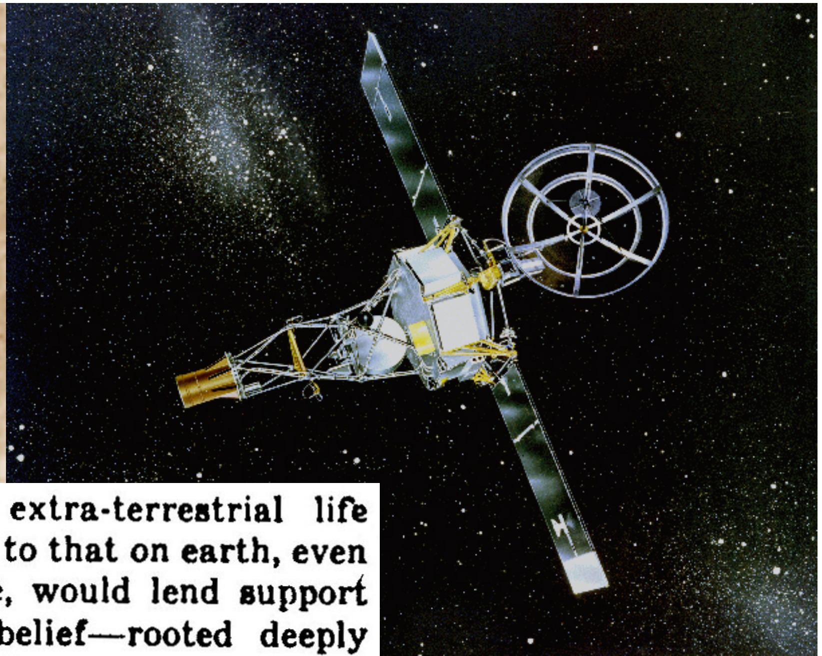
New York Times 2/26/1963

Venus Says 'No'

The first message from the Venus probe, Mariner 2, deciphered shortly after its historic fly-by of the planet on Dec. 14, at a distance of 21,564 miles, added important knowledge about Venus's magnetic field, its rate of rotation and other information shedding light on some of its mysteries. But one all-important question remained unanswered—whether or not life in some form existed on Venus and hence elsewhere in our solar system and possibly also beyond it.

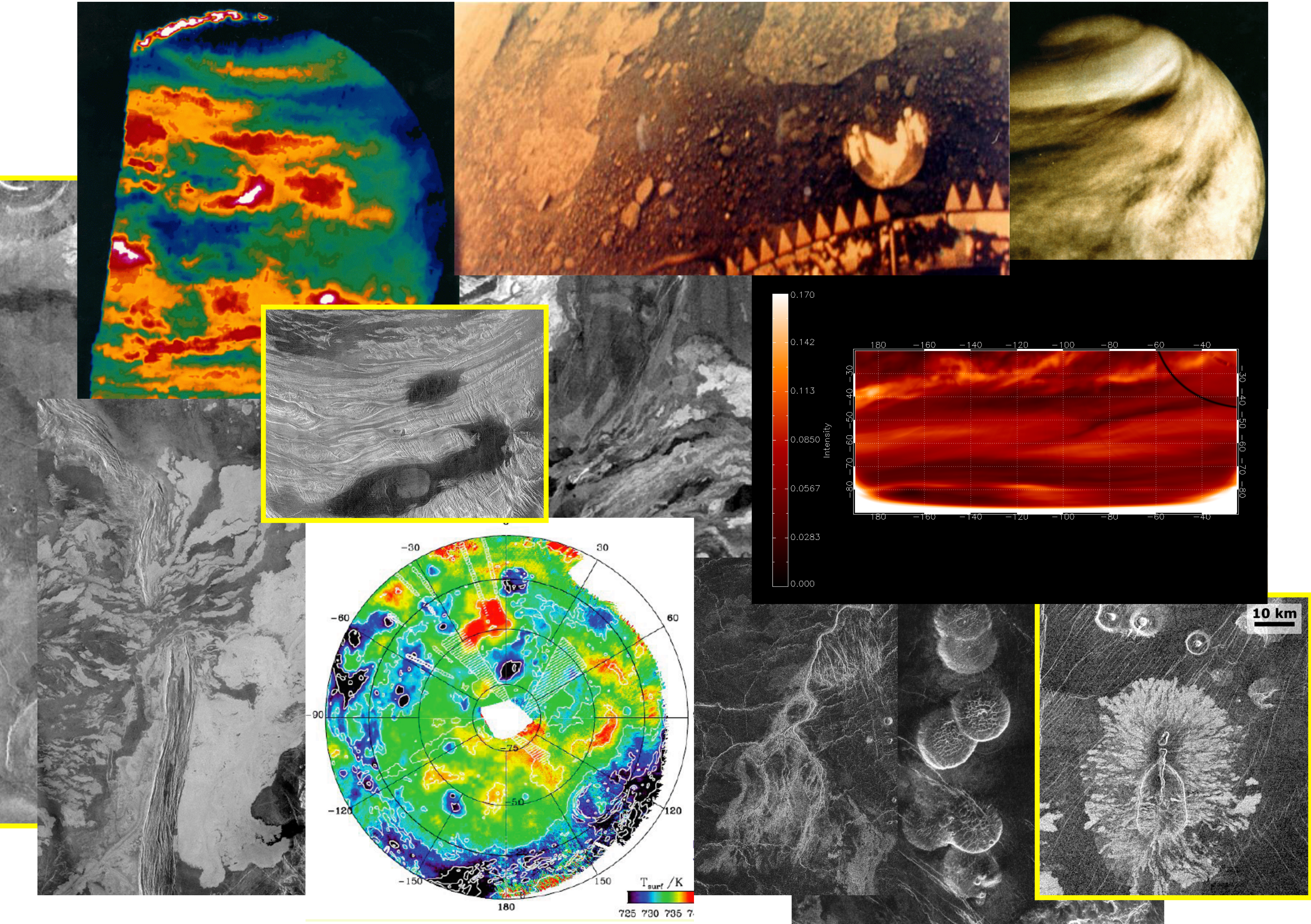
Now comes a second message from Venus, via Mariner 2, with the first definite eagerly-awaited answer to this vital question, and the answer is a disheartening, disillusioning "No! Not on Venus!"

The newest message from Venus, sent down by the "cosmic thermometer" on Mariner 2, which made the first direct measurements of the surface temperature of the planet, informs earthlings that the temperature at or near the surface of our cloud-covered, planetary neighbor is between 300 and 400 degrees Fahrenheit. This high temperature, established for the first time, definitely rules out the possibility of the existence of life in any form even remotely resembling life as we know it on earth.



The finding of extra-terrestrial life in some form similar to that on earth, even at the lowliest stage, would lend support to the widespread belief—rooted deeply in the aspirations of mankind—that life as we know it is not unique to this insignificant corner of the universe, but exists in many other systems similar to ours throughout the universe. Indeed, there has been speculation among scientists, philosophers and poets that some of these systems have reached a stage of evolution much superior to ours. The message from Venus now reduces the hope of finding evidence in support of this speculation to one half, so far as our solar system is concerned.

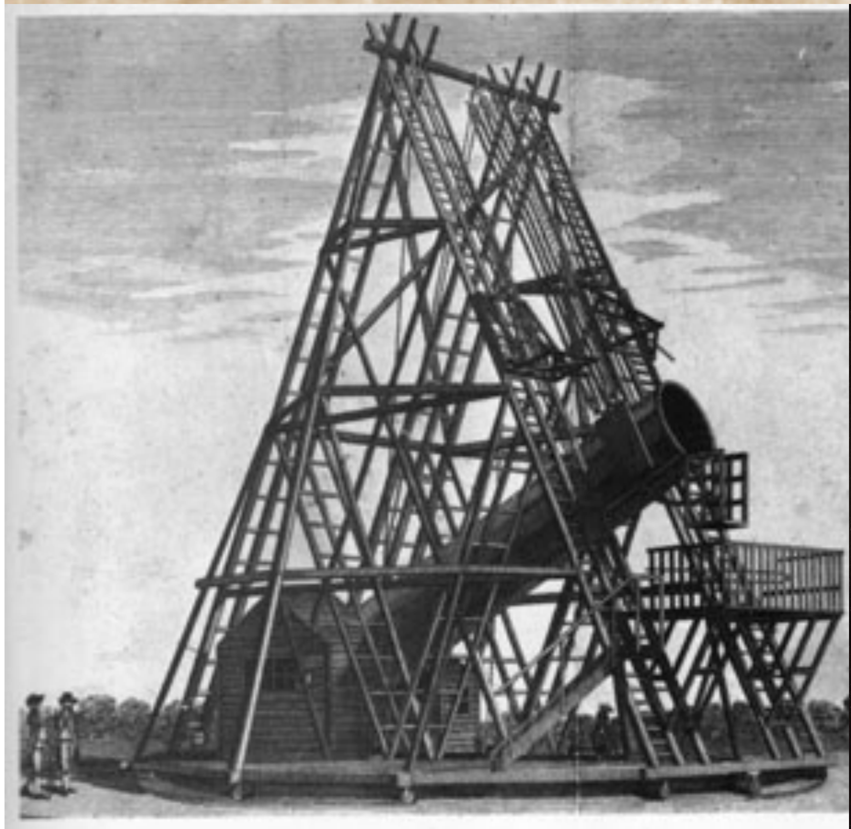
Mars now remains our only hope of turning this universal dream into reality, and the evidence so far is not very encouraging. The message from Venus may mark the beginning of the end of mankind's grand romantic dreams.

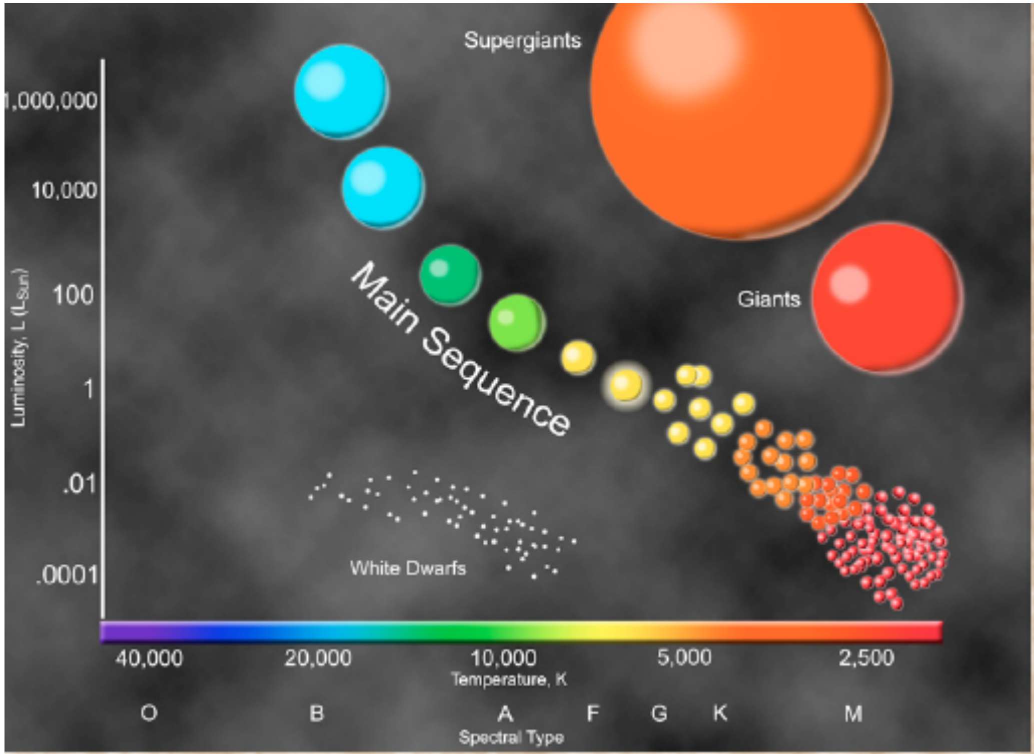

0.170
0.142
0.113
0.0850
0.0567
0.0283
0.000
Intensity
180 −160 −140 −120 −100 −80 −60 −40
−30 −40 −50 −60 −70 −80
30 60 −30 −60 −90 −120 120 −150 150 180
−75
−50
T_{surf} /K
725 730 735
10 km

The heavens … …now are seen to resemble a luxuriant garden, which contains the greatest variety of productions, in different flourishing beds; and one advantage we may at least reap from it is, that we can, as it were, extend the range of our experience to an immense duration.

…is it not almost the same thing, whether we live successively to witness the germination, blooming, foliage, fecundity, fading, withering, and corruption of a plant, or whether a vast number of specimens, selected from every stage through which the plant passes in the course of its existence, be brought at once to our view?

—William Herschel, *The Construction of the Heavens* (1789)



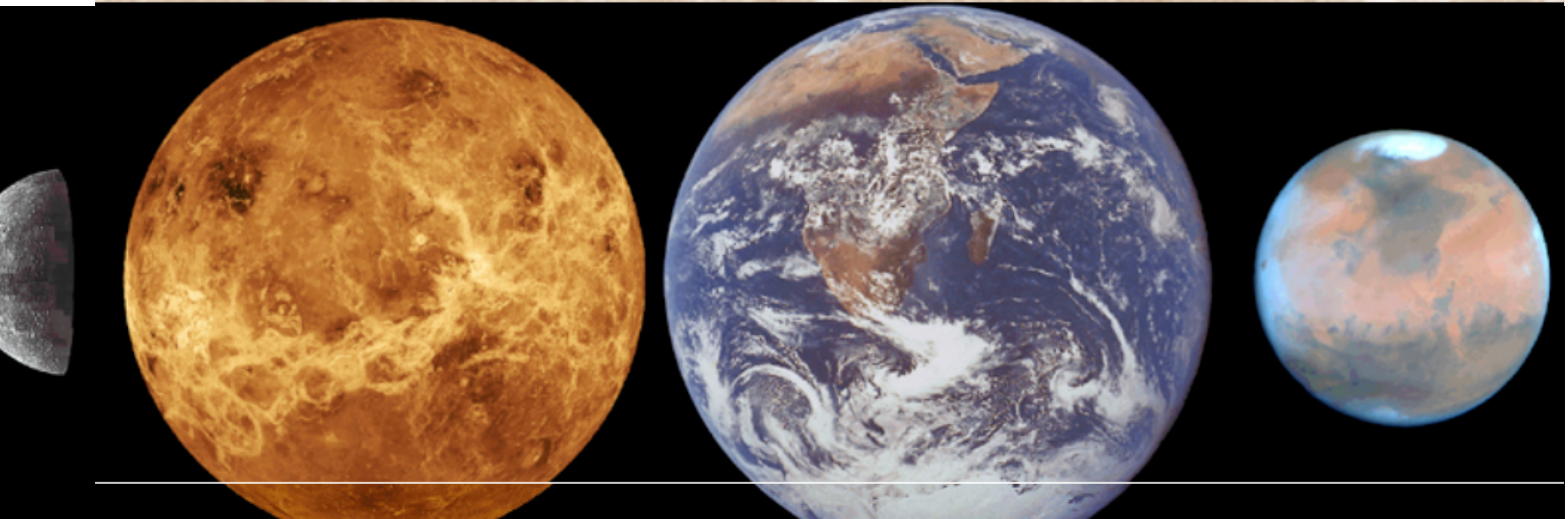


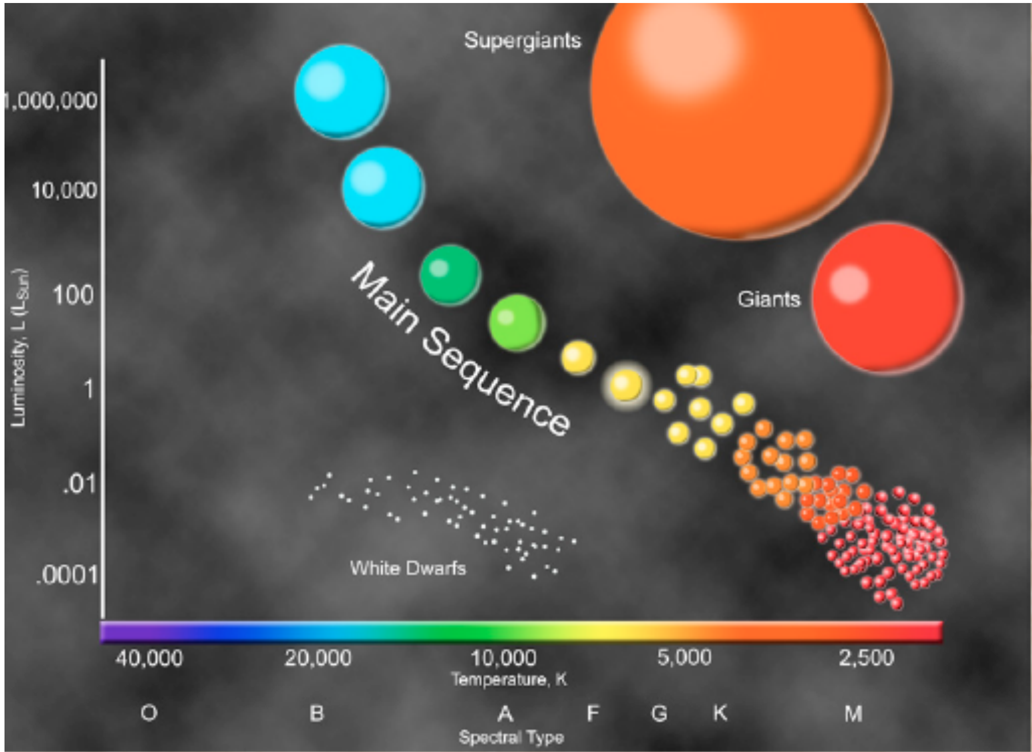
A luxuriant garden…

… of stars.

William Herschel,
The Construction of the Heavens (1789)

What grows in the galaxy's luxuriant garden of planets?





A luxuriant garden…

… of stars.

William Herschel,
The Construction of the Heavens (1789)

What grows in the galaxy's luxuriant garden of planets?

Comparative Planetology: Venus vs. Earth

	Venus	Earth
D (km)	12,104	12,756
M (10^{24} kg)	4.86	5.97
V_e (km/s)	10.4	11.2
P (bars)	92	1
T_s (K)	750	293
H_2O (kg)	5.9×10^{16}	1.4×10^{21}
C (10^{-5} gm/gm)	$2.67 \pm 0.30^{*}$	4.5^{**}

*Assuming all Venus C in atmosphere

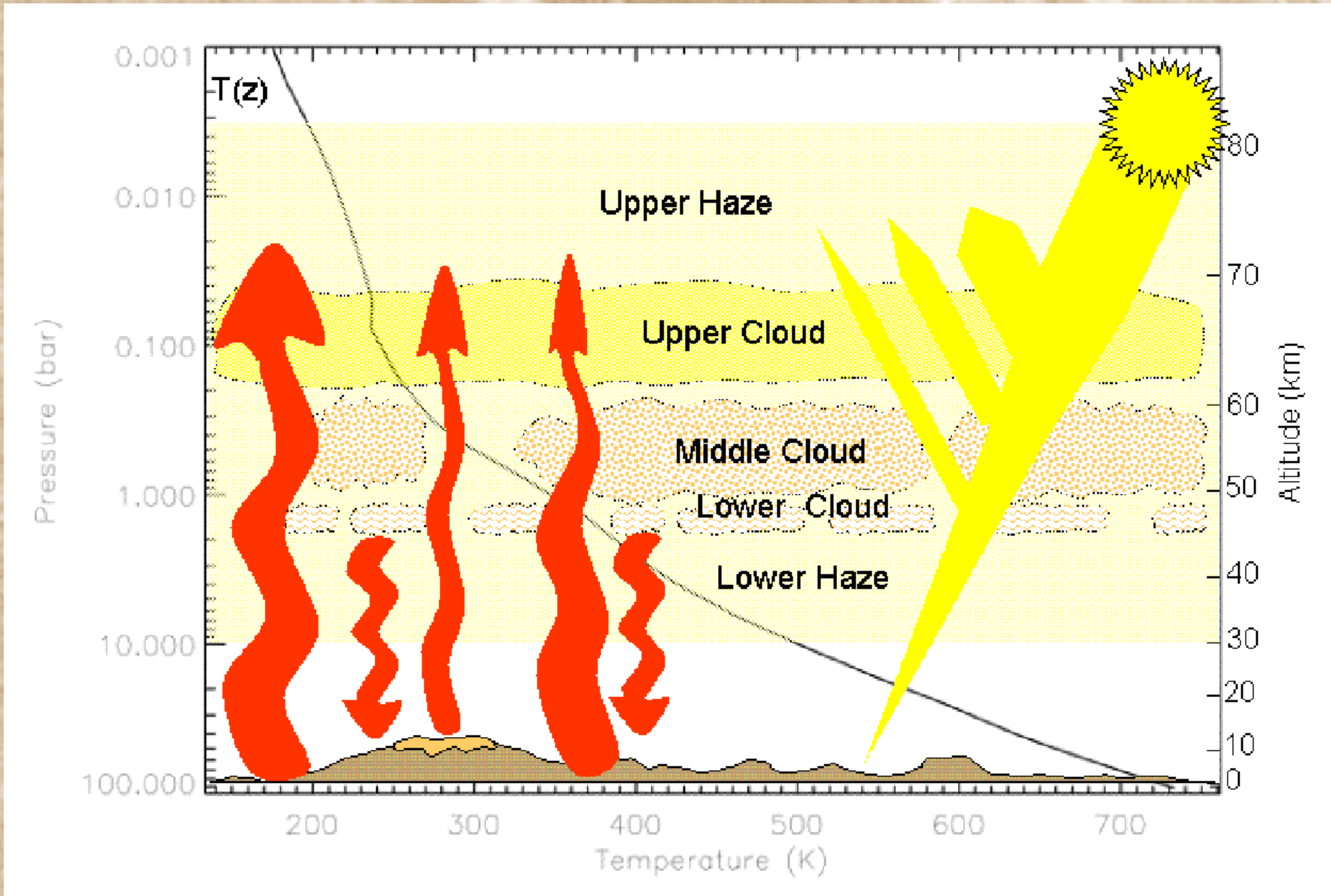
**Including crust and mantle

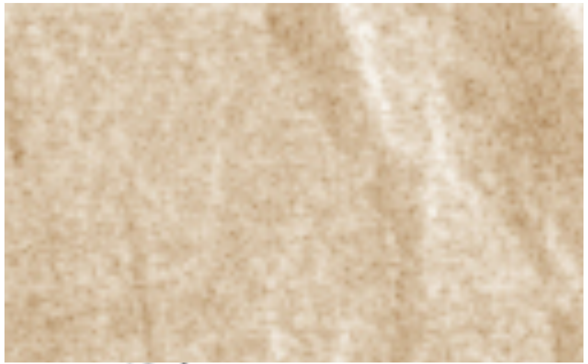
COMMON ASSUMPTION:

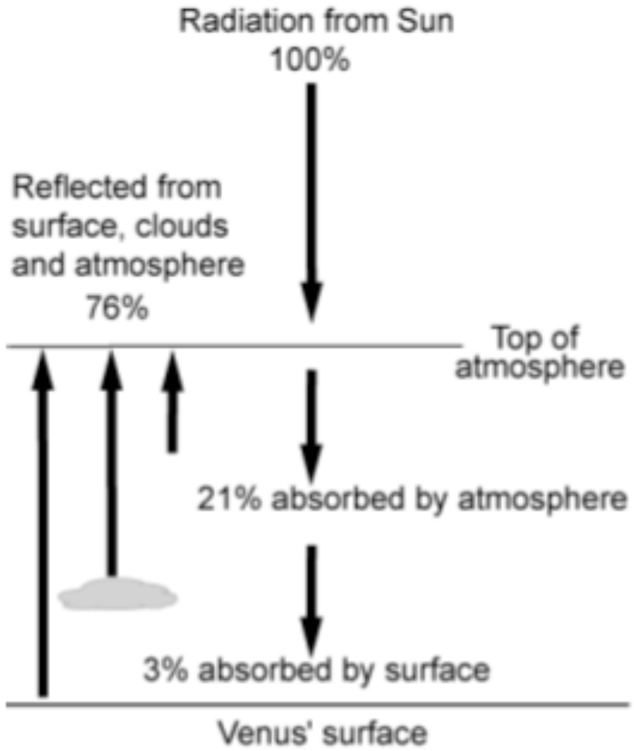
Initial conditions were the same.

Divergence represents triumph of nature over nurture.

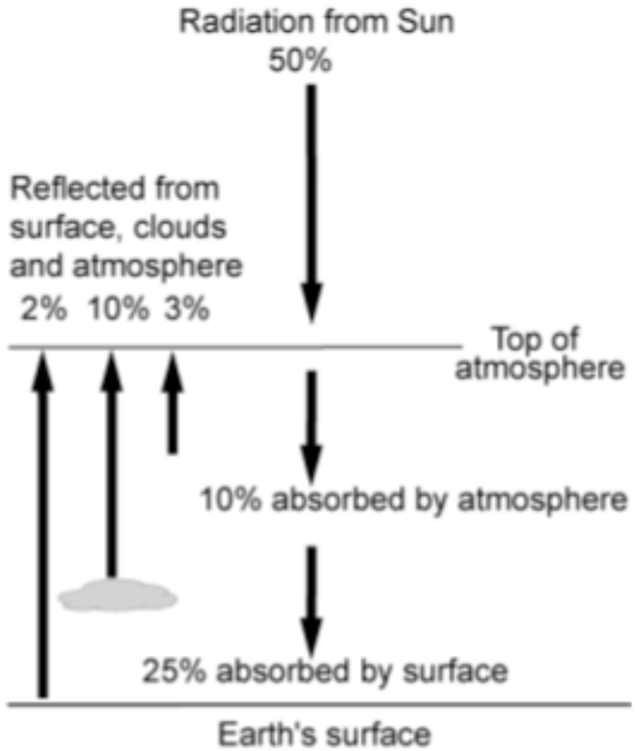
Radiative Processes



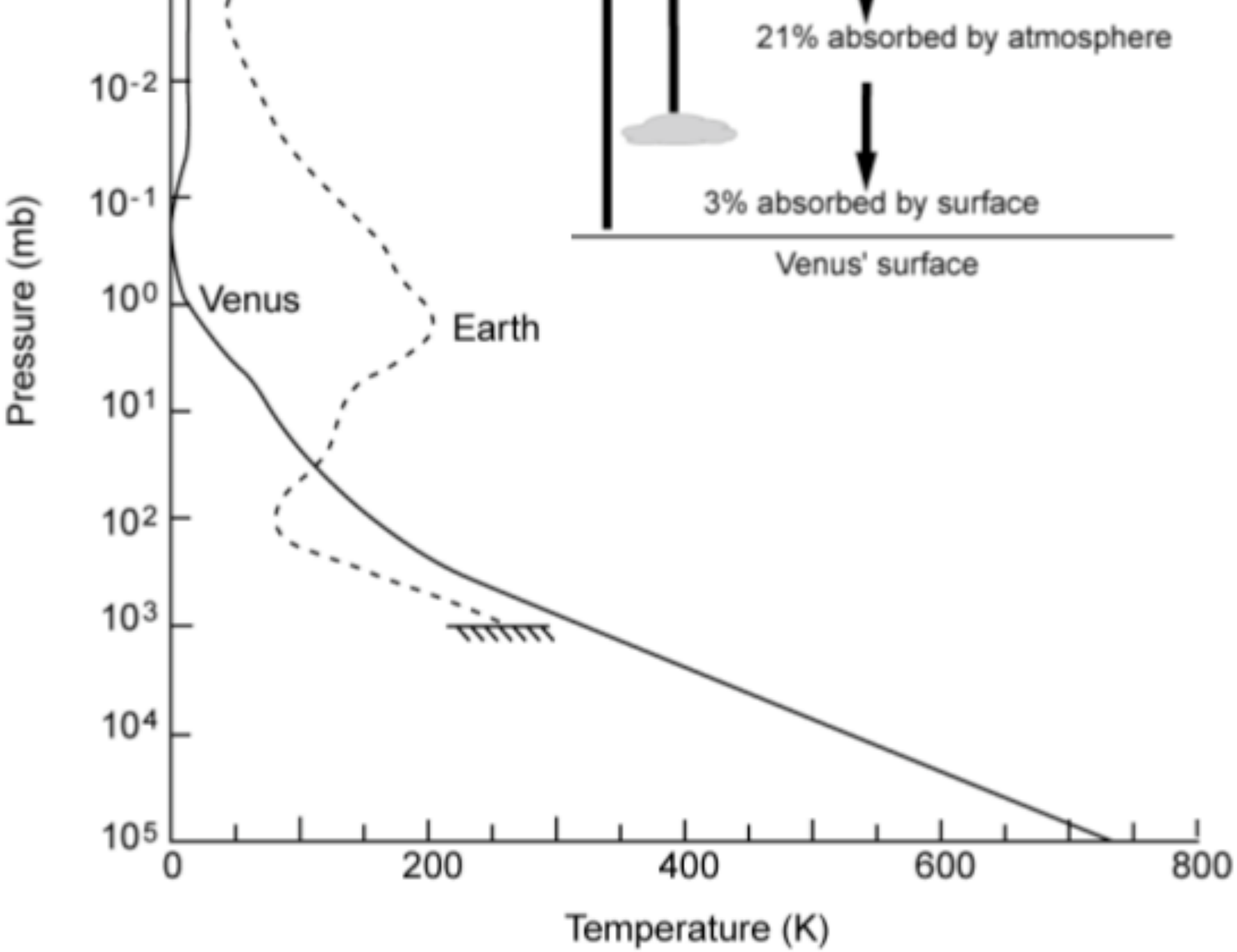




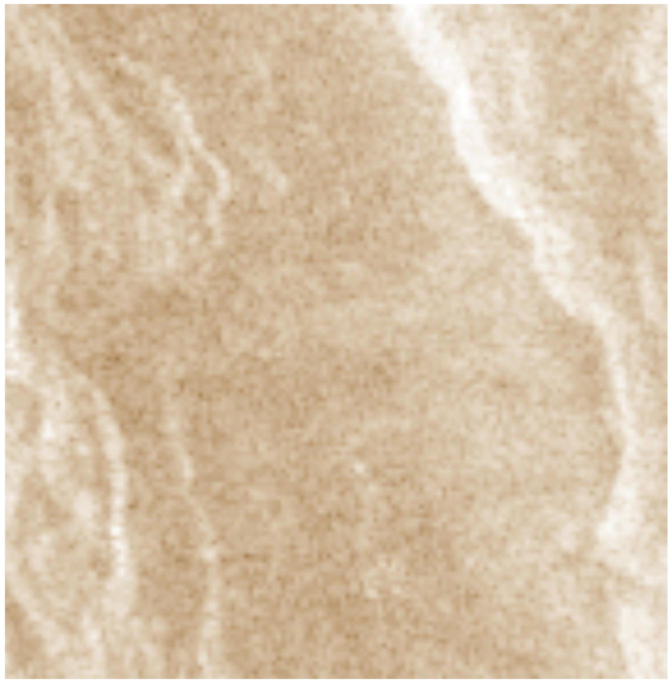
Radiation from Sun
100%
Reflected from surface, clouds and atmosphere
76%
Top of atmosphere
21% absorbed by atmosphere
3% absorbed by surface
Venus' surface



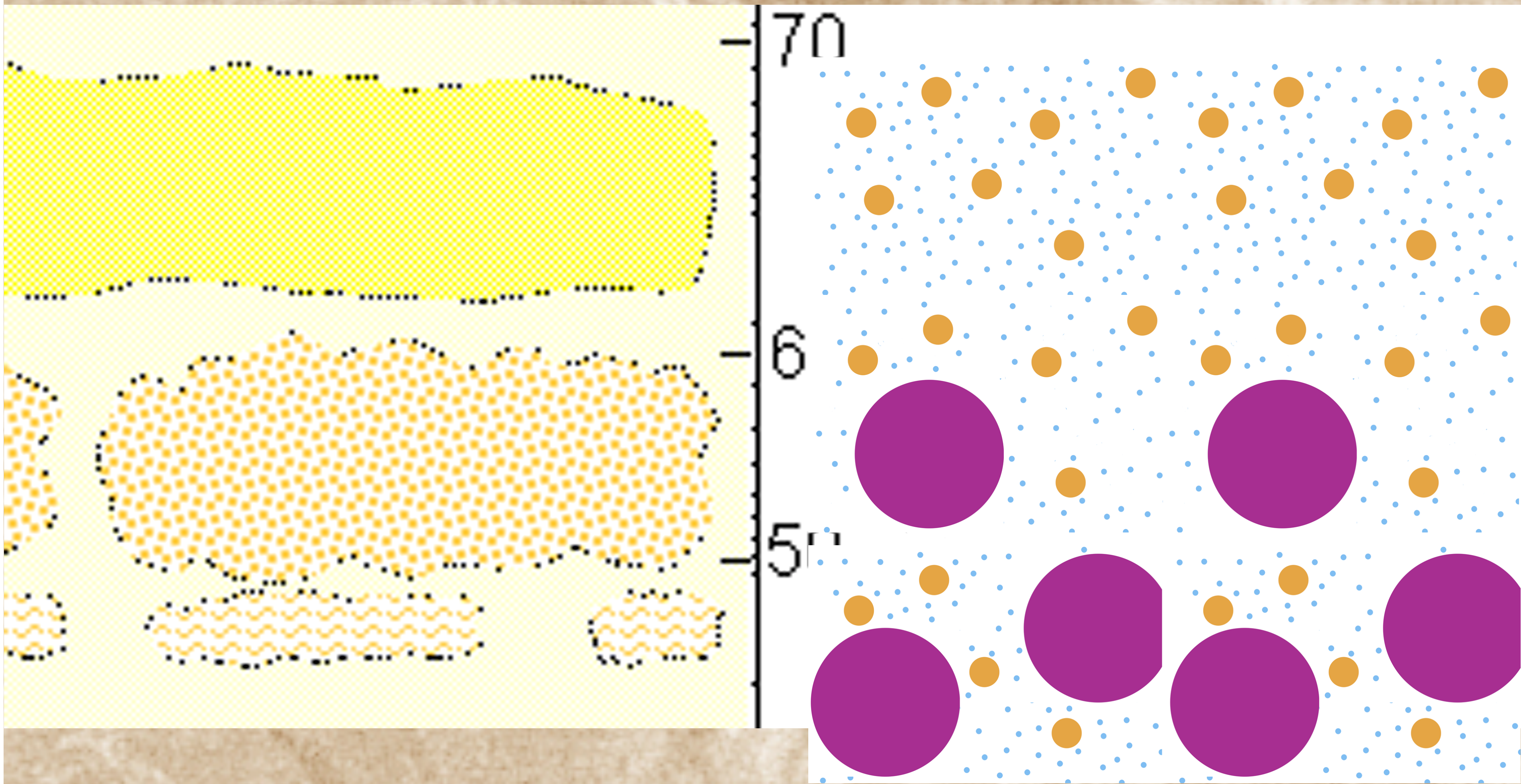
Radiation from Sun
50%
Reflected from surface, clouds and atmosphere
2% 10% 3%
Top of atmosphere
10% absorbed by atmosphere
25% absorbed by surface
Earth's surface



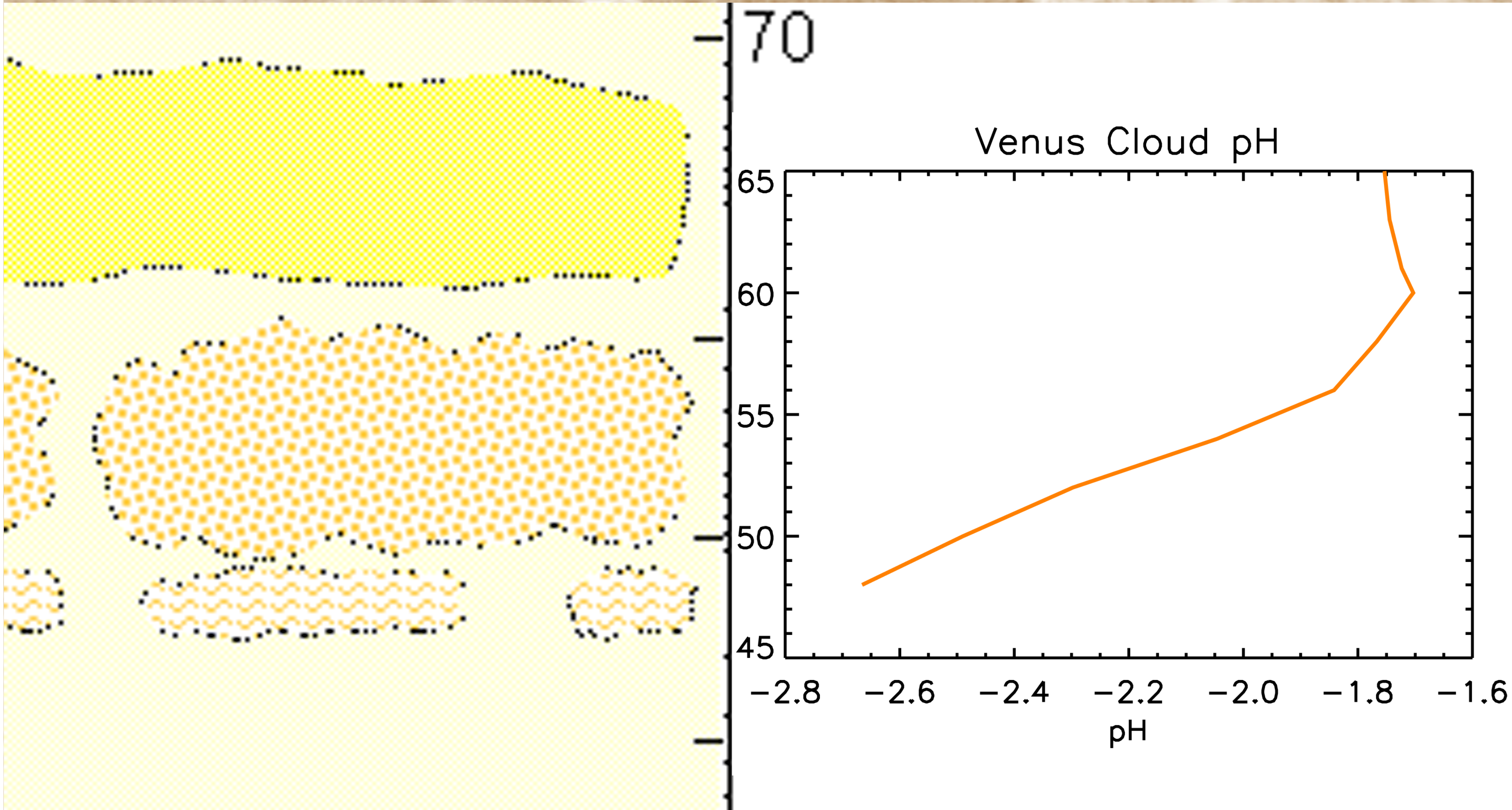
Pressure (mb)
10-4
10-3
10-2
10-1
100
101
102
103
104
105
Venus
Earth
0
200
400
600
800
Temperature (K)



Cloud Particles: Physical Properties



Cloud Particles: Chemical Properties

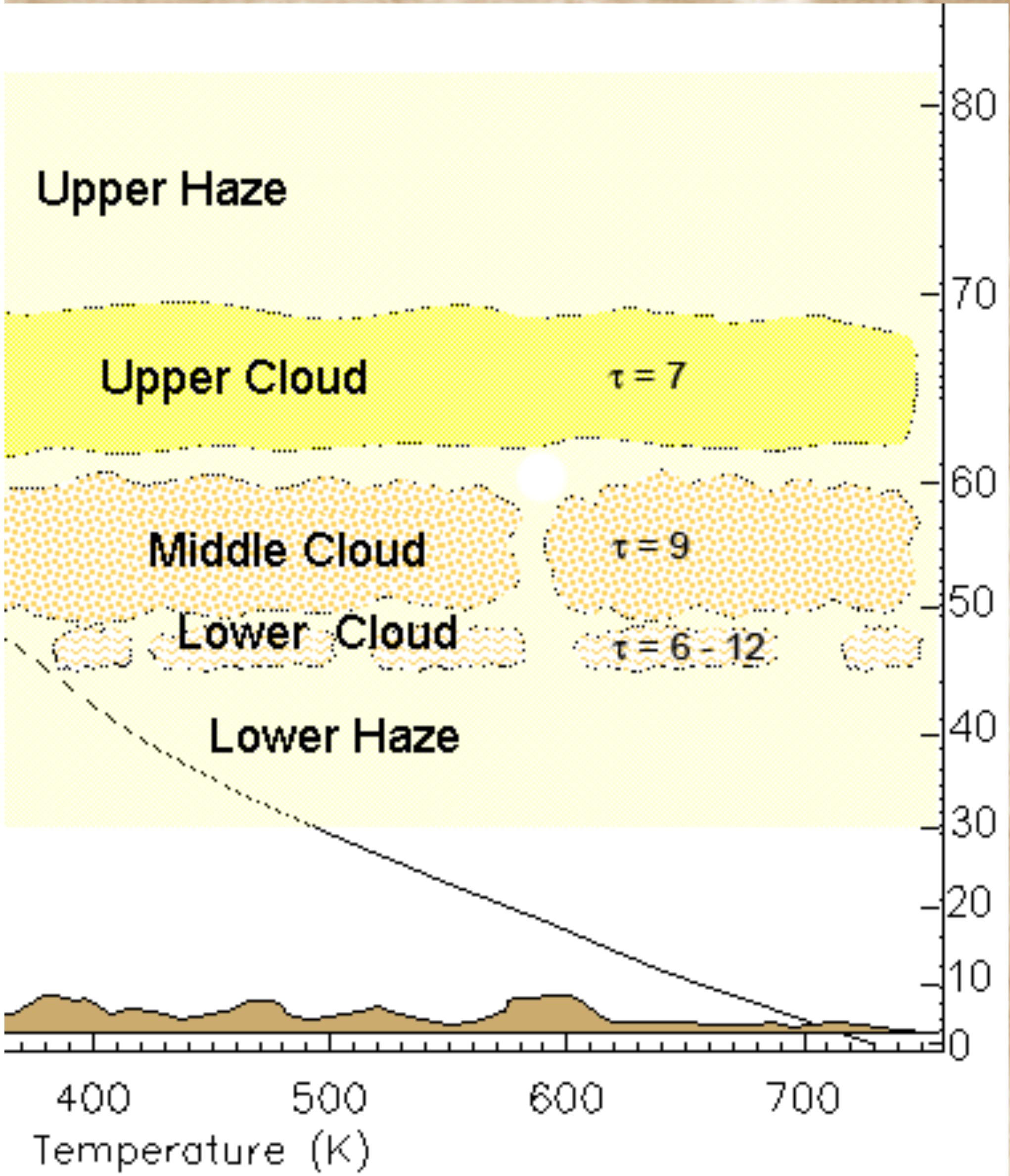


pH = -log[H_2SO_4]

Sulfur Cycles

- Fast Atmospheric
  - Photochemical production of H_2SO_4
  - CO is consumed beneath the clouds
- Slow Atmospheric
  - Distributes S between SO_2, COS, and H_2S, and S_n.
- Slow Geologic
  - Sulfides decompose to COS and H_2S.
  - S is taken up by calcite conversion to anhydrite
  - Anhydrite converted back to sulfides.

Fast Atmospheric S Cycle



$CO_2 \rightarrow CO + O$

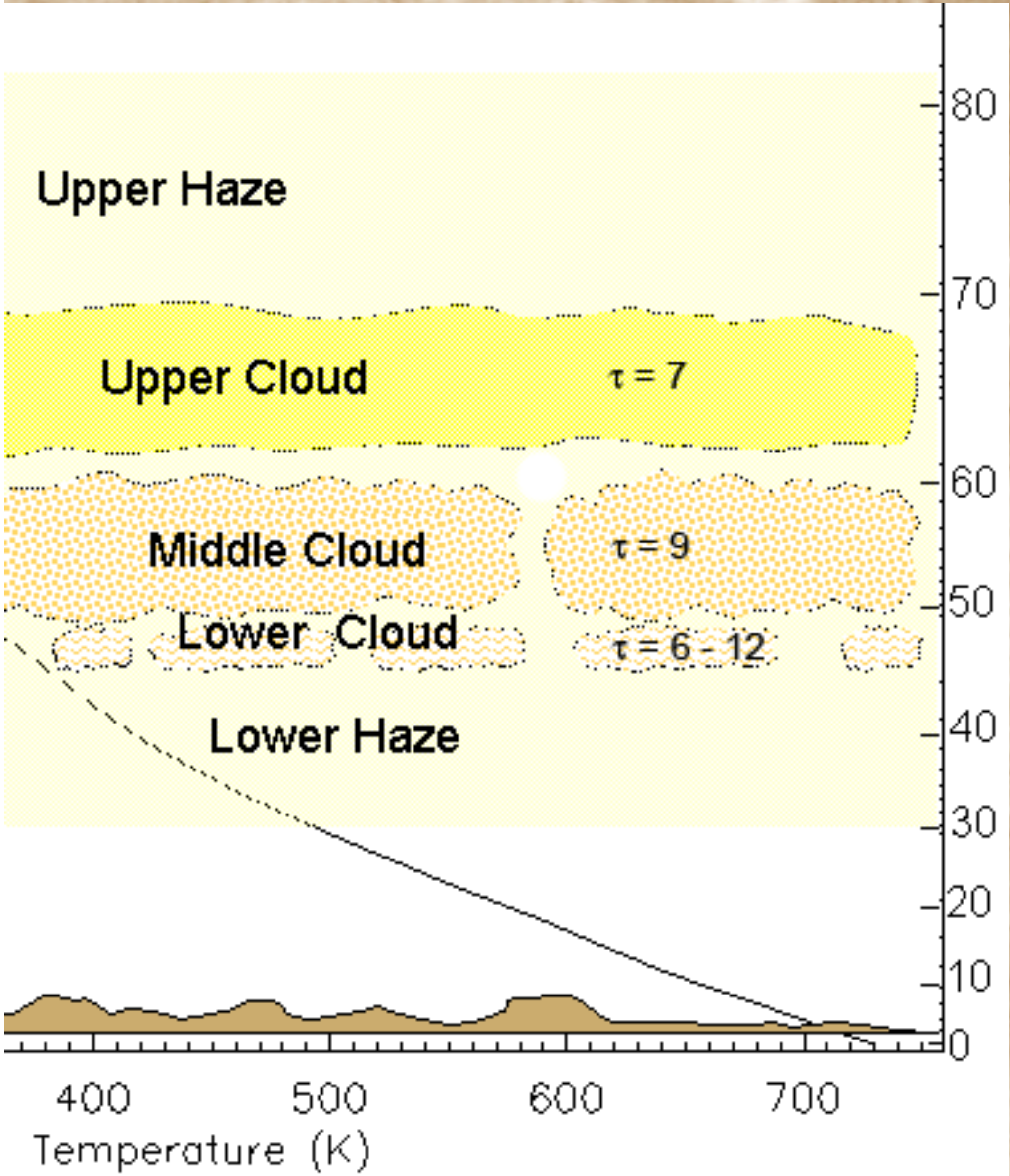
$O + SO_2 \rightarrow SO_3$

$SO_3 + H_2O \rightarrow H_2SO_4$

$H_2SO_4 \rightarrow H_2O + SO_3$

$SO_3 + CO \rightarrow SO_2 + CO_2$

Slow Atmospheric S Cycle



$CO_2 \rightarrow CO + O$

$3/2O_2 + H_2S \rightarrow SO_3 + H_2$

$3/2O_2 + COS \rightarrow SO_3 + CO$

$SO_3 + H_2O \rightarrow H_2SO_4$

$H_2S \rightarrow H_2 + (1/n)S_n$

$COS \rightarrow CO + (1/n)S_n$

$H_2SO_4 \rightarrow H_2O + SO_3$

$SO_3 + 4CO \rightarrow COS + 3CO_2$

$H_2 + SO_3 + 3CO \rightarrow H_2S + 3CO_2$

$H_2 + (1/n)S_n \rightarrow H_2S$

$CO + (1/n)S_n \rightarrow COS$

Geologic Sulfur Cycle

$2H_2S + 3O_2 \rightarrow 2H_2O + 2SO_2$

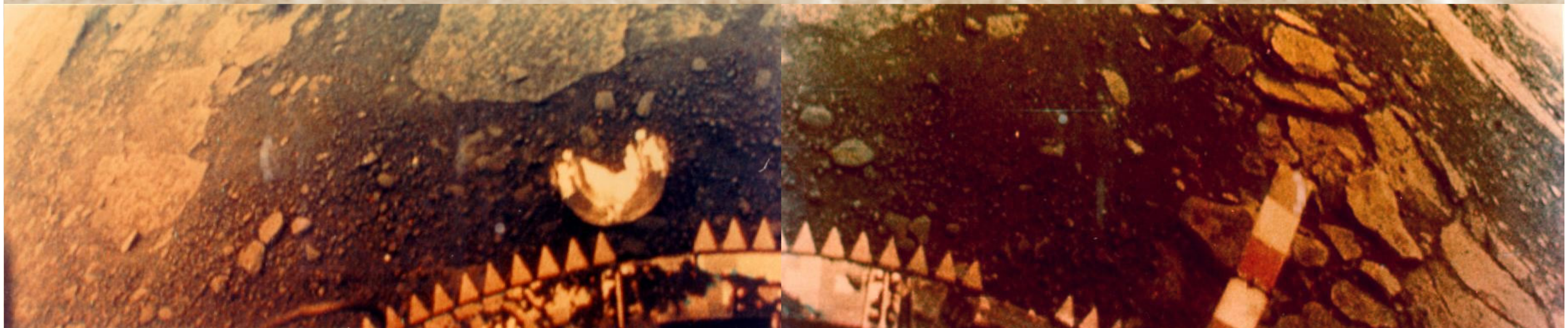
$2COS + 3O_2 \rightarrow 2CO_2 + 2SO_2$

$FeS_2 + 2H_2O \rightarrow FeO + 2H_2S + 1/2O_2$

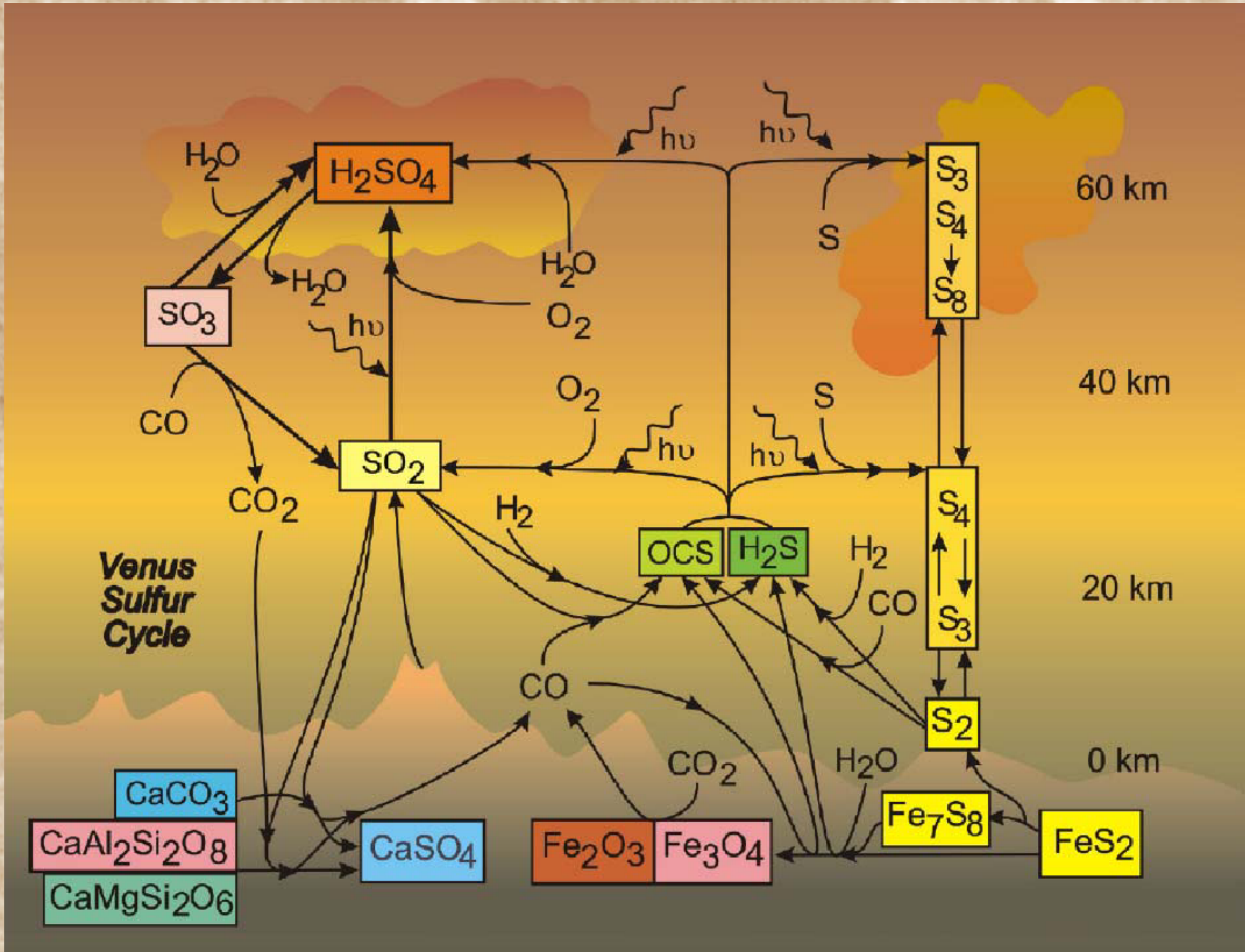
$FeS_2 + 2CO_2 \rightarrow FeO + 2COS + 1/2O_2$

$SO_2 + 1/2O_2 + CaCO_3 \rightarrow CaSO_4 + CO_2$

$2CaSO_4 + FeO + 2CO_2 \rightarrow FeS_2 + 2CaCO_3 + 7/2O_2$



Surface and Atmosphere S



Large Impacts, Steam Atmospheres, Hydrodynamic Escape

The earliest atmospheres were mostly hot water vapor.

The young planets existed in a swarm of impacting material. On Earth and Venus (and Mars?) energy from large impacts would have created steam atmospheres. (Matsui & Abe; Zahnle et al.)

The young sun had high EUV flux -> hydrodynamic escape.

Atmosphere expands into space, (similar to solar wind). Hydrogen drags along heavy atoms => escape; mass fractionation.

Effect is seen in noble gas isotopes.

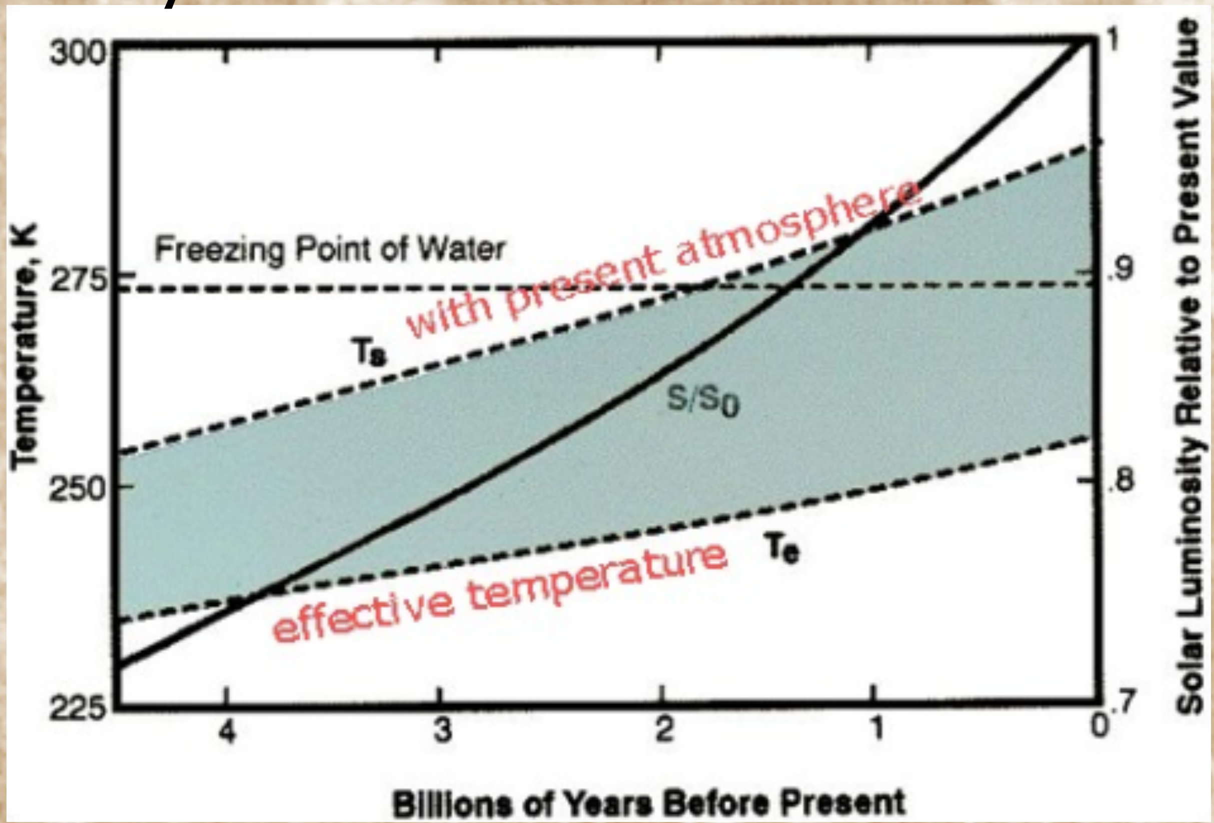
For example: ^{20}Ne escapes more easily than ^{22}Ne,

This lowers $^{20}Ne/^{22}Ne$

Solar ~ 13, earth ~9.8, Mars atm ~10?, Venus ~11.8

The Faint Young Sun

Early Earth:



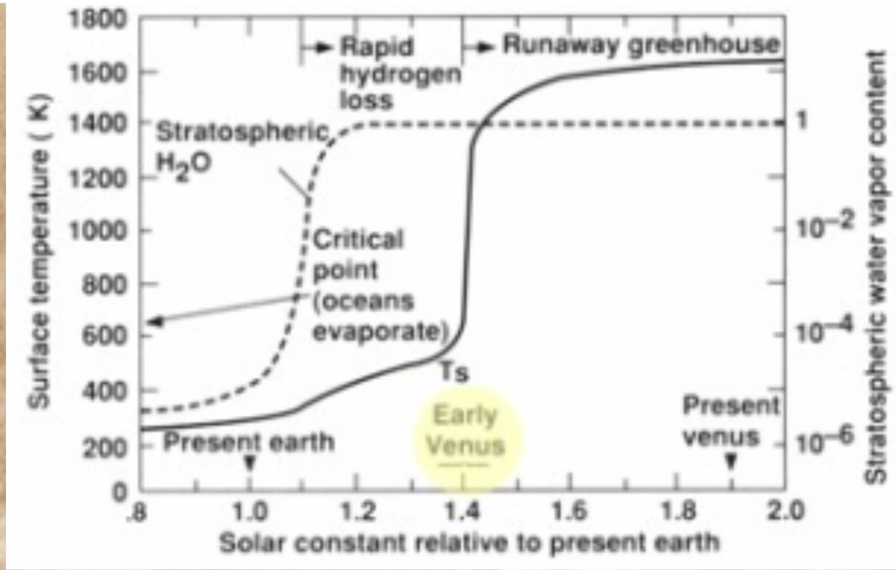
Why wasn't Earth frozen over?

Greenhouse effect was stronger.
Atmosphere must have evolved.
CO_2? Biogenic CH_4?

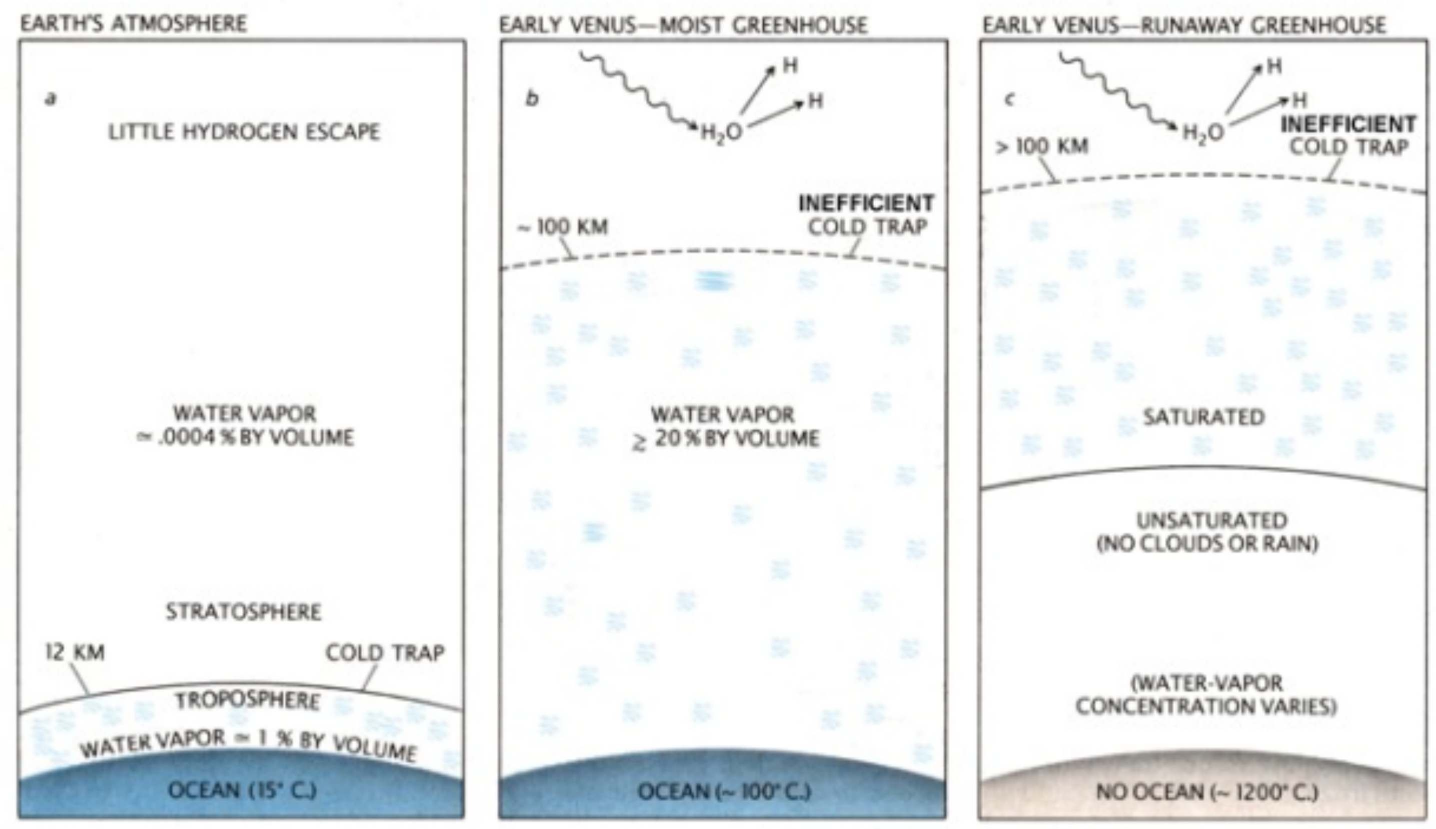
The Faint Young Sun and Early Venus:

S ≈ 1.4 x present Earth.

This is right on the edge of a runaway condition.



Venus can have warm oceans and a "moist greenhouse"



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Earth and Planetary Science Letters xx (2008) xxx – xxx

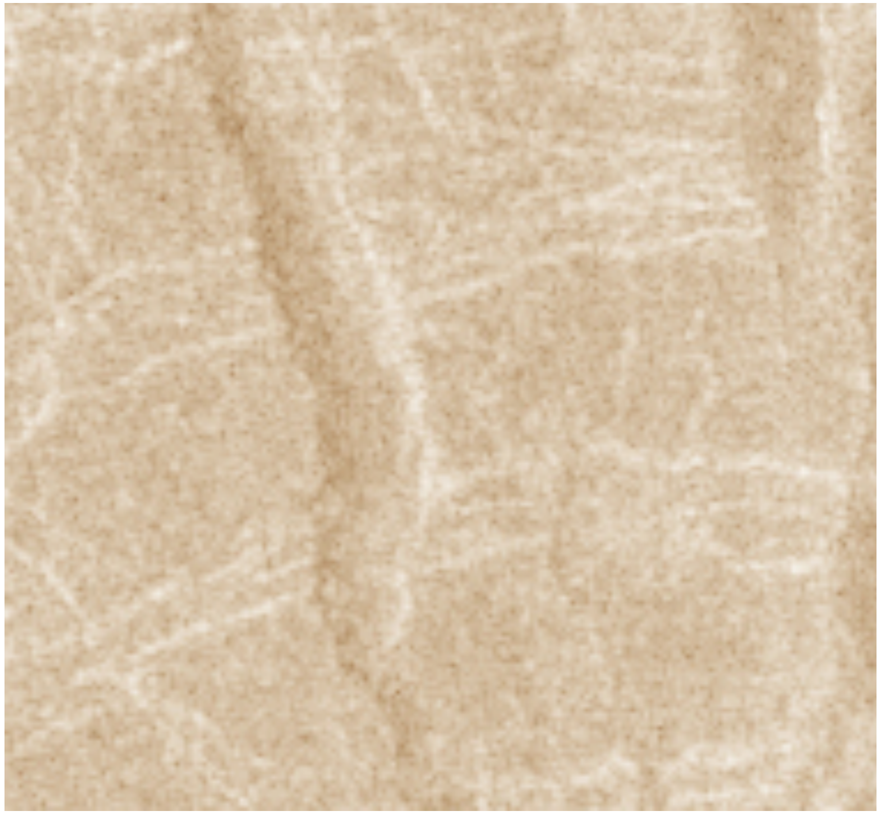
www.elsevier.com/locate/epsl

Did a mega-collision dry Venus' interior?

J. Huw Davies *

School of ~~Earth, Ocean and Planetary~~ Sciences, Cardiff University, Main Building, Park Place, Cardiff, CF10 3YE, Wales, UK

Received 10 July 2007; received in revised form 13 January 2008; accepted 20 January 2008



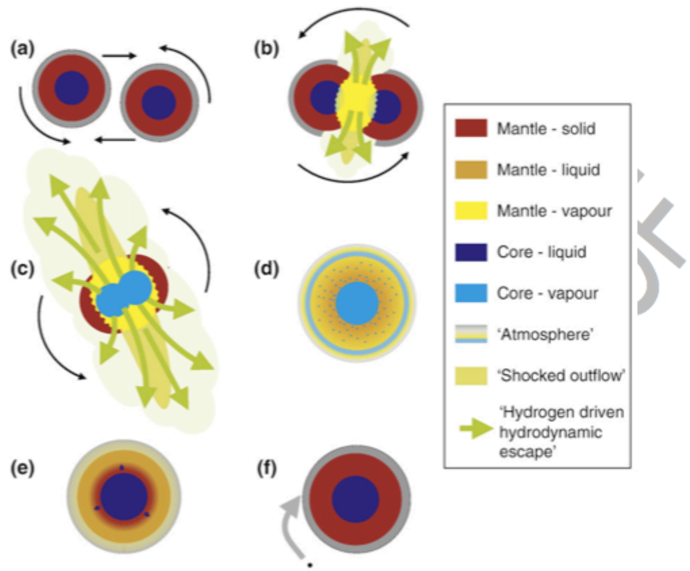
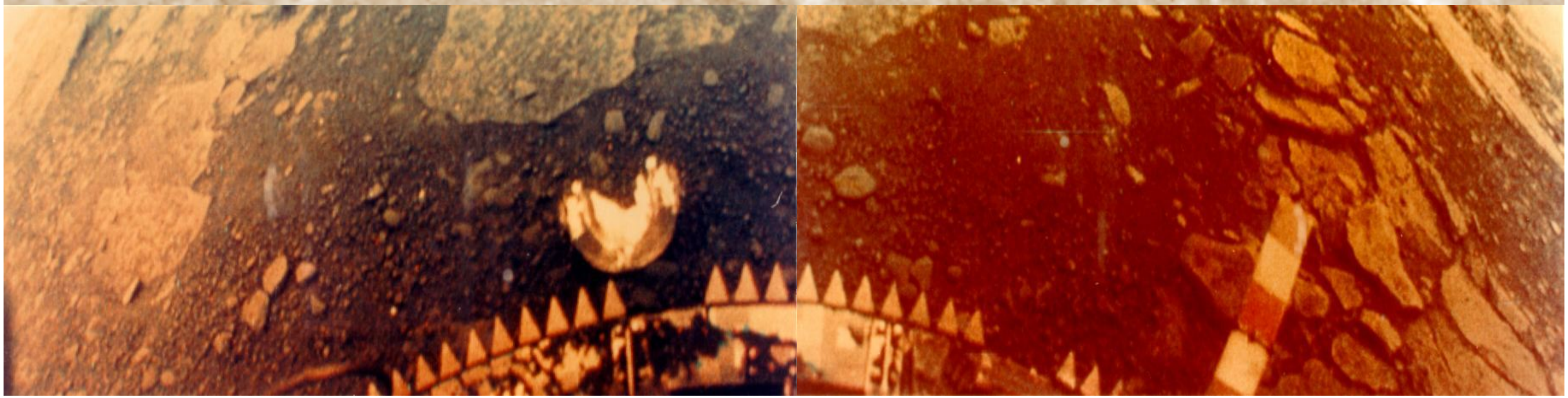


Fig. 1. This diagram presents a schematic of the stages of a massive collision. For further information see Section 2, Mega-collision. (a) Two hot, approximately equal-sized planetary embryos colliding close to head-on, possibly in a manner leading to the final body having a retrograde rotation. (b) Shock waves from the collision propagating into and fluidising both bodies. The hot turbulent fluids encourage reactions, including reactions between iron and water producing hydrogen that can escape Venus. (c) Collision continues, the two cores coalesce, and hydrodynamic escape gathers pace. (d) Some hours to days later, the body recaptures most of its shocked outflow. It has a very hot molten core, a molten mantle with droplets of iron, a primitive crust, overlain by an iron vapour, silicate vapour and atmophilic atmospheres. Note there is no liquid ocean. There will be turbulent mixing and entrainment between the various atmospheric layers. (e) Some thousands of years later, as the body cools further the mantle would start to solidify from its base, and remaining liquid iron would penetrate as diapirs through to the core. (f) Millions of years later the final planet has a primarily solid mantle, a liquid core, and thick carbon dioxide atmosphere. There is no reason why Venus should not collect a 'late veneer' if one was collected by Earth.

The First Great Transition:

Venus lost its ocean after perhaps 600 m.y.

(Kasting, 1988) (But timescale is very uncertain…)



Venus vs. Earth. Extreme desiccation explains:

- 735K, 90 bar CO_2 atmosphere

  No water → no carbonate precipitation.
  Mass of mineral carbon on Earth ≈ mass of atmospheric carbon on Venus. Equilibrium pressure of CO_2 with carbonates at 735 K ≈ 90 bar.

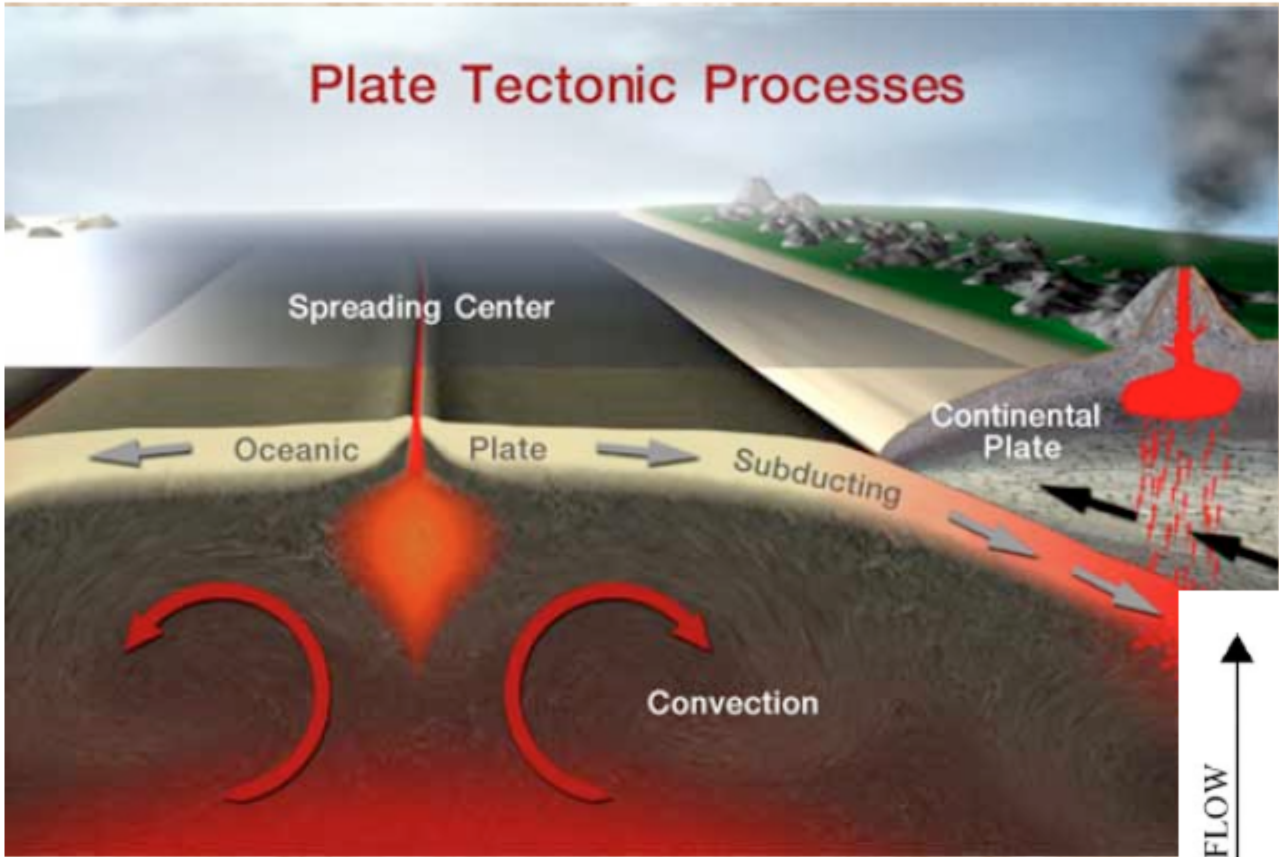
- Apparent uniform age of much of the surface.

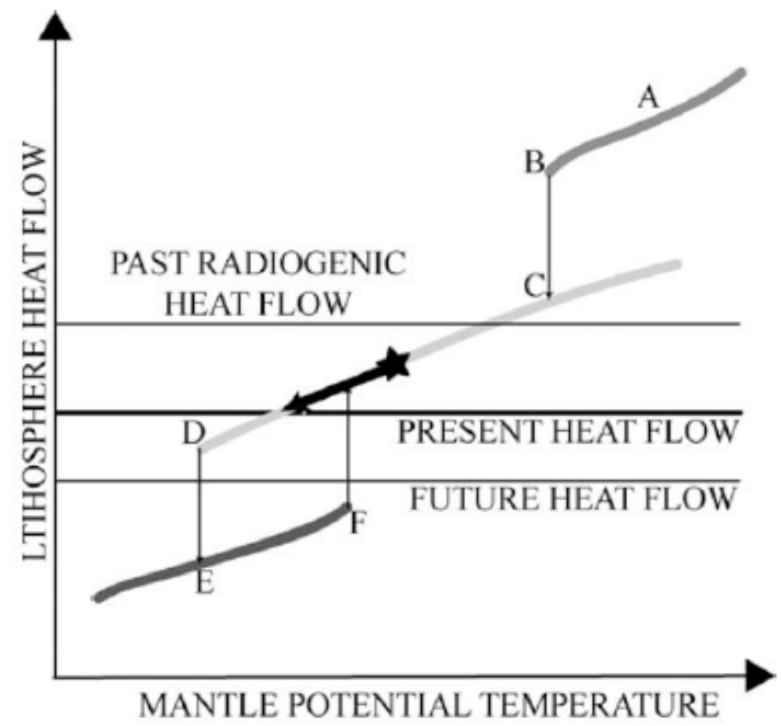
  Heat flow is not smooth and relatively steady like Earth's, but episodic (?)

- Lack of Earth-style lithospheric recycling on Venus,

  Lack of hydrated silicates → no low velocity zone at base of lithosphere (?)

Tectonic style may depend on water content.





A-B: Magma Ocean

C-D: Plate tectonics

E-F: Stagnant lid

Role of Water in Plate Tectonics

- "Hydrolytic weakening"
  Lack of water -> greater creep resistance ->thicker lithosphere.

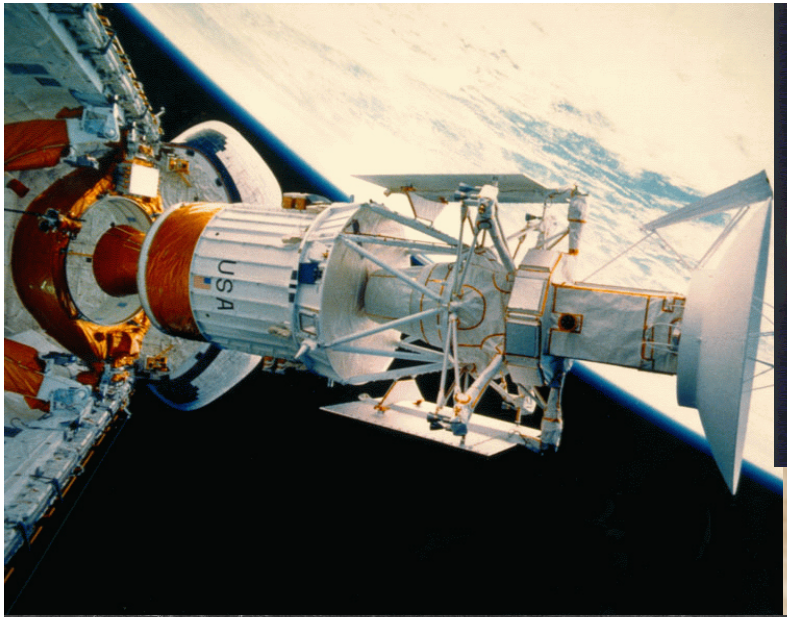
- Hydrated silicates -> asthenosphere
  Without water, strong coupling of mantle to lithosphere.

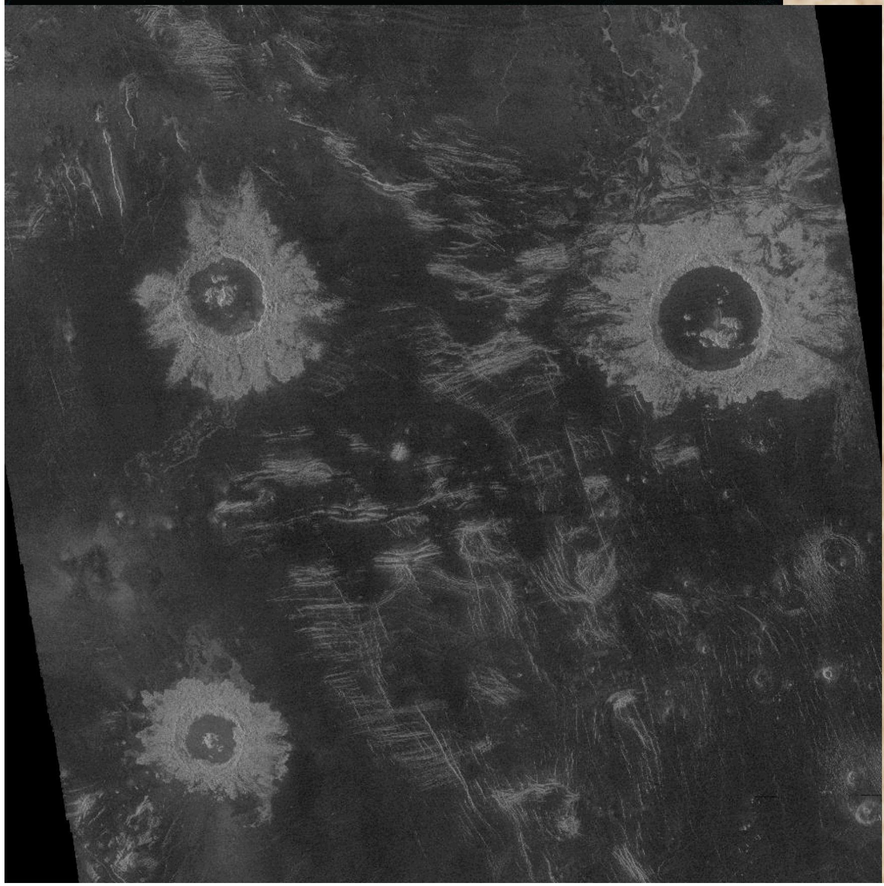
- Water is an essential ingredient for silicic volcanism.
  No water, no granites, no continents, no plate tectonics

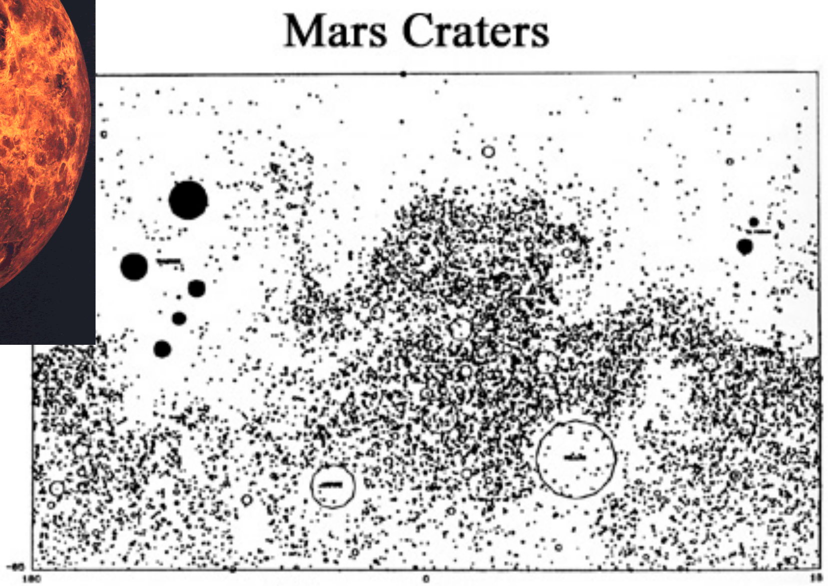
- Variable viscosity convection models
  desiccated mantle -> more sluggish convection

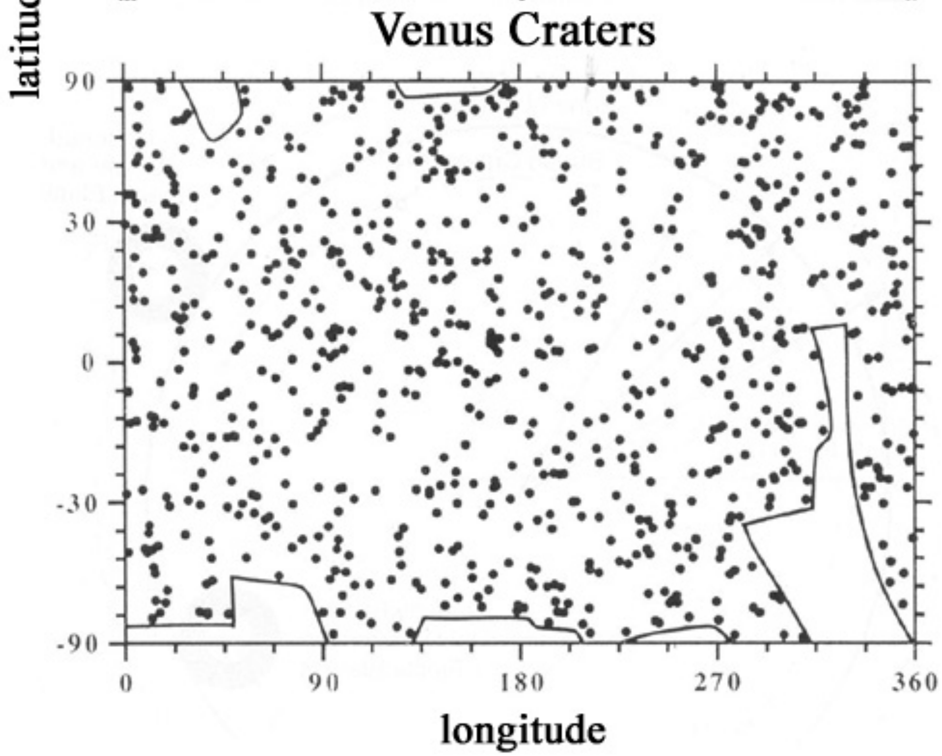
So, terrestrial-style plate tectonics is, in many ways, facilitated by water.

No water, -> no plate tectonics?


USA




Mars Craters


Venus Craters
latitude
90
30
0
-30
-90
0
90
180
270
360
longitude

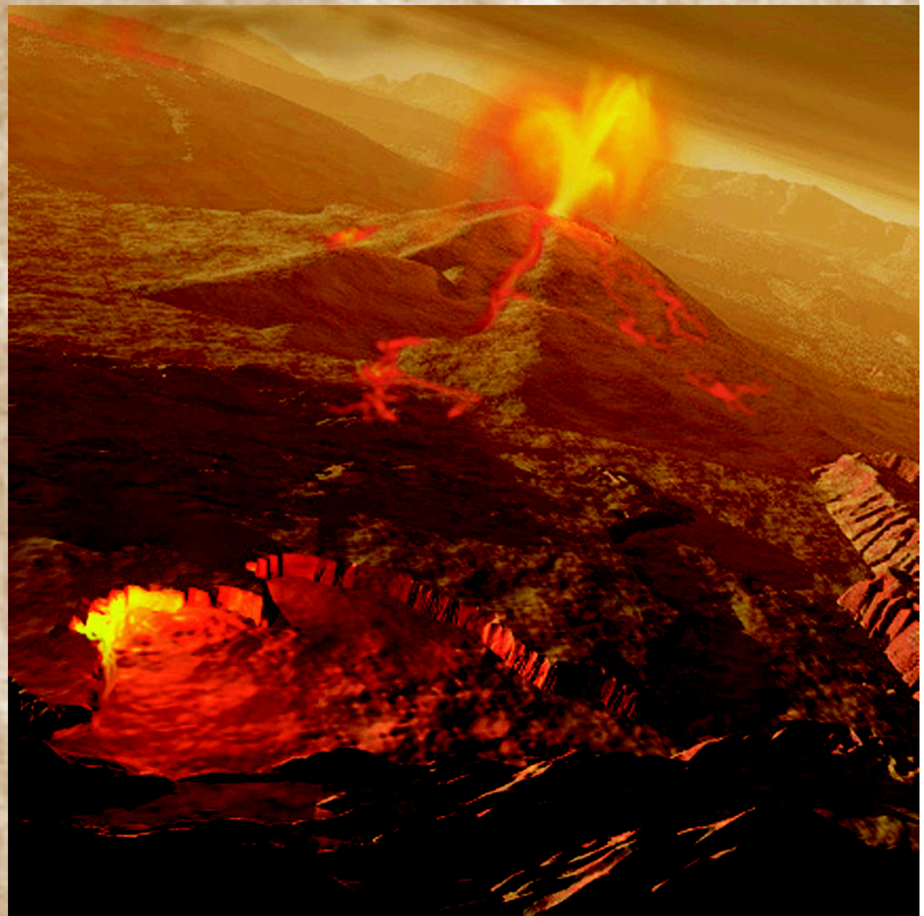
The Second Great Transition:

Much of the present surface was created in a resurfacing epoch 700±200 m.y. ago.

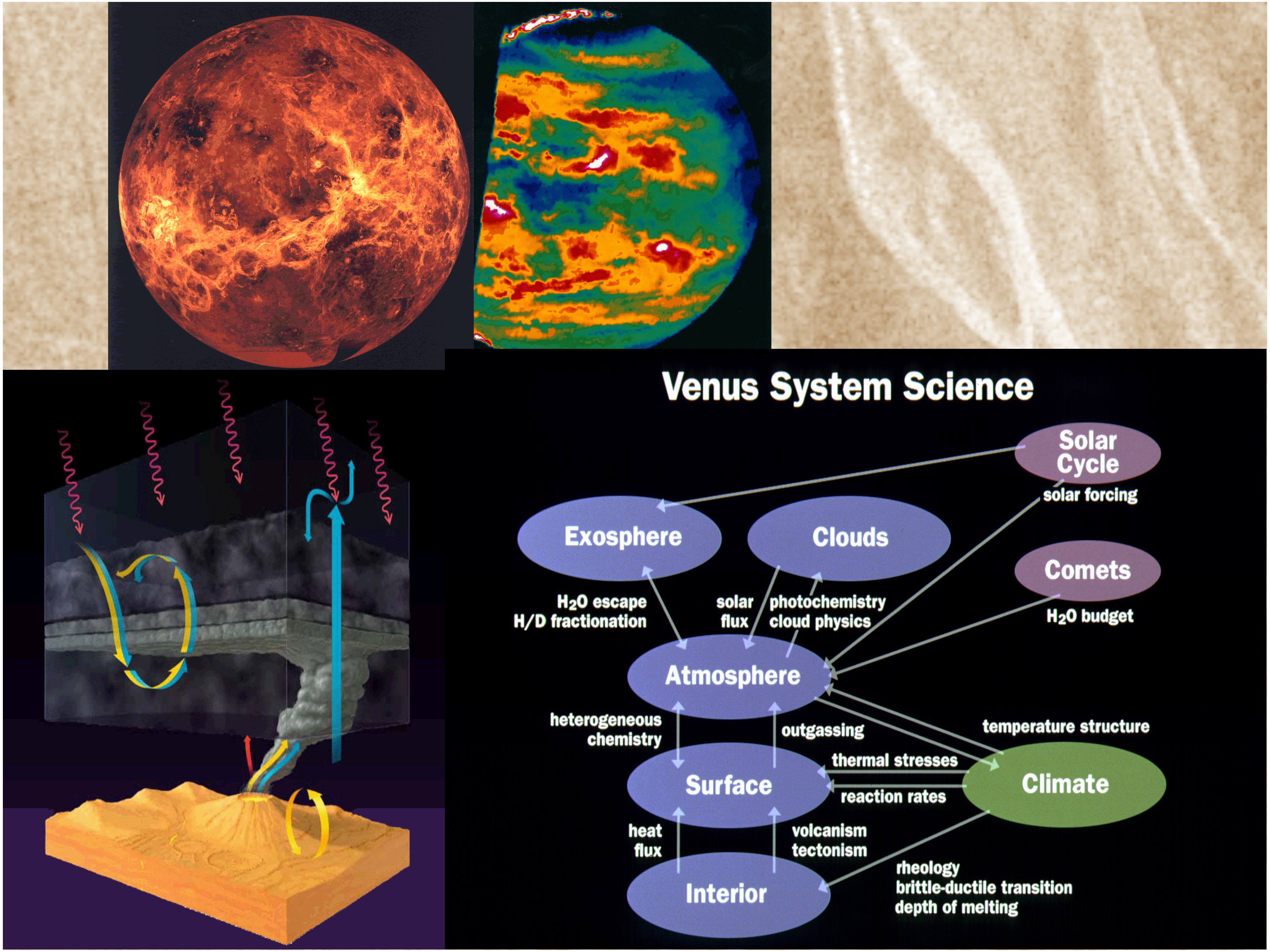
700 m.y. ago, Venus was a **very different planet**! What were the atmosphere and climate like?

Outgassing rates were much higher.

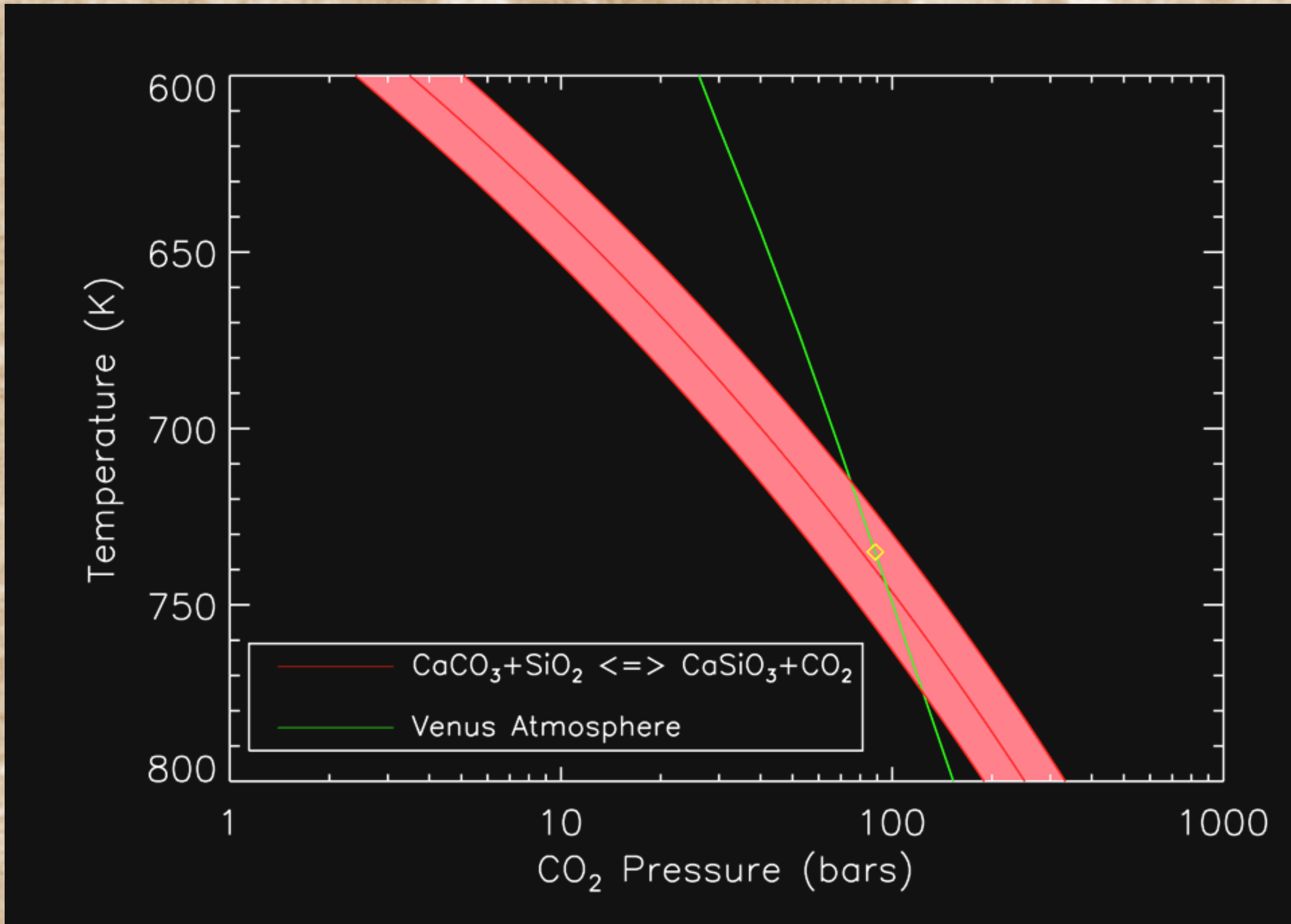
Climate balance depends on volcanogenic trace greenhouse gasses, and on the radiative properties of the clouds, which are a volcanic byproduct.



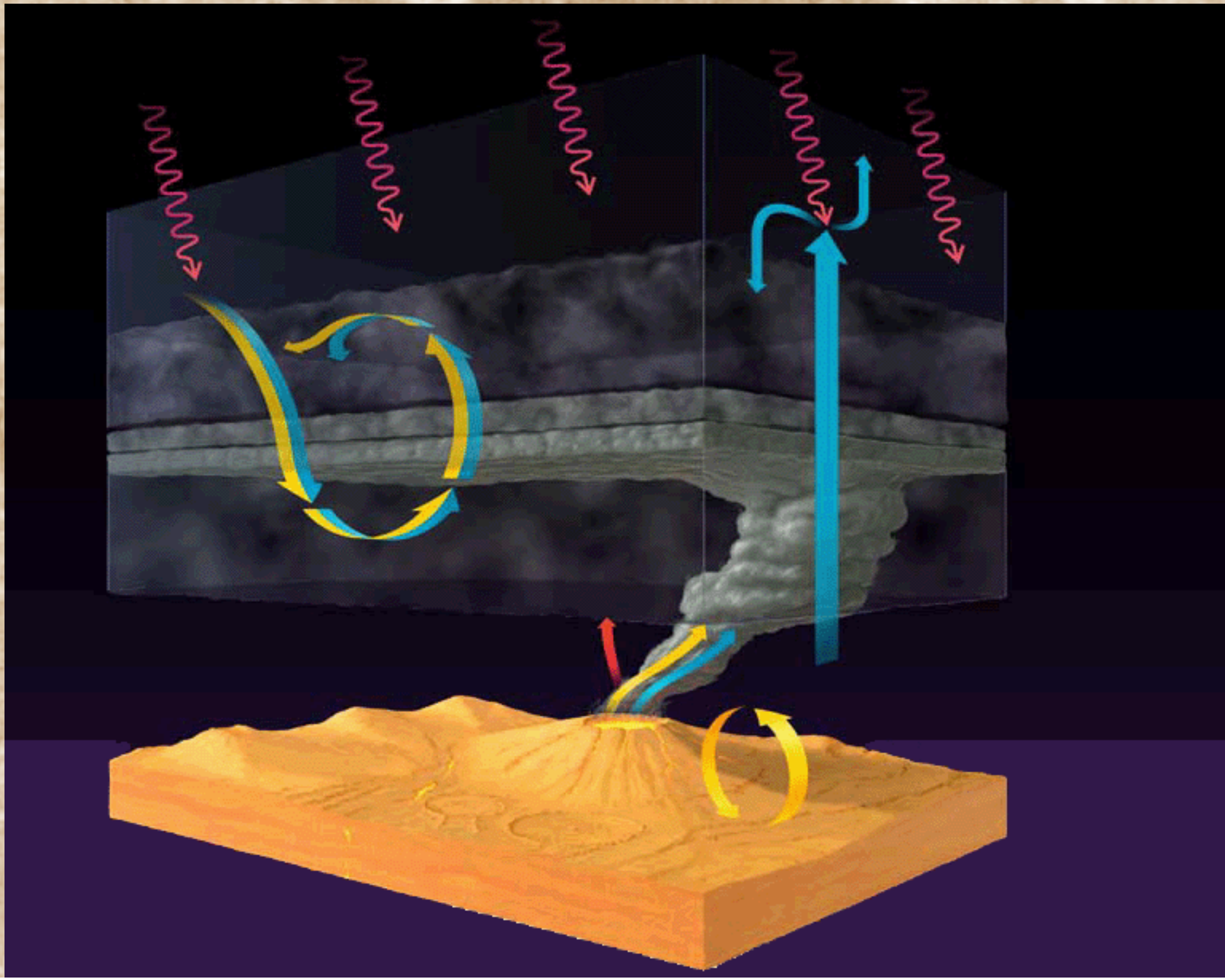
Bullock and Grinspoon (2001) , The recent history of climate on Venus, *Icarus*.


Venus System Science
Solar Cycle
solar forcing
Exosphere
Clouds
Comets
H2O escape
H/D fractionation
solar flux
photochemistry
cloud physics
H2O budget
Atmosphere
heterogeneous chemistry
outgassing
temperature structure
thermal stresses
Surface
Climate
reaction rates
heat flux
volcanism
tectonism
rheology
brittle-ductile transition
depth of melting
Interior

CO_2 Atmosphere-Mineral Equilibrium



The Venus Climate System



Radiative Transfer Model

Non-grey, one-dimensiona,l two stream radiative-convective model of infrared radiative transfer

Infrared emission, absorption and scattering by gases and aerosols in 24 atmospheric layers.

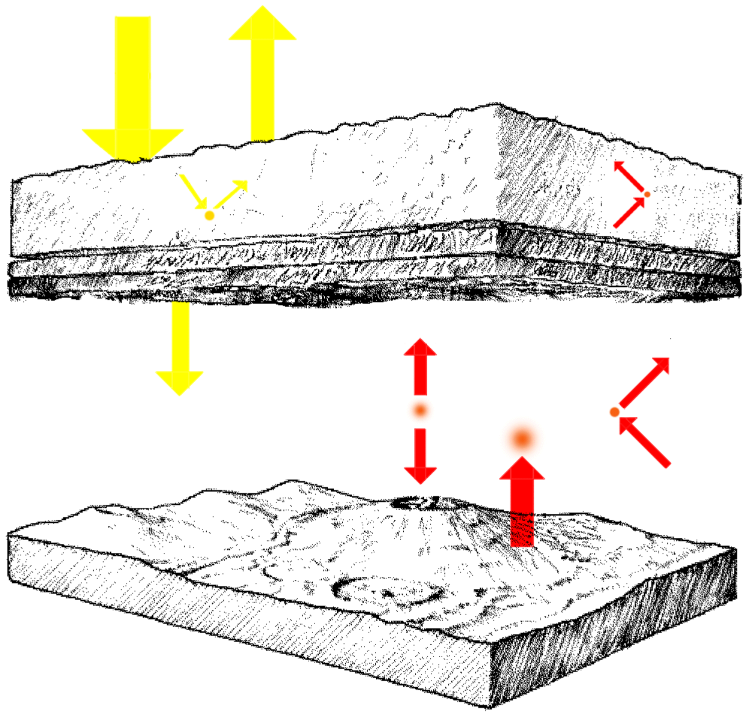
Uses HITEMP spectral database for CO2, H2O, HDO and CO. HITRAN 96 database for SO2, OCS, H2S, HCl and HF.

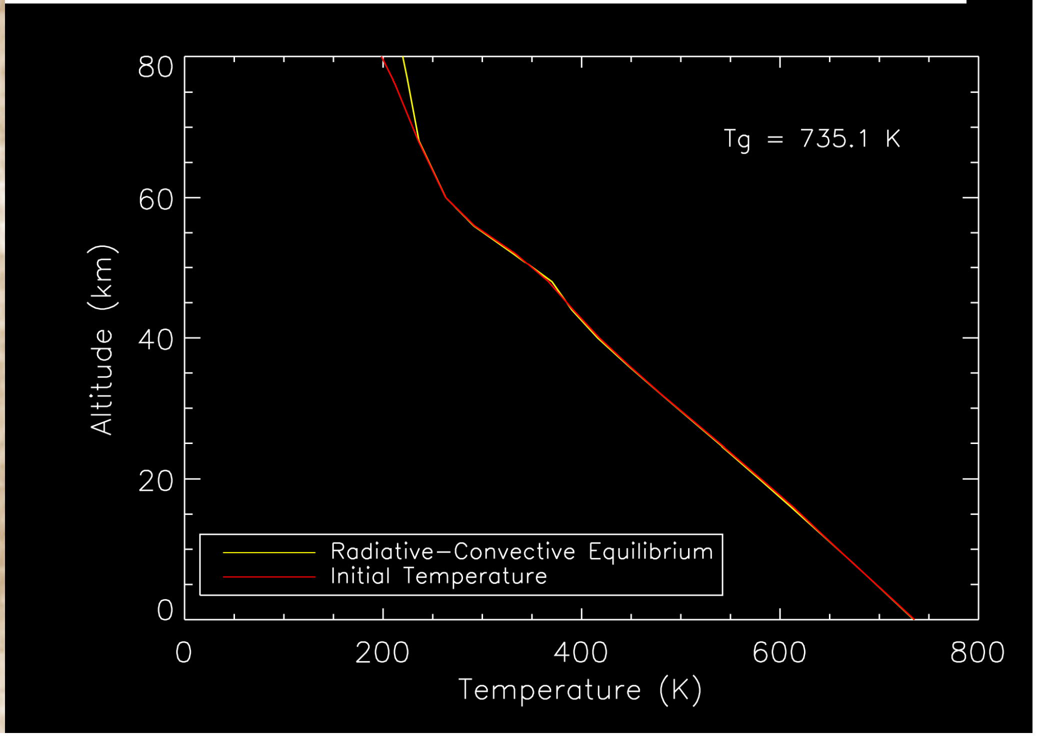
Correlated-k absorption coefficients used to calculate infrared opacities in 68 spectral intervals from 1.7 mm to 250 mm.

Mie theory used for treating infrared scattering by cloud aerosols.

Includes infrared Rayleigh scattering due to CO2 and N2.

Infrared fluxes calculated using the hemispheric mean algorithm of Toon et al. 1989.

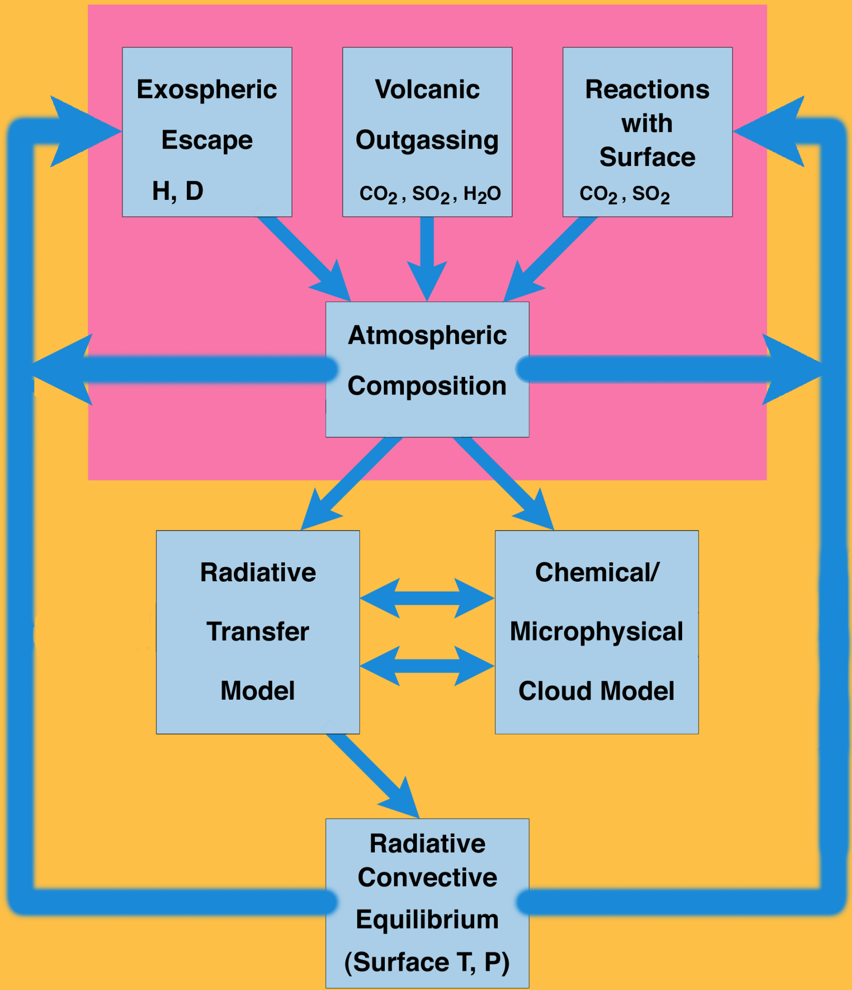




Venus Greenhouse Sensitivity Studies

Source Deleted	Change in Surface Temperature
HCl	1.5 K
CO	3.3 K
SO_2	2.5 K
Clouds	142.8 K
H_2O	68.8 K
OCS	12.0 K
CO_2	422.7 K

Venus Climate Model



Climate Evolution

- Radiative-Convective Model
- Coupled Cloud Microphysics
- Exospheric Escape of H,D
- Volcanic Outgassing
- Reactions with Surface

EVOLUTIONARY CLIMATE MODEL CONCLUSIONS :

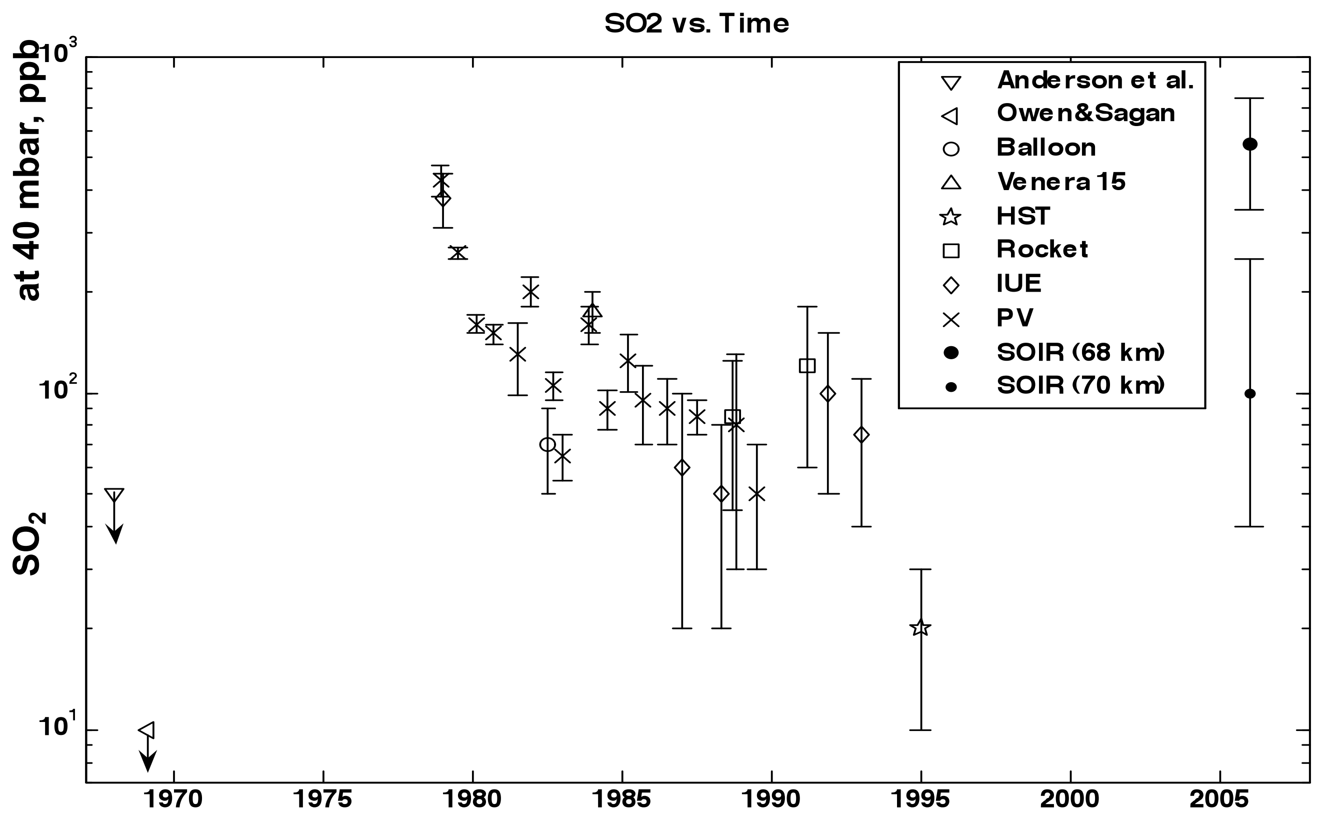
Bullock and Grinspoon (2001) , The recent history of climate on Venus, *Icarus*.

1) Changes in outgassing rate associated with the onset and decline of an epoch of rapid resurfacing can lead to changes in surface temperature on the order of 100 K.

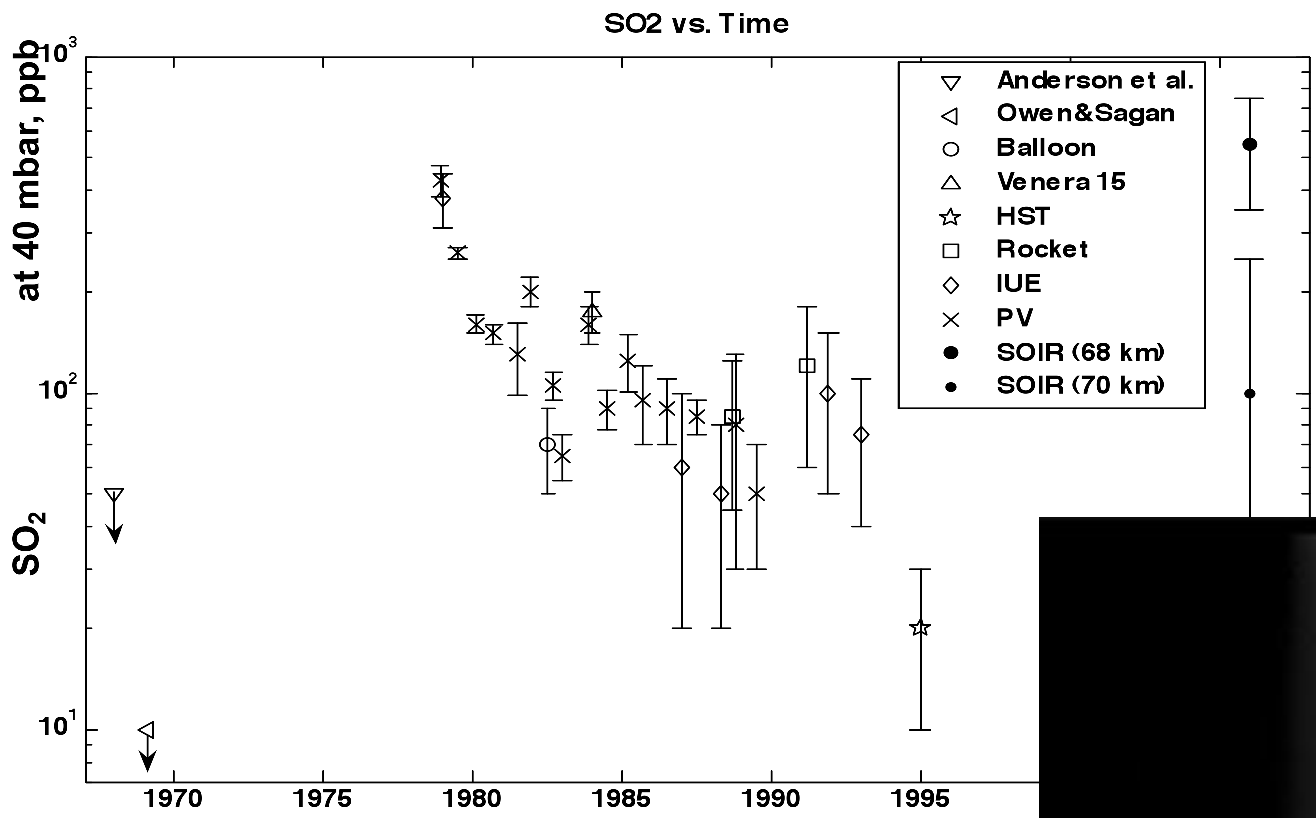
2) Sources of outgassed SO_2 in the recent past (10-50 m.y.) must be presently supporting the clouds. Without such a source the clouds would disappear as SO_2 equilibrates with surface minerals.

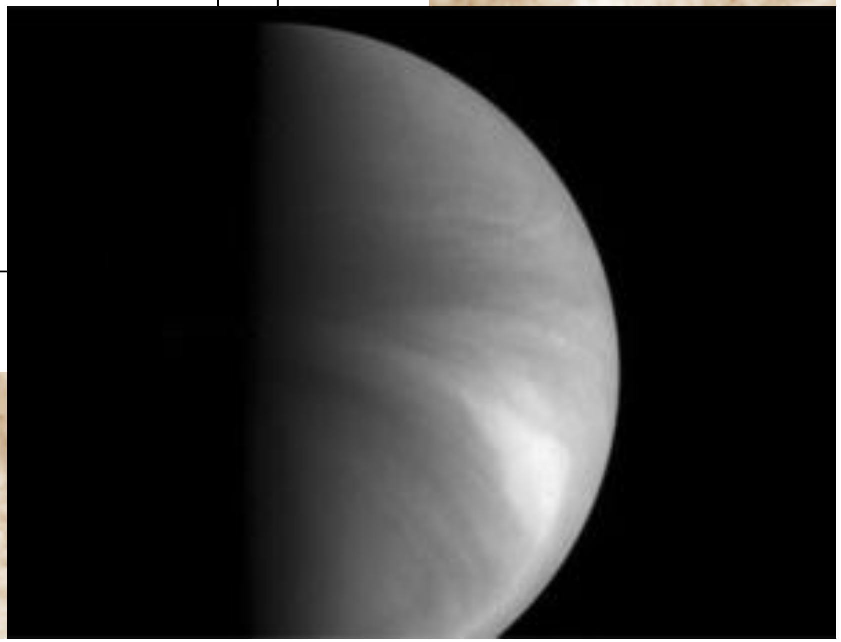
The clouds may be a transient phenomenon.
Venus may have been cloud-free for much of its history!

SO_2 variations & cloud brightenings: volcanism, dynamics or?..

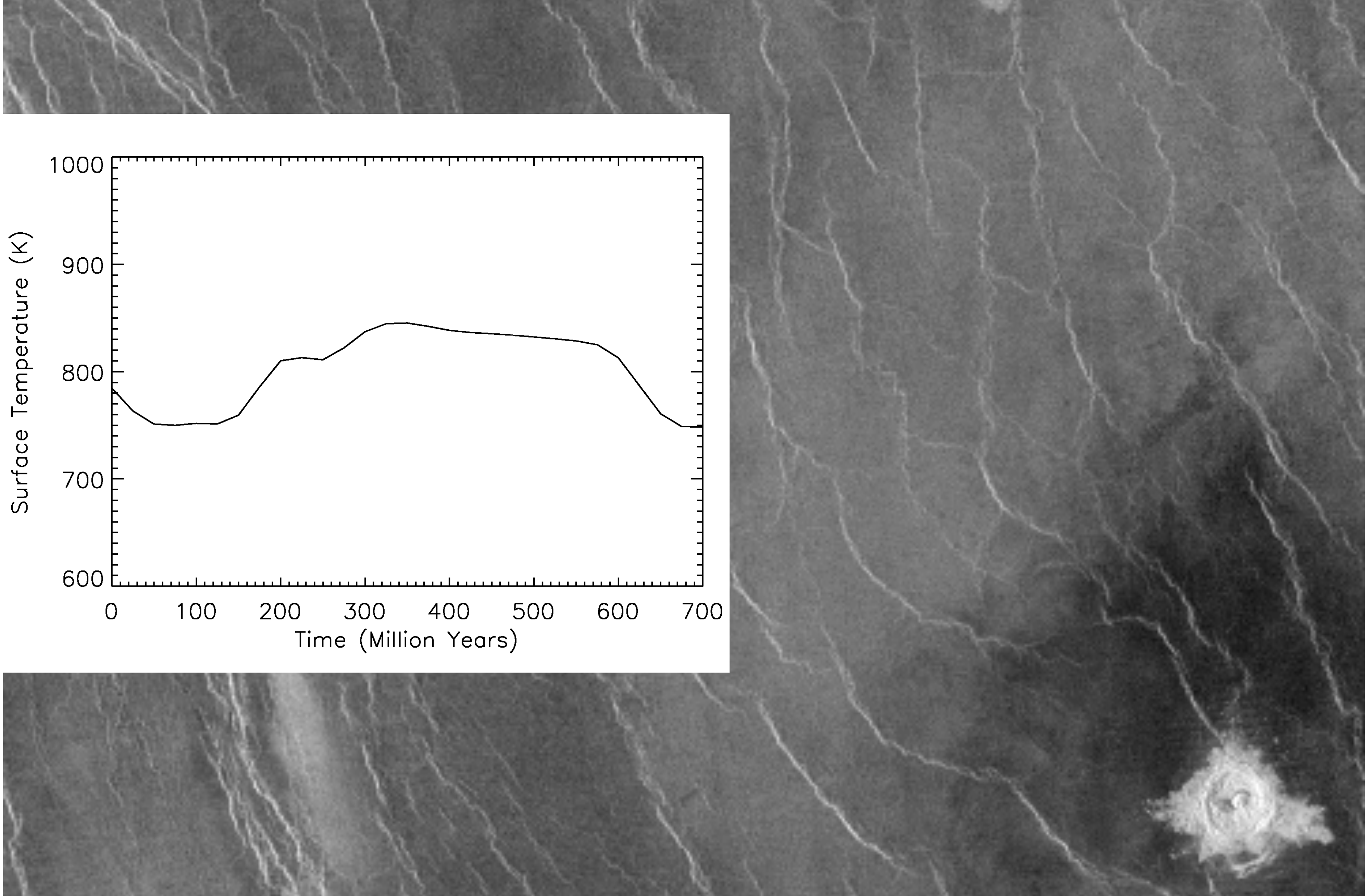


SO_2 variations & cloud brightenings: volcanism, dynamics or?..

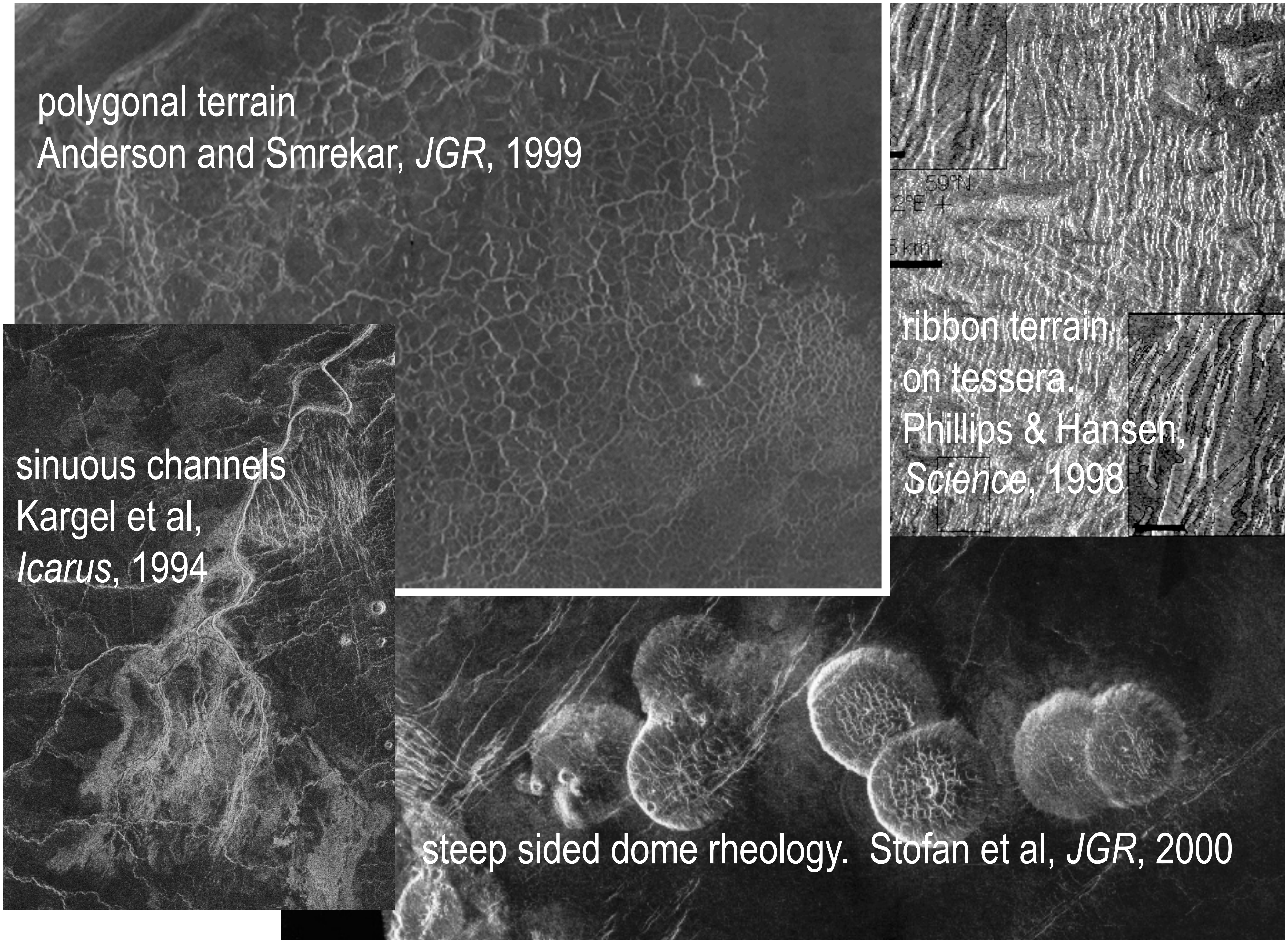




Globally synchronous formation of wrinkle ridged plains. (Solomon, Bullock and Grinspoon, *Science*, 1999)



SURFACE OBSERVATIONS ON VENUS THAT MAY INDICATE CLIMATE CHANGE INCLUDE:



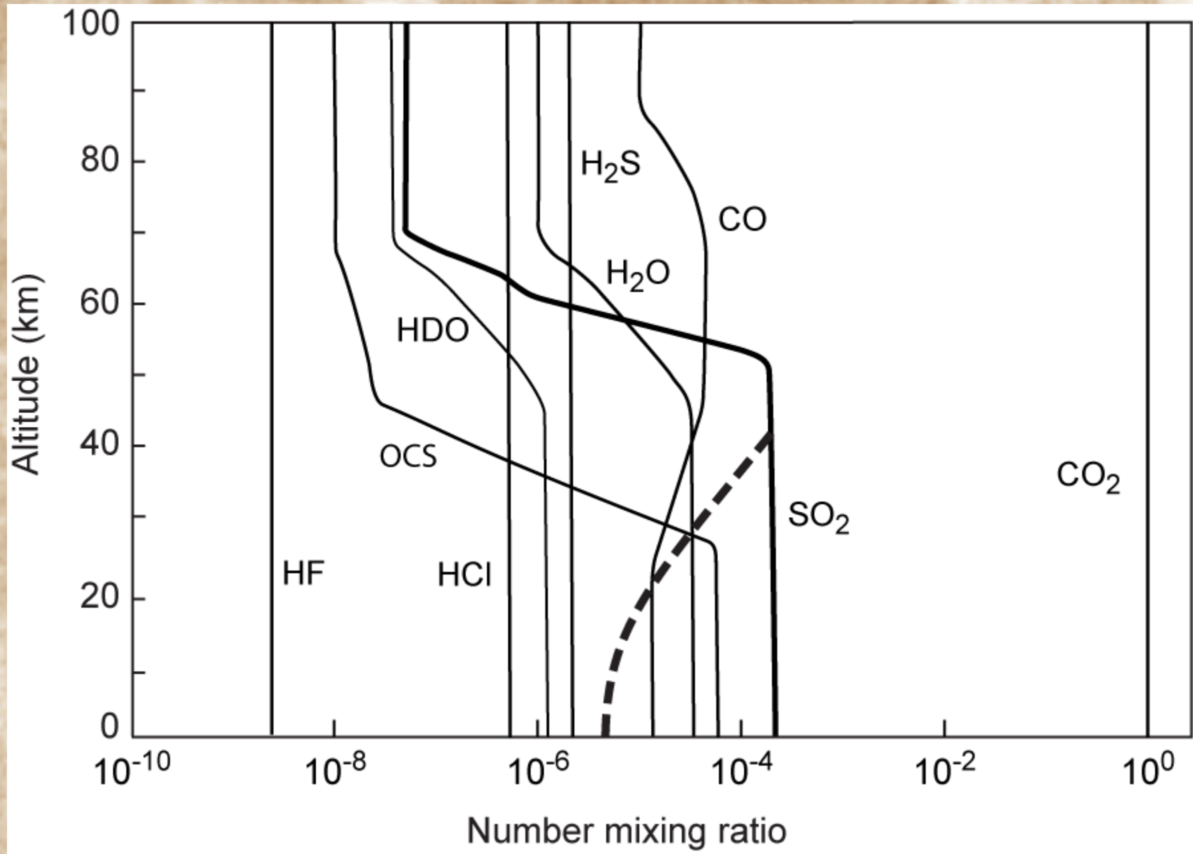
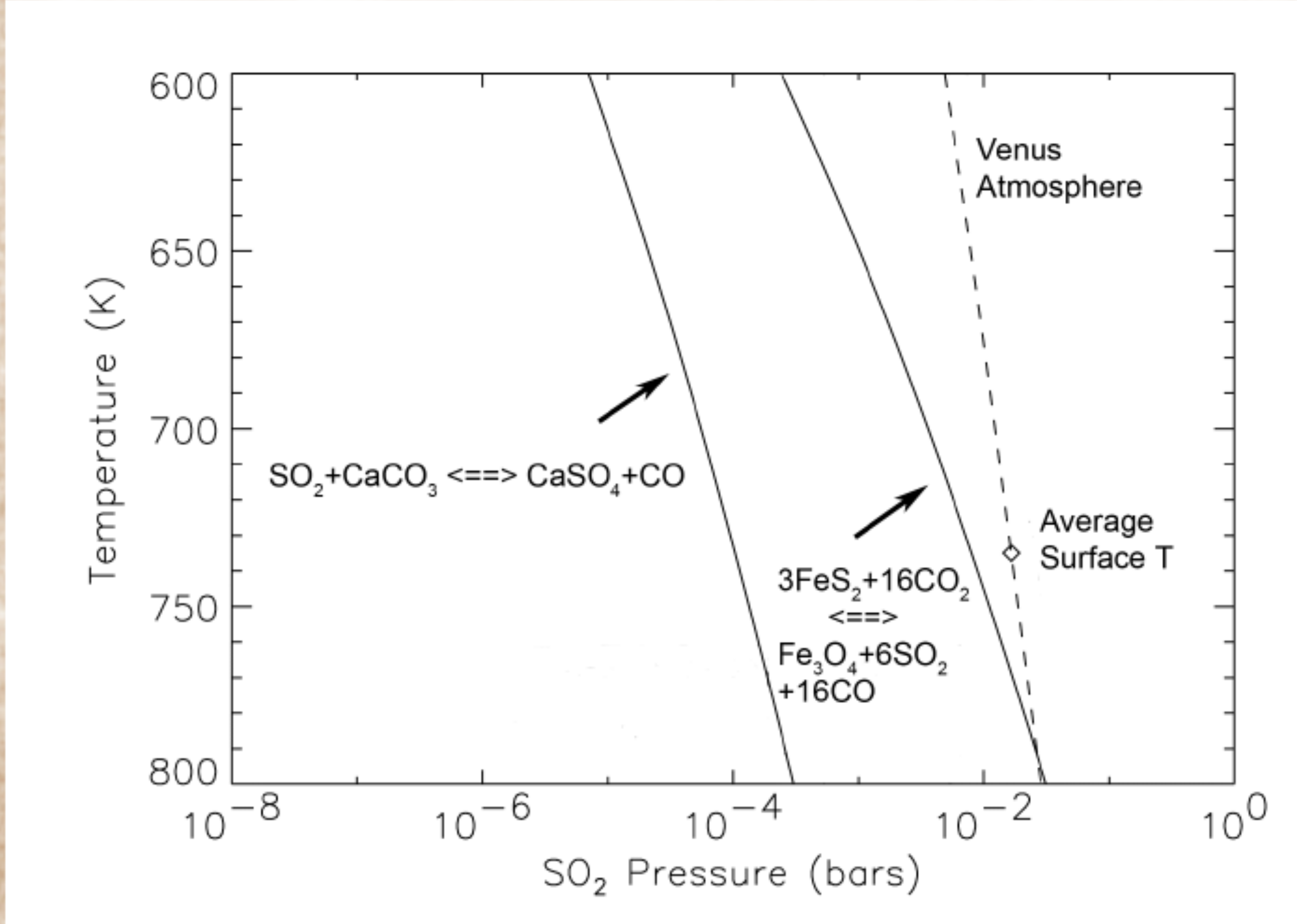


Figure 8. Mixing ratios assumed in the baseline models of Grinspoon and Bullock (2001) shown as a function of altitude. Dotted line shows SO_2 mixing ratio as a function of altitude derived by Bertaux et al. (1996) from VEGA 1 and 2 entry probe data.



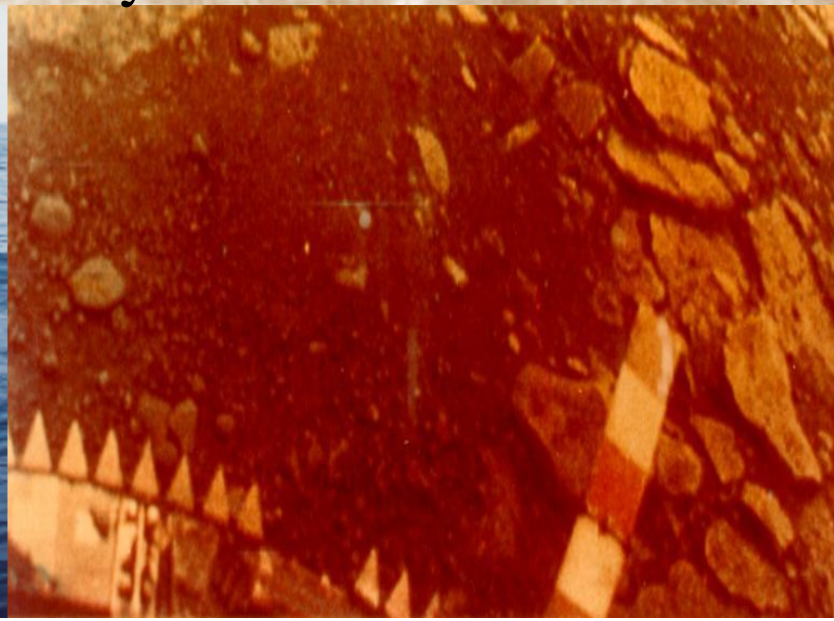
Thermochemical equilibrium of atmospheric SO_2 with Venus surface minerals. The temperature/pressure curve for the Venus atmosphere is shown by the dashed line on the right, with the globally averaged surface temperature indicated by the diamond. SO_2 equilibrium with calcite is shown by the solid line on the left, SO_2 equilibrium with pyrite is shown by the solid line on the right. SO_2 is more than two orders more abundant on Venus than required for equilibrium with calcite, but it is close to equilibrium with pyrite and magnetite. However, for either of these reactions to be in equilibrium the reactants must exist at the surface. While there are no unequivocal data for the existence of either of these phases, $CaCO_3$ is a possible interpretation of the Venera XRF data for Ca. FeS_2 has been shown in laboratory experiments to have a lifetime of ~100 days at Venus surface conditions (Fegley *et al.* 1995), so it is unlikely to exist for geologically relevant timescales.

Did Venus experience one great transition or two?

1) Loss of Oceans. Kasting (1988) (Timing unconstrained.)

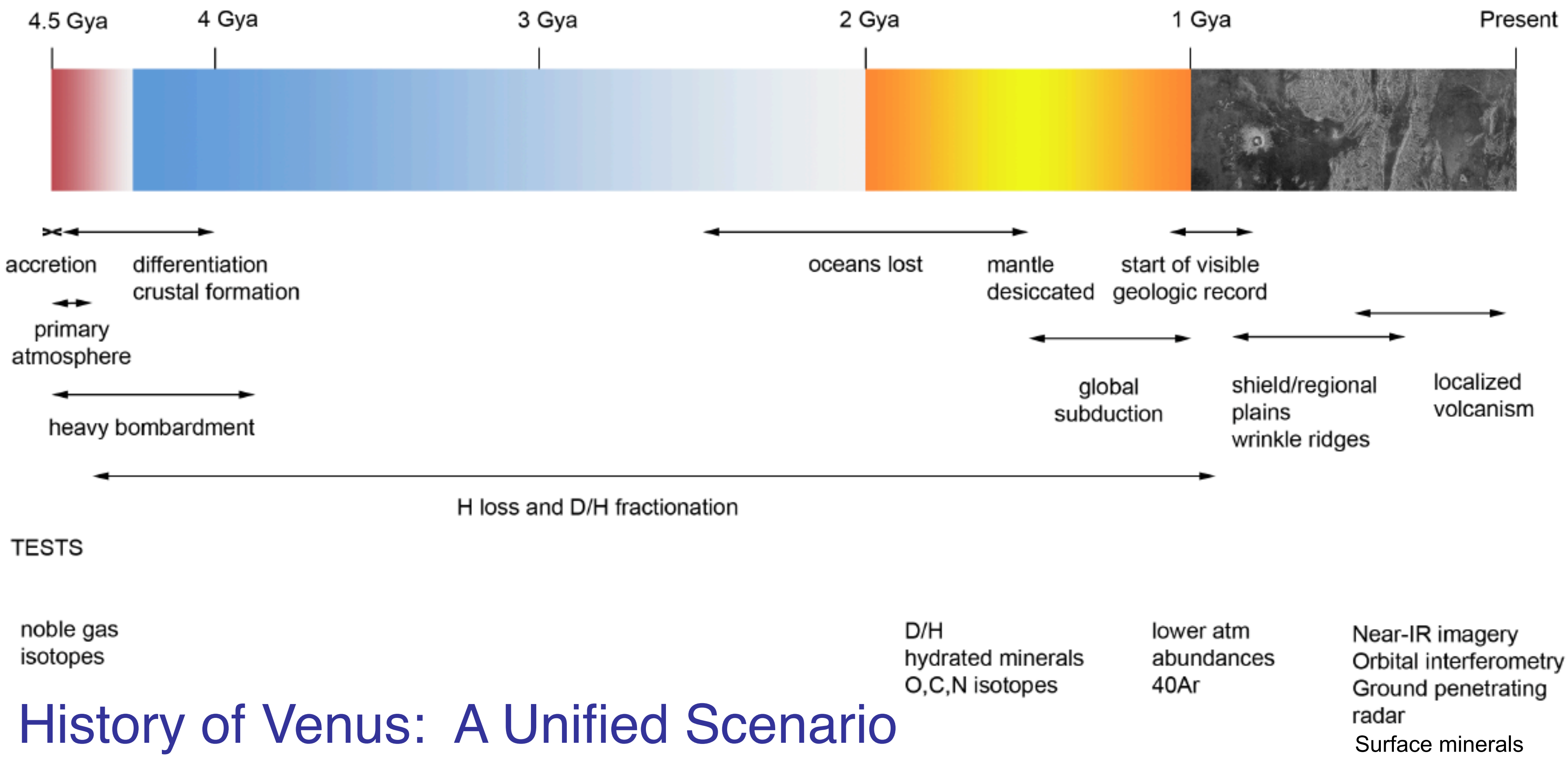
2) Global decline in resurfacing rate.

IF the lifetime of the moist greenhouse is ≈ 2 G.Y., geological and atmospheric evolution may tell a consistent and unified story…



History of Venus: A Unified Scenario

- ≈ 2 -3 Gya (???) Loss of surface water, subduction of hydrated sediments ceases.
- Mantle becomes desiccated.
- Lack of water makes lithosphere thicker & more difficult to break.
- Loss of asthenosphere -> lithosphere is tightly coupled to mantle.
- Crustal recycling is inhibited.
- ≈ 1 Gy Plate tectonics ceases, Venus becomes a “1 plate planet”
- ≈ 700 My, global resurfacing rate declines precipitously.
- 700 My to present: localized volcanism and tectonism, conductive heat release, production population of craters.
  - Tessera are remnants of more vigorous past tectonics. (continents?)
  - Plains record “global resurfacing”, or at least an epoch of much higher resurfacing rates that ended “suddenly” enough to allow very few craters modified by plains volcanism.
  - Venus may have been a habitable planet (with an oxygenated atmosphere?) for much of Solar System history!



History of Venus: A Unified Scenario

≈ 2 - 4 Gya (???) Loss of surface water, subduction of hydrated sediments ceases.

Mantle becomes desiccated.

Lack of water makes lithosphere thicker & more difficult to break.

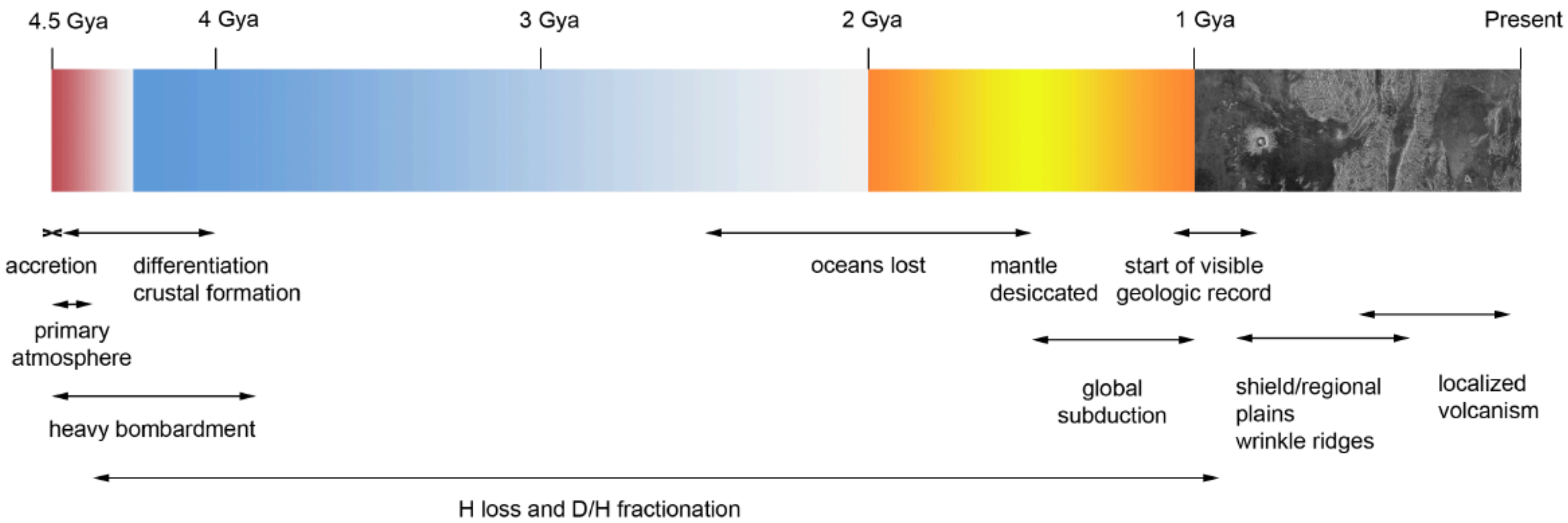
Loss of asthenosphere -> lithosphere is tightly coupled to mantle.

Crustal recycling is inhibited.

≈ 1 Gy Plate tectonics ceases, Venus becomes a “1 plate planet”

≈ 700 My, global resurfacing rate declines precipitously.

700 My to present: localized volcanism and tectonism, conductive heat release, production population of craters.



TESTS

noble gas
isotopes

D/H
hydrated minerals
O,C,N isotopes

lower atm
abundances
40Ar

Near-IR imagery
Orbital interferometry
Ground penetrating
radar
Surface minerals

History of Venus: A Unified Scenario

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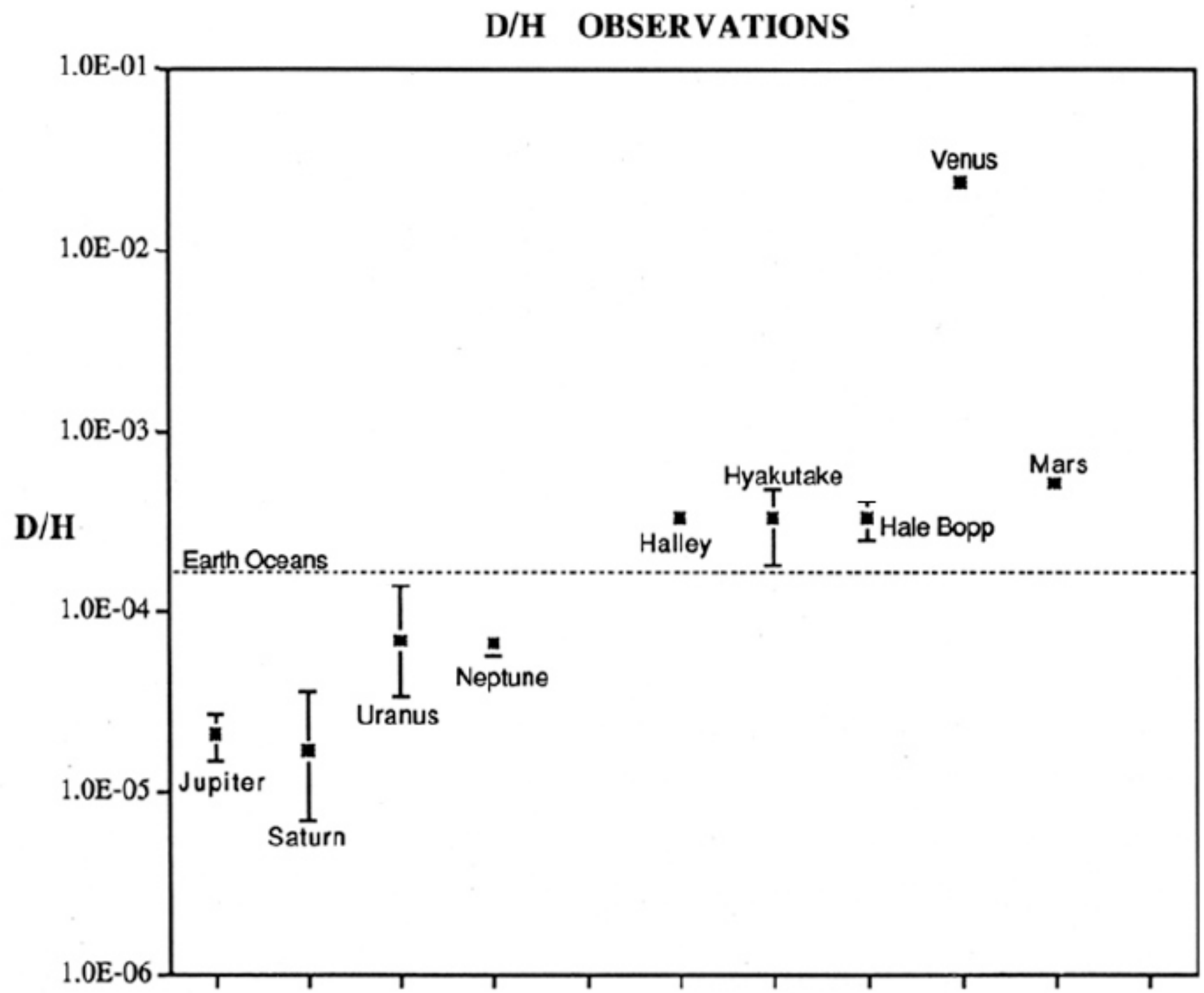
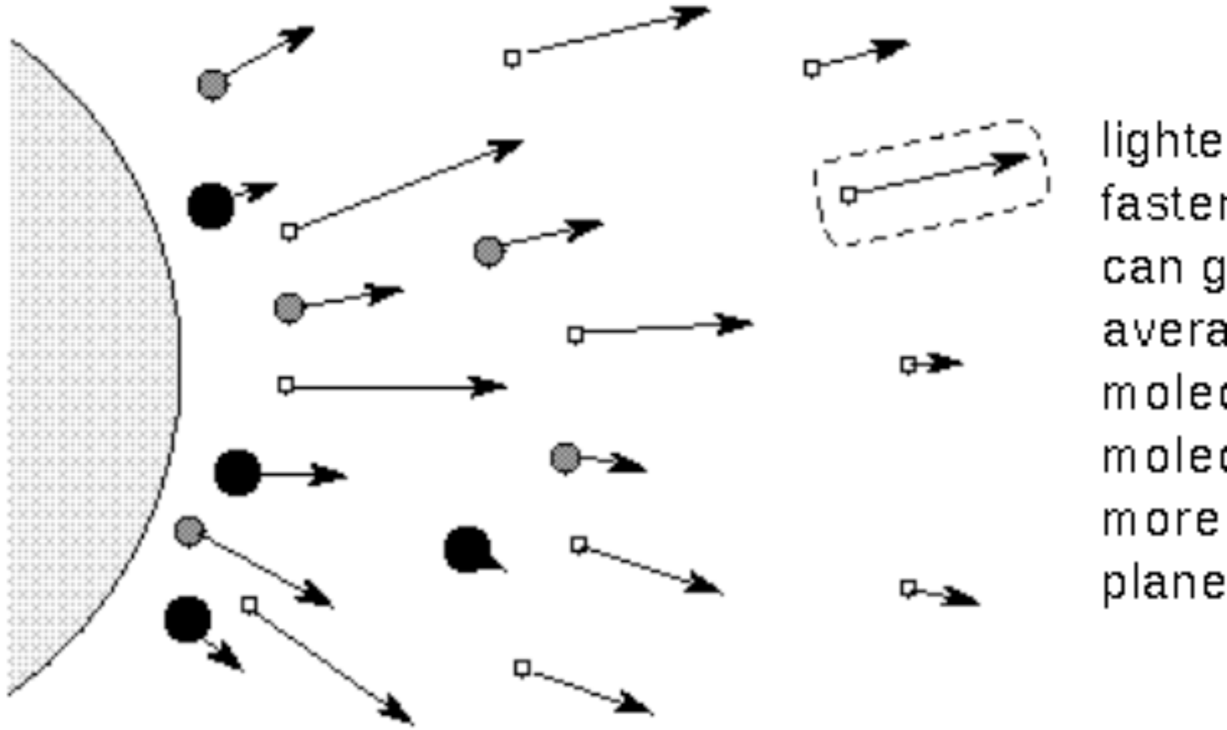
Venus may have been a habitable planet (with an oxygenated atmosphere?) for much of Solar System history!

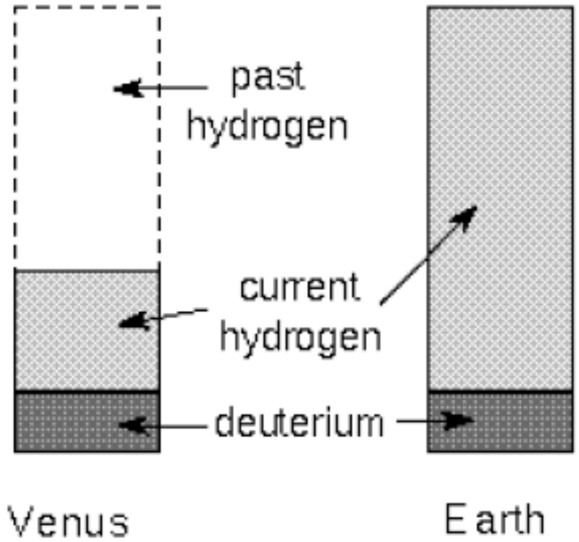
$(D/H)_{VENUS} = 120 \pm 40 \times (D/H)_{EARTH}$

(Bezard et al, 2007)



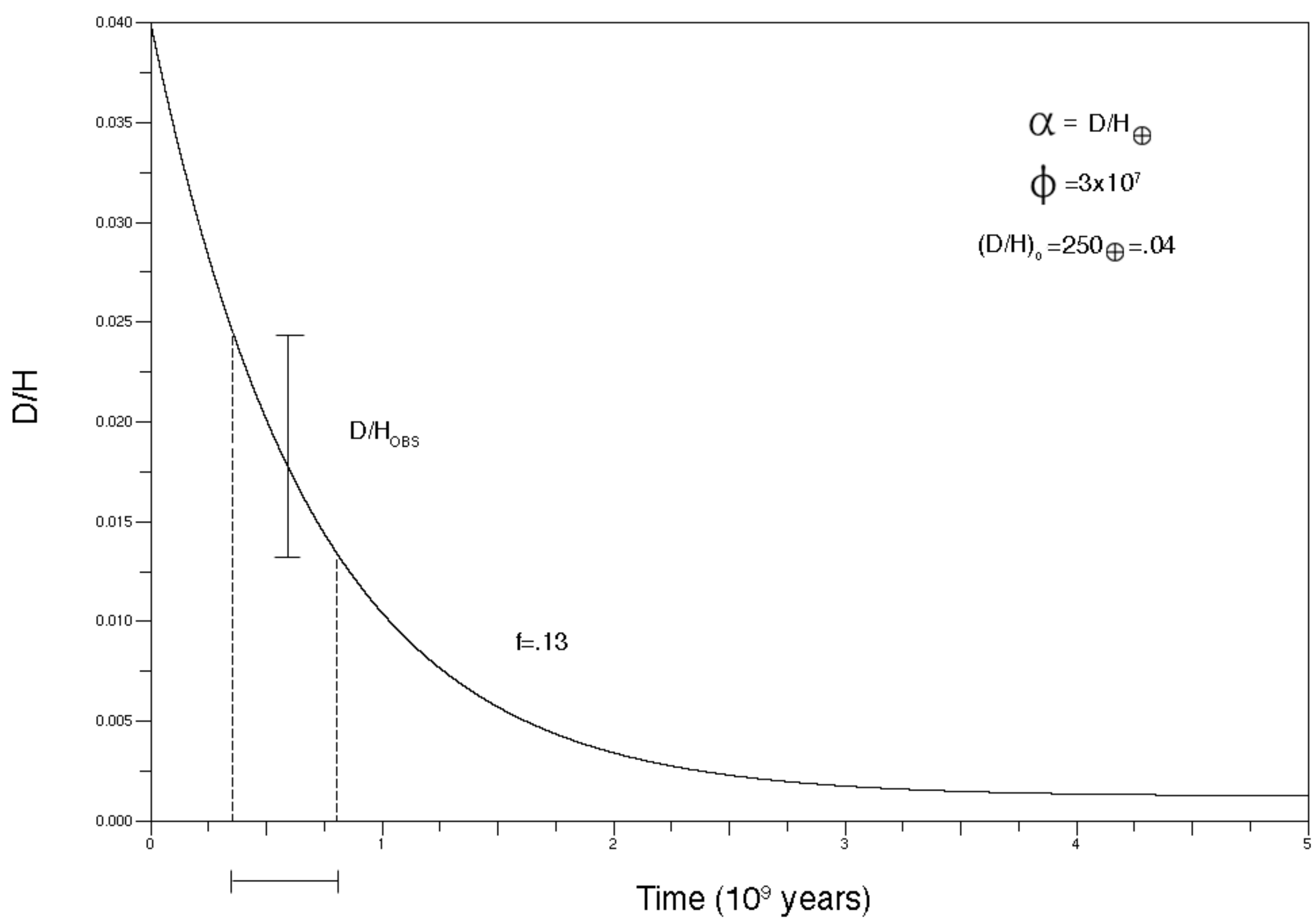
Fractionating Escape:





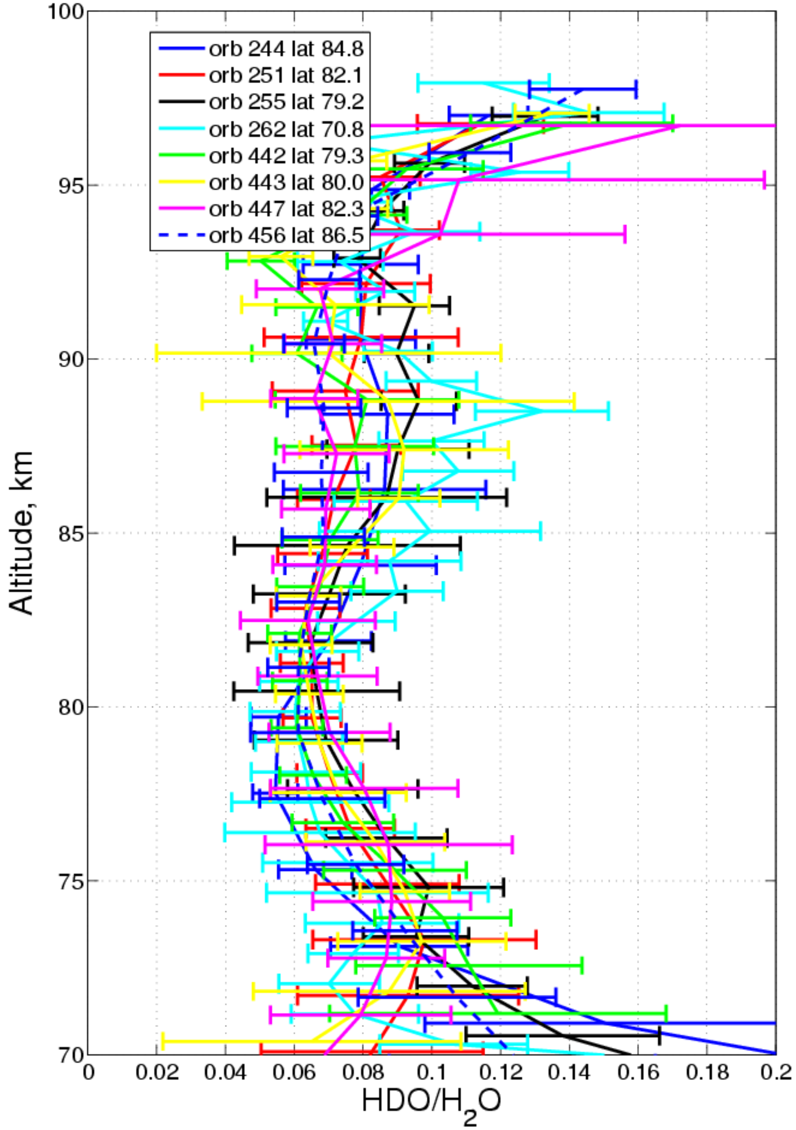
Presently, the problem is underdetermined.

Improved measurements of D/H, constraints on escape flux and fractionation factor will allow us to rule out many interpretations of D/H and allow more definitive derivations of history of water.



HDO/H_2O ratio from SOIR

High northern latitudes



The averaged isotopic HDO/H_2O ratio equals **240±25 times** the ratio in the Earth' ocean

≈ 2 x bulk atmosphere value.

could result from:

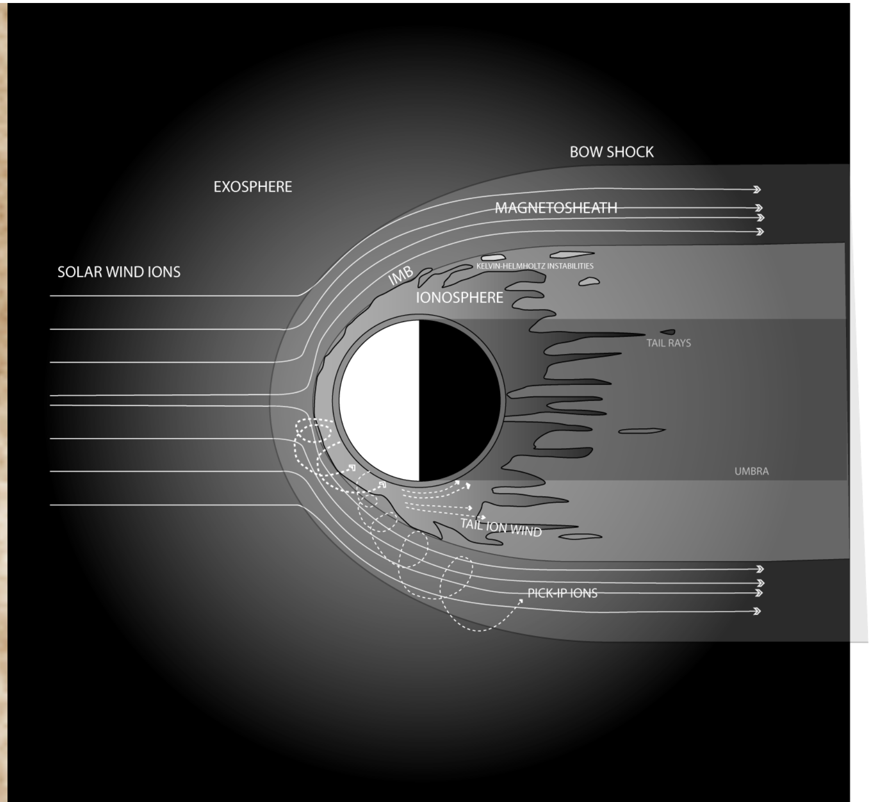
(1) preferential destruction of H2O relative to HDO, perhaps from photolysis-induced isotopic fractionation (PHIFE), (Liang and Yung, 2008)

(2) preferential escape of H relative to D, which enhances the abundance of HDO

Solving this problem will depend on understanding global dynamics and photochemistry.
Not a simple problem.
Future Venus Express observations that can help:
Lattitude distribution of HDO/H2O (and SZA?)

ASPERA

Escape of H+ occurs mostly through the plasma wake. With a flux of 7.1×10^{24} s^{-1} . (Federov, Barabash et al. 2008)



column escape flux of 1.5×10^{6} cm^{-2} s^{-1}

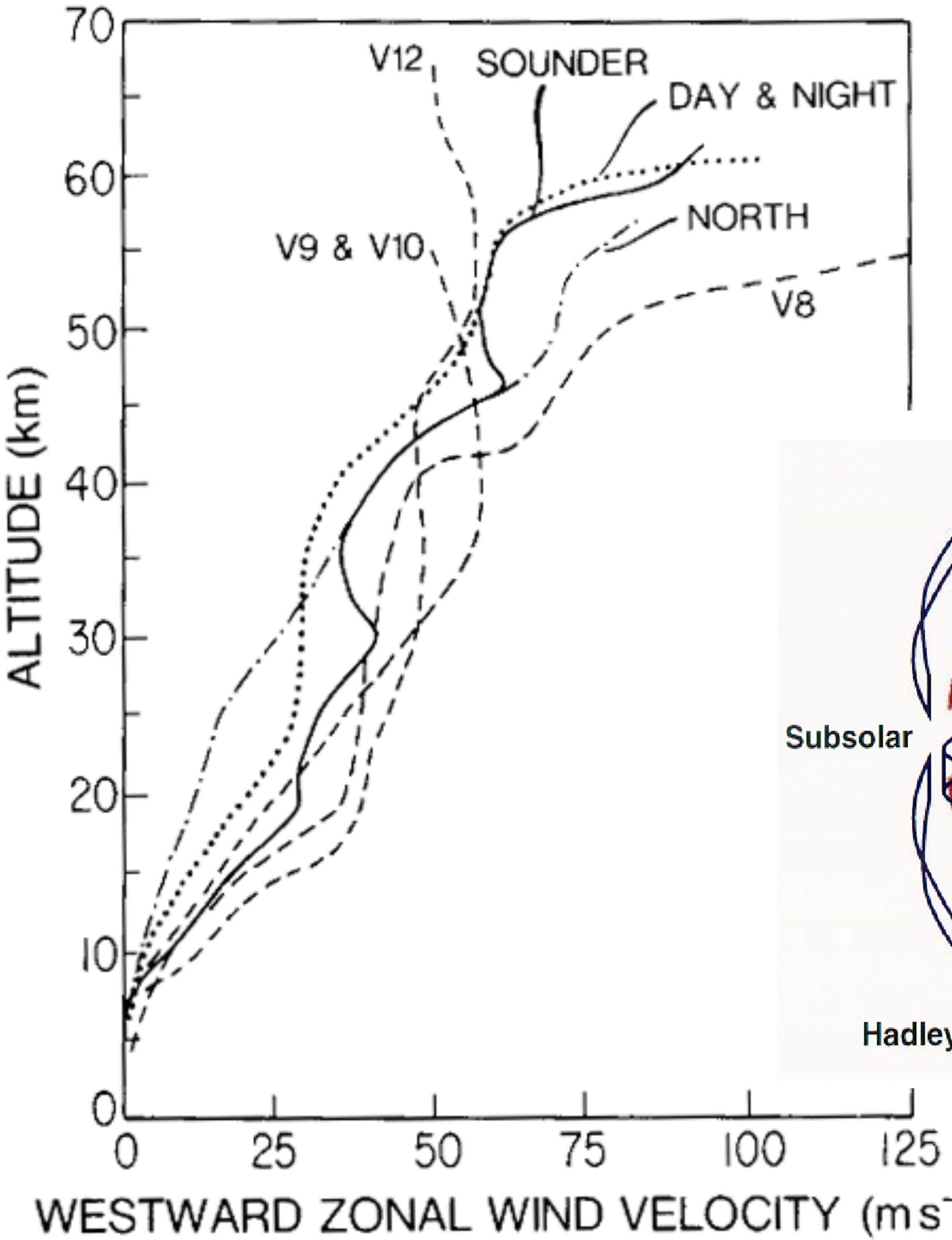
Does this represent the time averaged Hydrogen escape flux? (Escape of neutrals? Low energies? Solar cycle variations?)

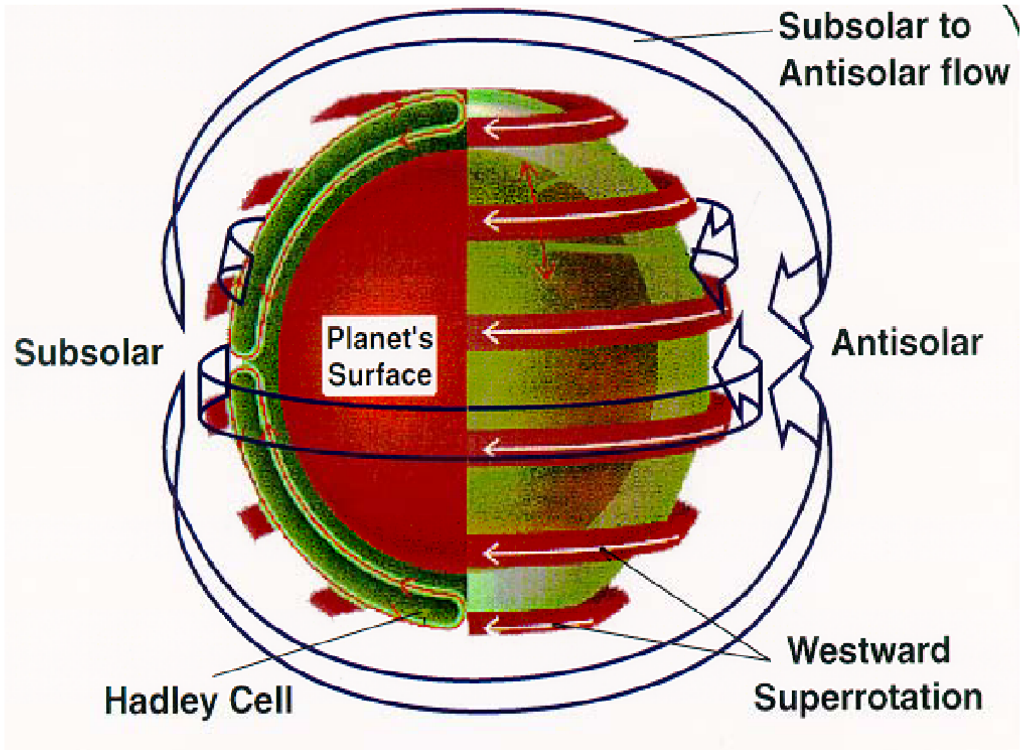
An order of magnitude lower than fluxes commonly assumed in evolutionary models!

Implies $T_{H2O} \approx 1$ GY (roughly $\approx T_{surface}$!)

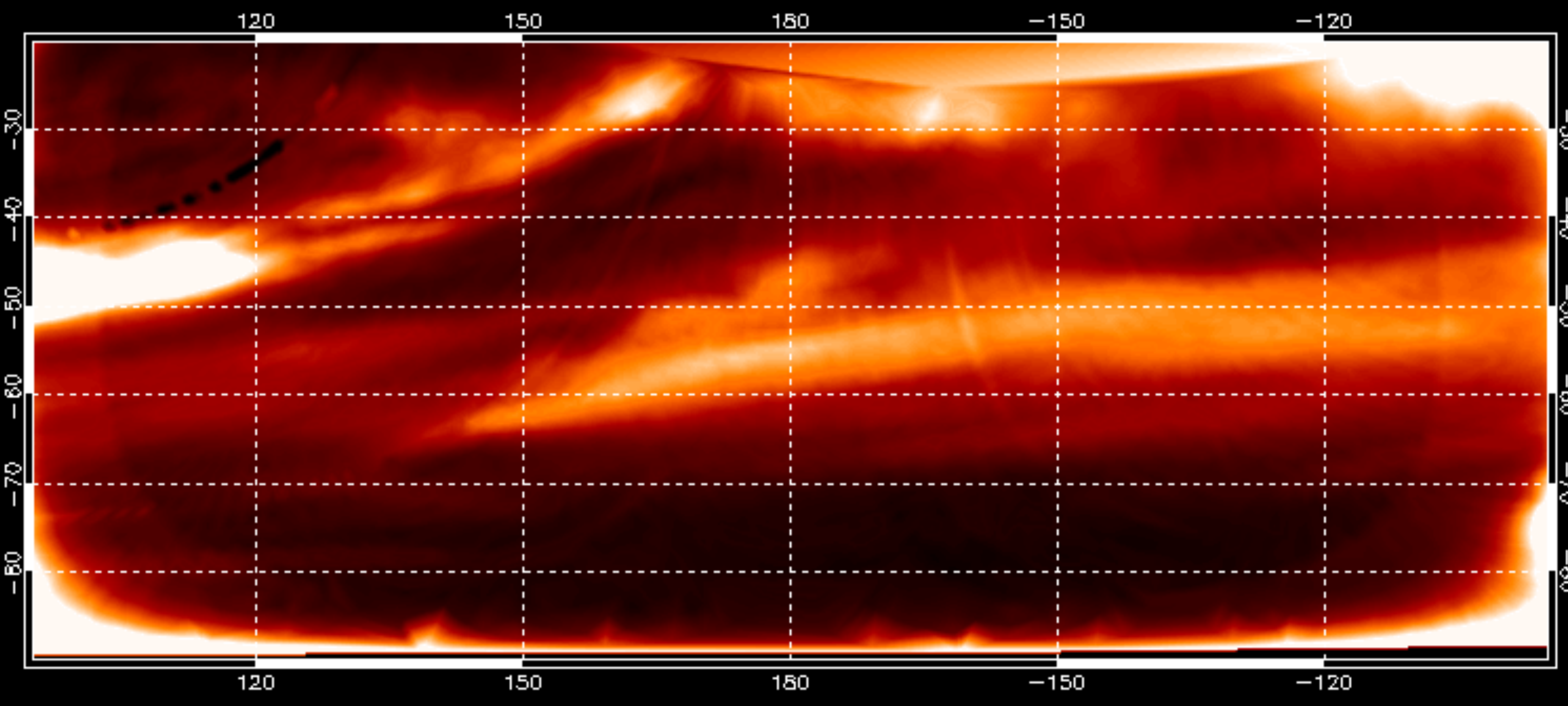
If in steady state with outgassing from post-plains volcanism, Implies that magmas are very dry! ≈ 5 ppm by mass. (2 orders of magnitude drier than driest terrestrial magmas!)

Winds and General Circulation

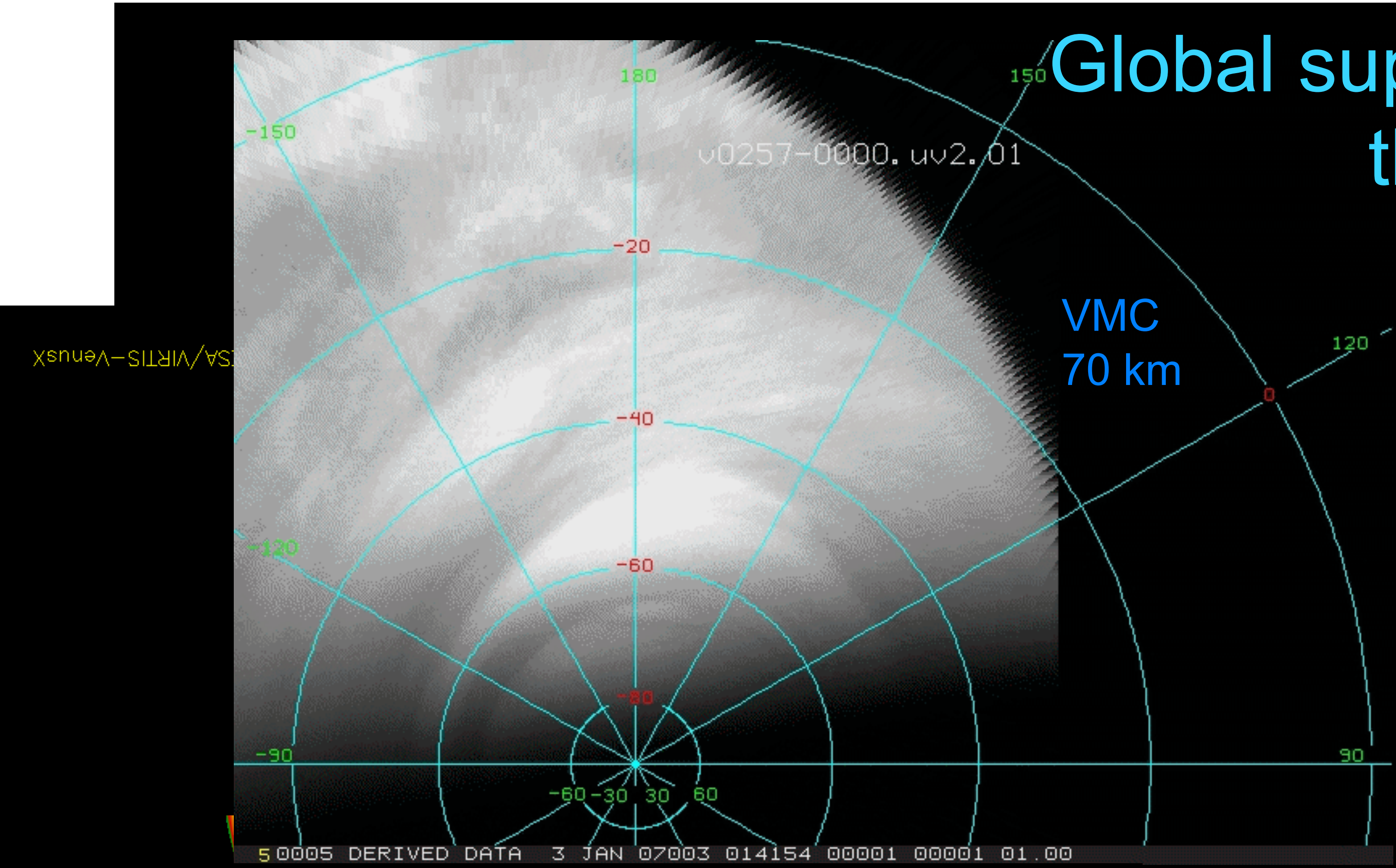




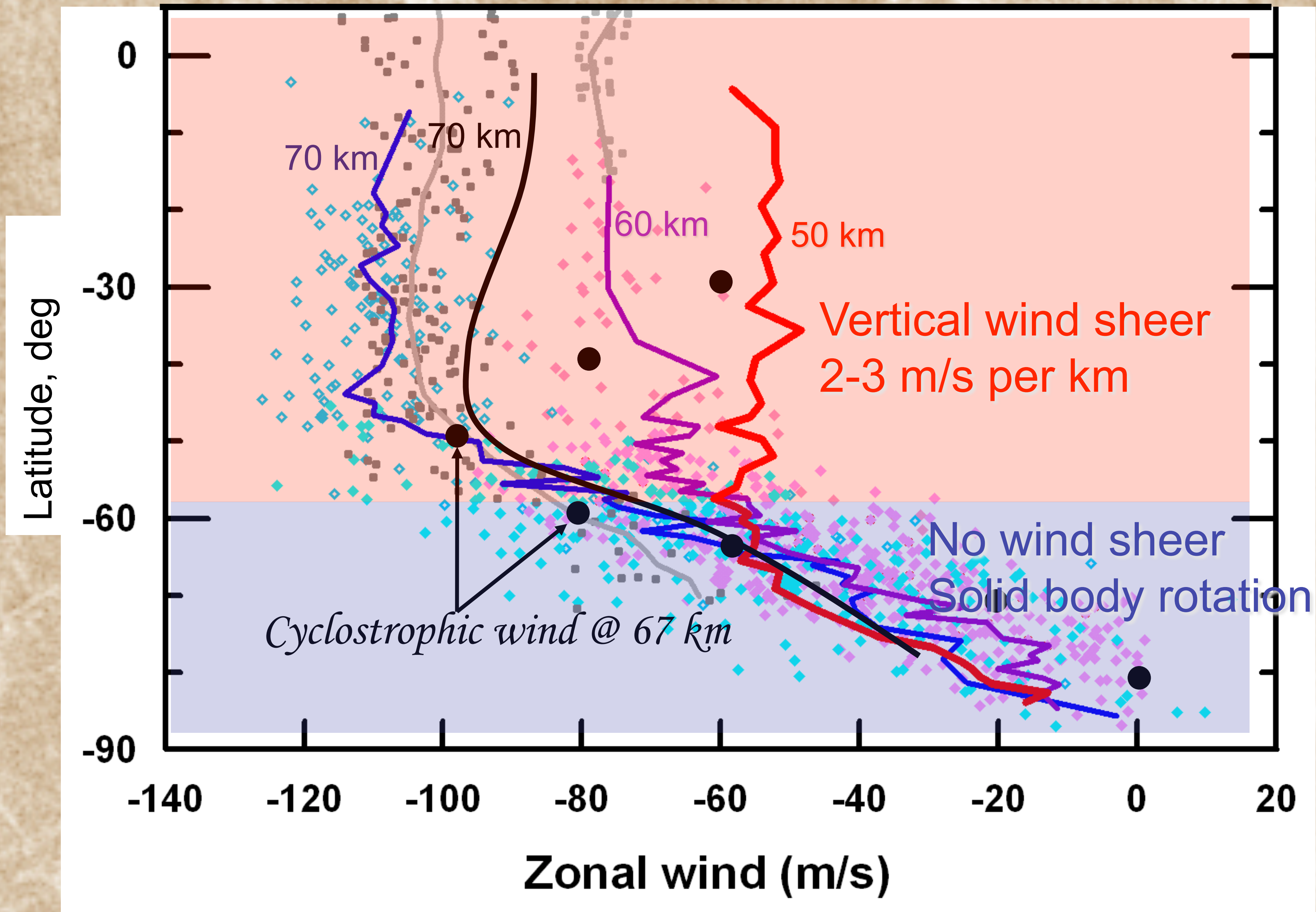
Determination of wind fields from Virtis data at 1.73 µm, corresponding to 50km altitude



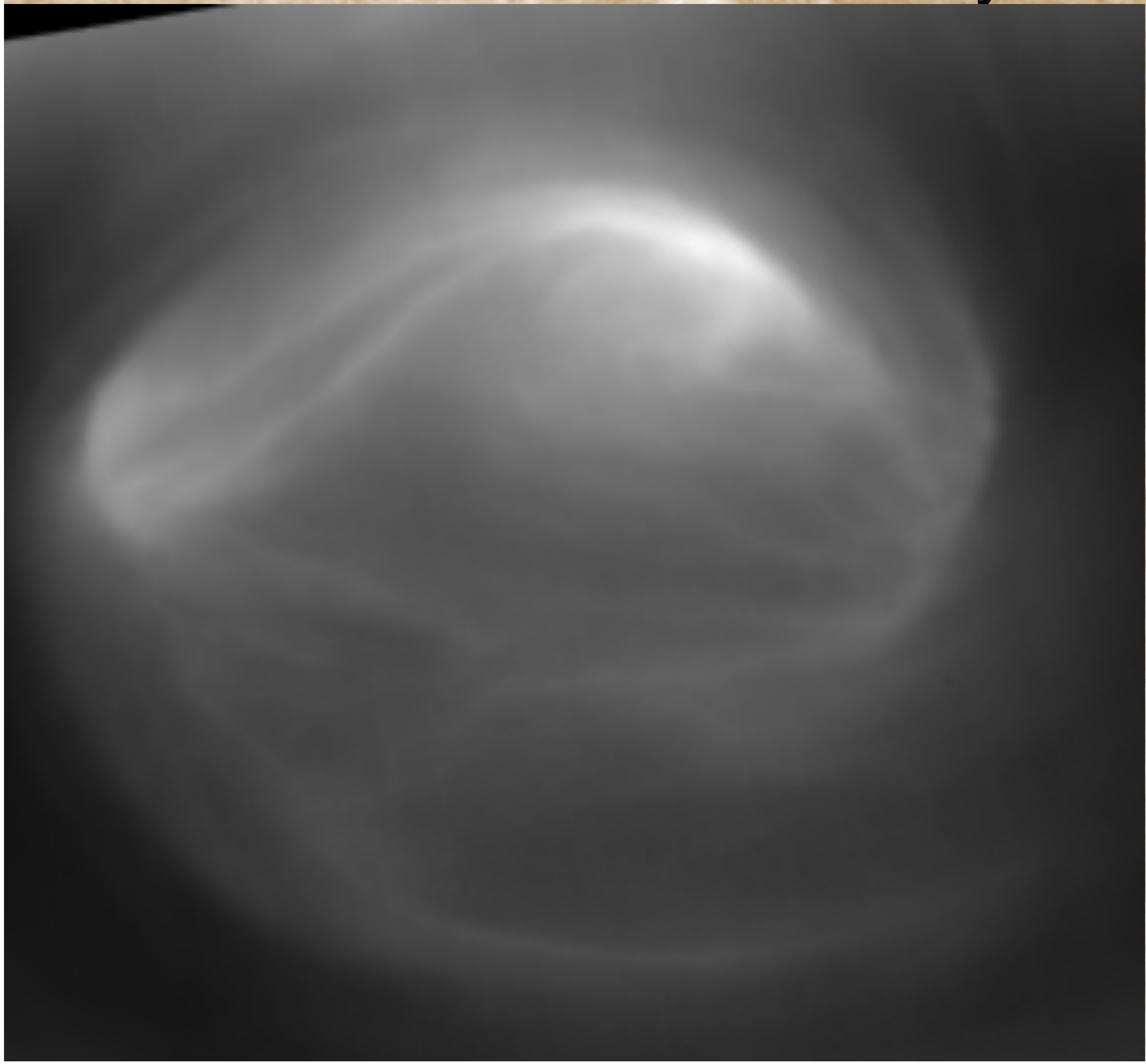
Global super-rotation at the cloud level



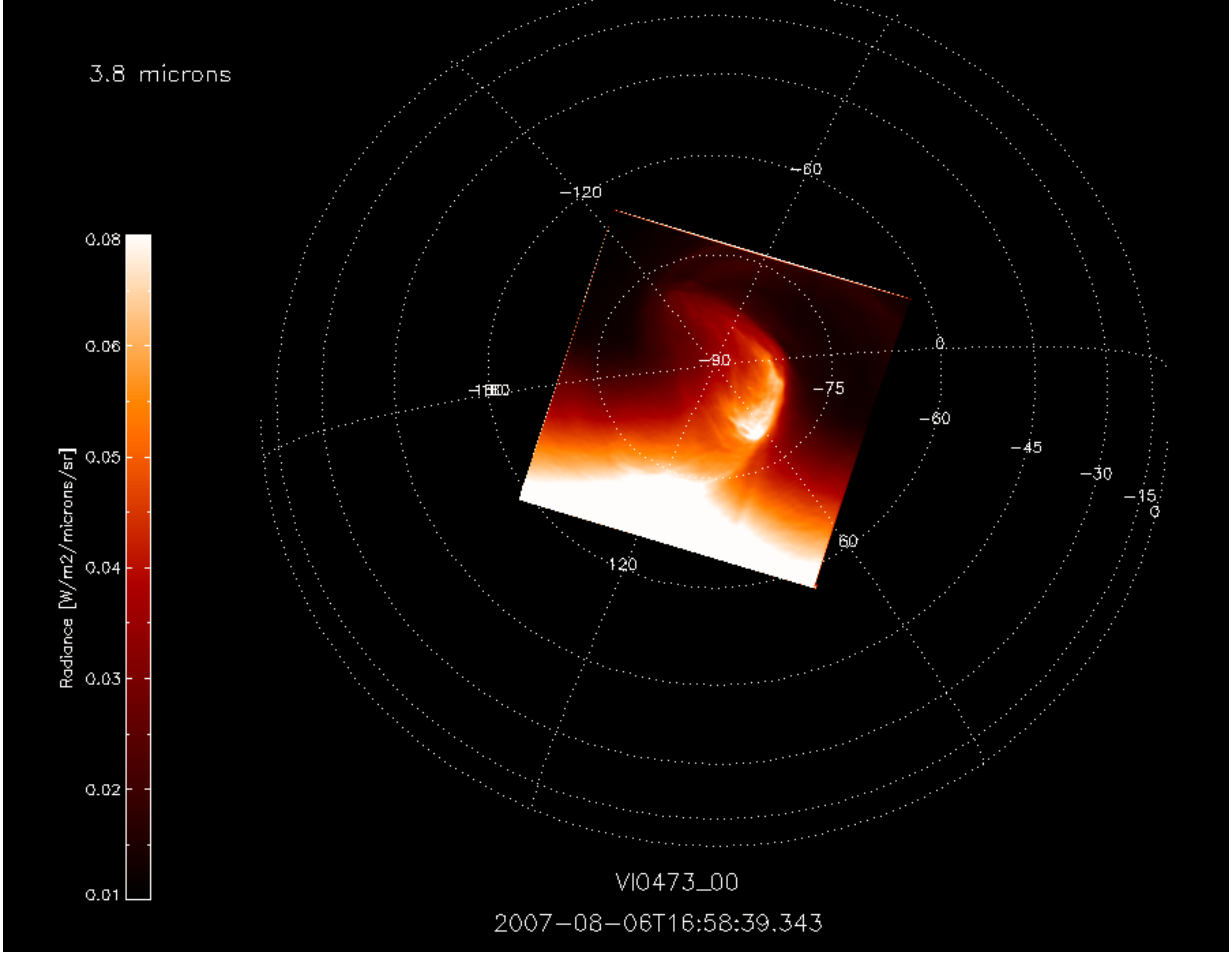
Zonal wind field from VIRTIS & VMC



Polar vortex dynamics

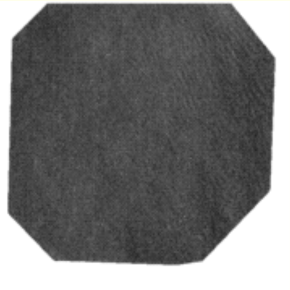


Virtis data @5μm, sampling altitude ~65km



3.8 microns
Radiance [W/m2/microns/sr]
0.08
0.06
0.05
0.04
0.03
0.02
0.01
-120
-60
0
-90
-75
-60
-45
-30
-15
60
120
VI0473_00
2007-08-06T16:58:39.343

Waves in polar region (65-70 N)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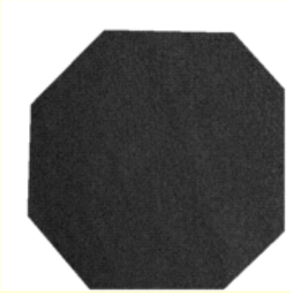
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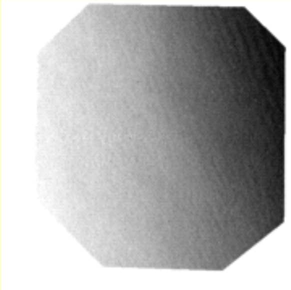
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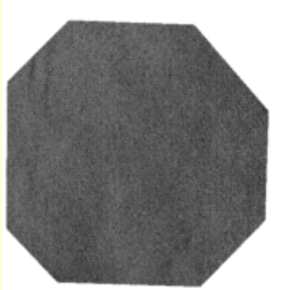
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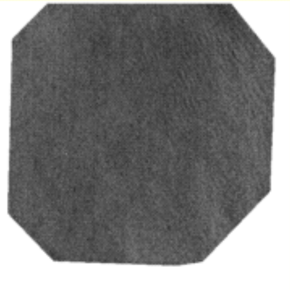
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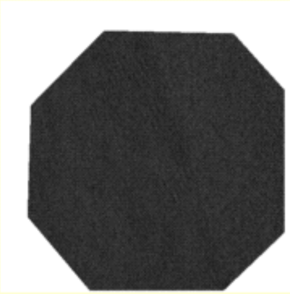
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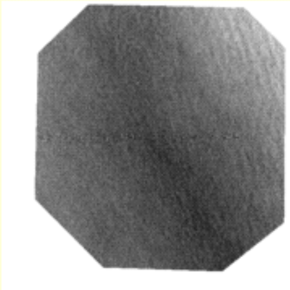
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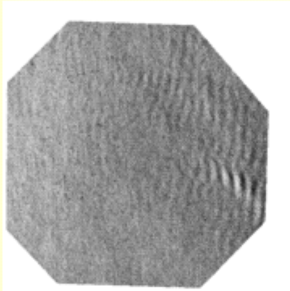
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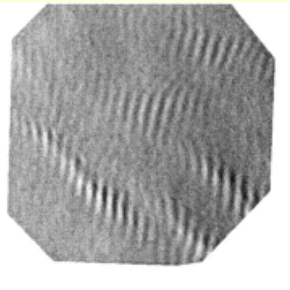
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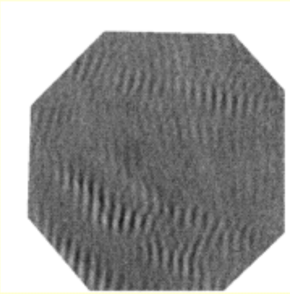
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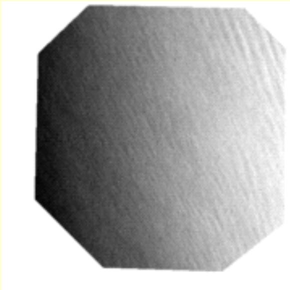
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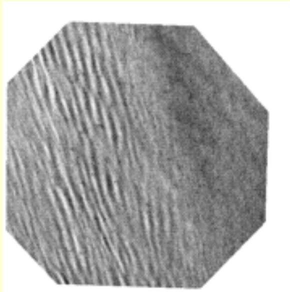
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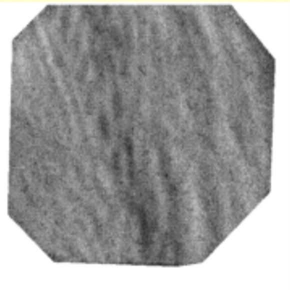
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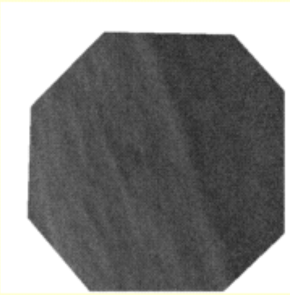
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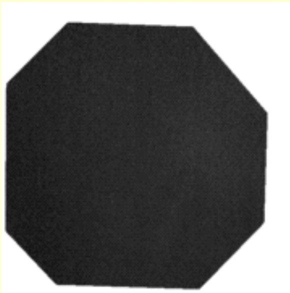
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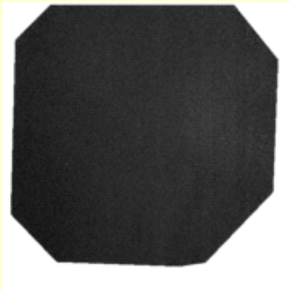
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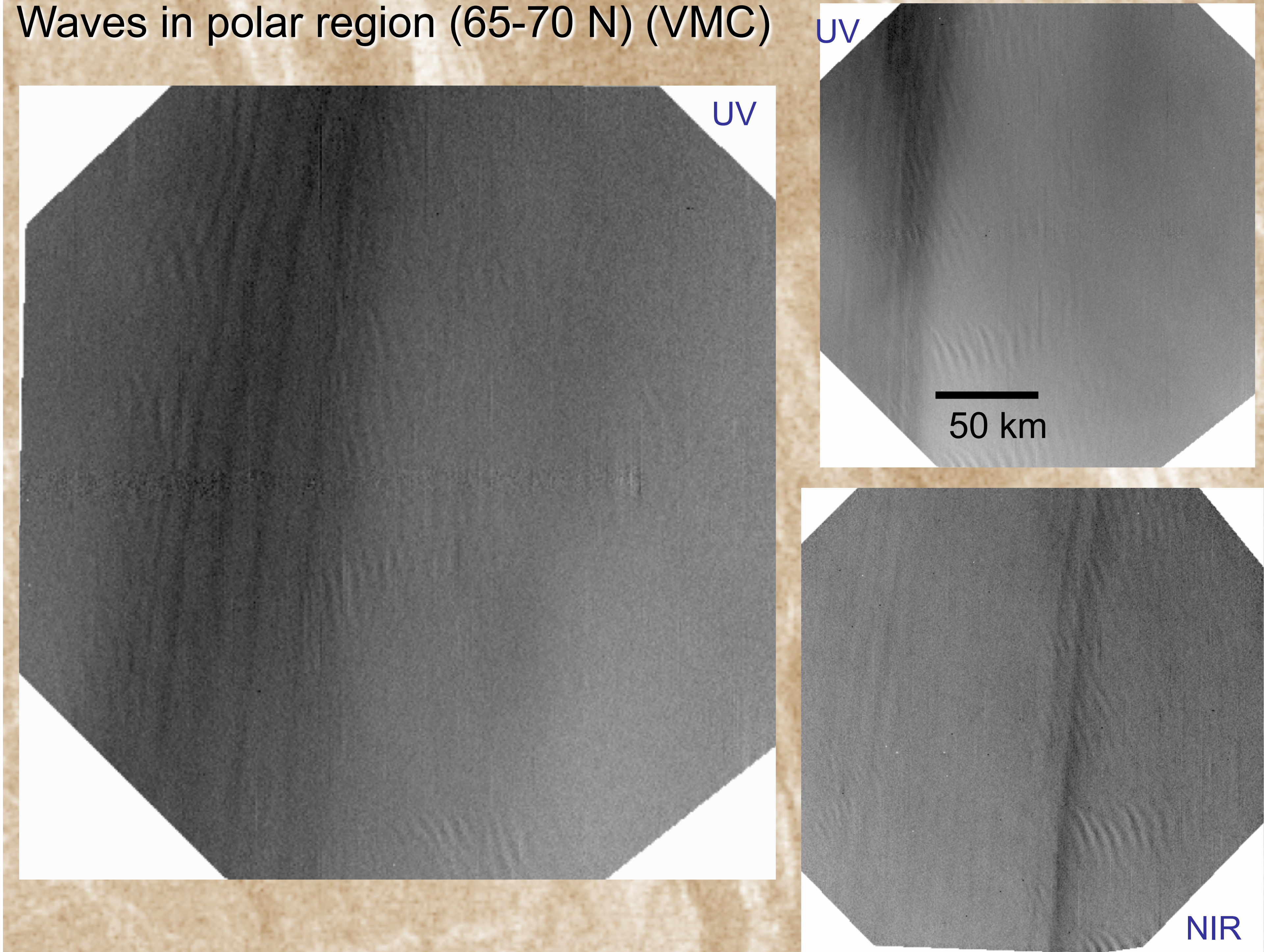
Waves in polar region (65-70 N) (VMC)



Open questions:

- When and how was Venus resurfaced?
- What is the surface mineralogy and how does it effect atmosphere and climate?
- Active volcanoes today?
- What processes are involved in zonal super-rotation?
- How does the Hadley circulation work?
- What is the blue absorber in the clouds?
- Lightning?
- What events led to the greenhouse?
- What is the stability and history of climate?
- Did Venus have an ocean and when did it lose it?
- Was Venus ever conducive to life?
- Will future Earth resemble Venus?