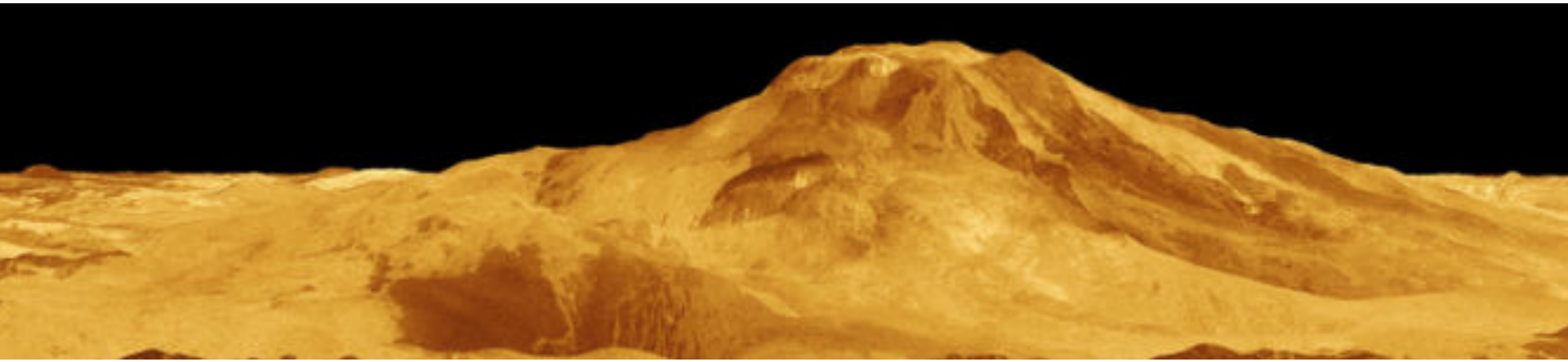

VENUS: FROM A TERRESTRIAL OCEAN TO A POSSIBLE HABITAT IN THE LOWER ATMOSPHERE

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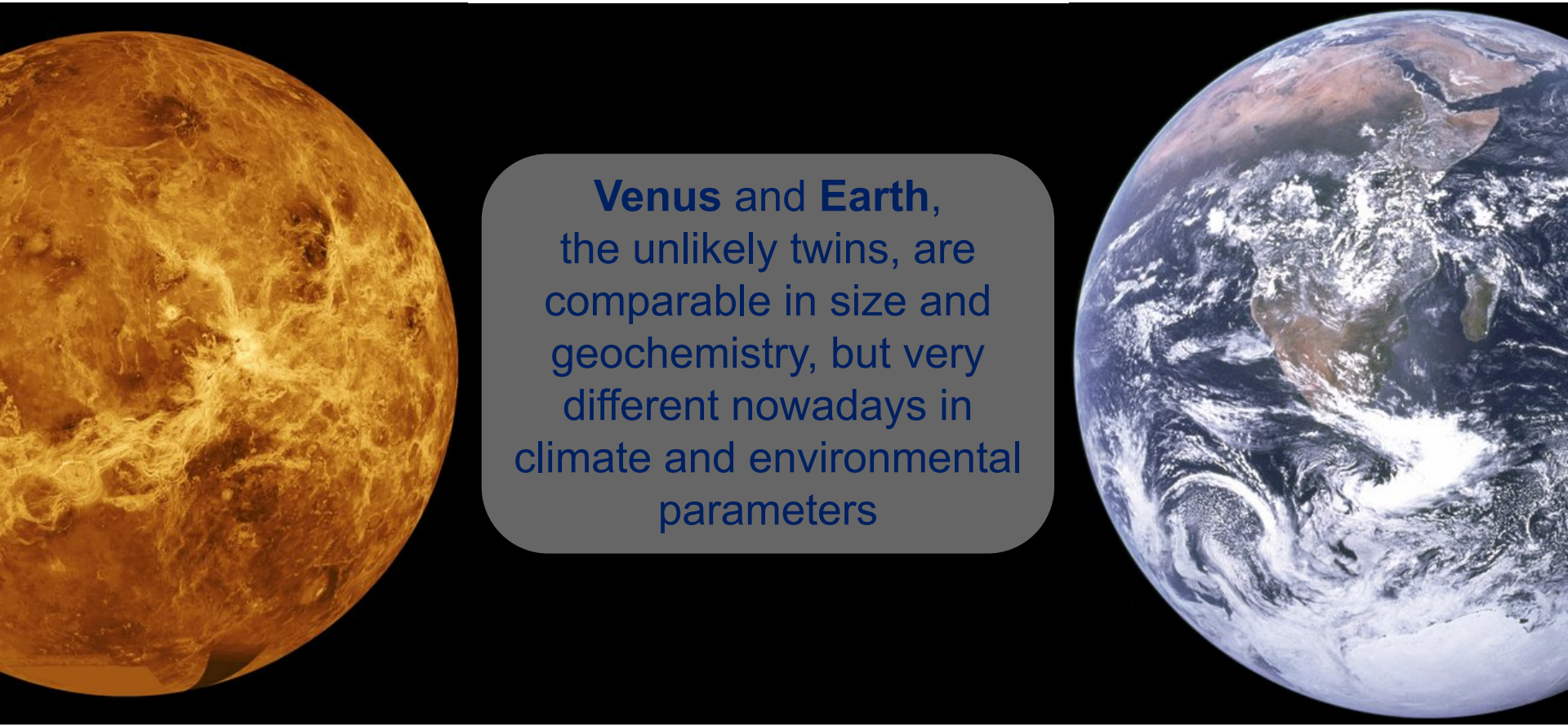
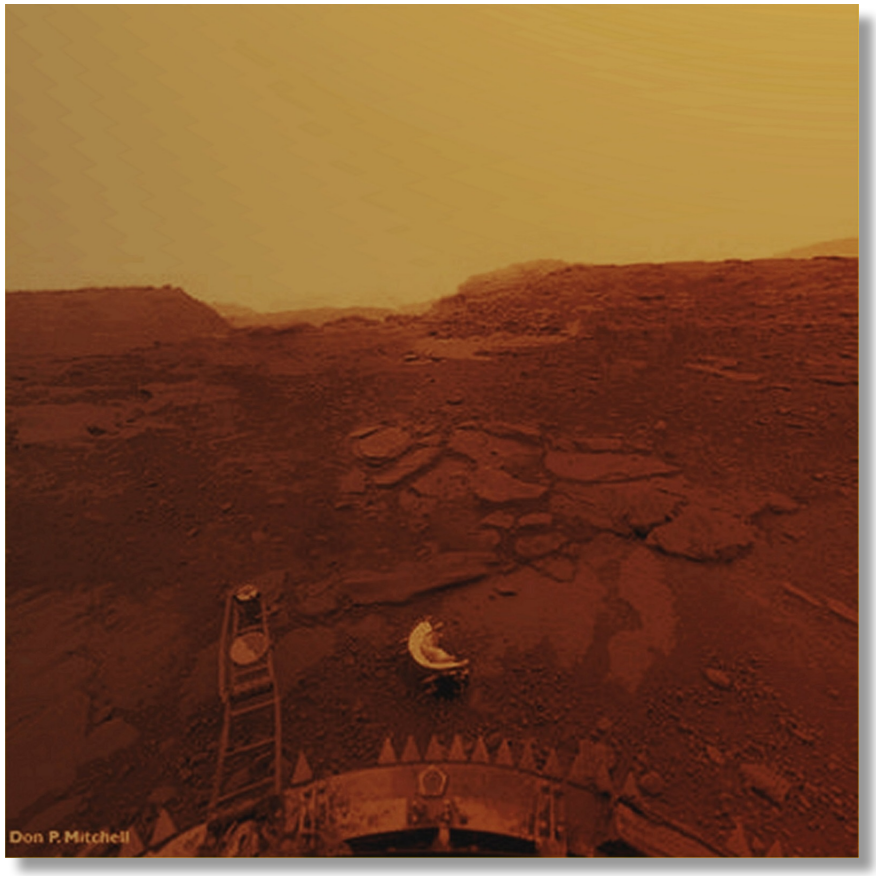
Venus and Earth



Venus today

- Average Surface Temperature: ~ 733 K
- Pressure: ~ 92 bar
- Little seasonal or latitudinal temperature variations
- Very dehydrated: water vapor concentrations ~ 44 ppm *(Bézard et al., 2009)*



Venera 13

Early Venus

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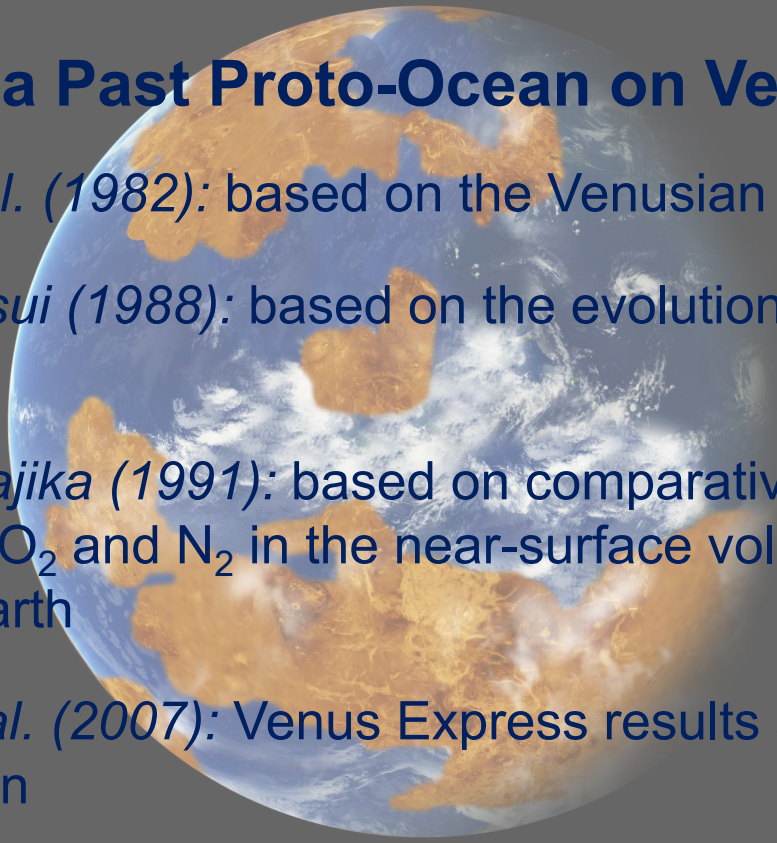
Evidence for a Past Proto-Ocean on Venus:

- *Donahue et al. (1982):* based on the Venusian enhanced D/H ratio
- *Abe and Matsui (1988):* based on the evolution of H_2O-CO_2 atmospheres
- *Matsui and Tajika (1991):* based on comparative analyses of similar amounts of CO_2 and N_2 in the near-surface volatile reservoirs of Venus and Earth
- *Svedhem et al. (2007):* Venus Express results support the notion of an early ocean



How long did the Ocean(s) last on Venus?

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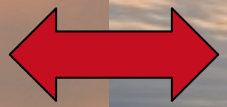
Hydrodynamic escape and a strong solar wind could have eroded the early Venusian ocean very quickly
(Kasting and Pollack, 1983; Donahueand Hartle, 1992; Chassefiere, 1996, 1997a&b; Lundin et al, 2004)



Grinspoon (2004) argues that the ocean(s) could have been present for billions of years.

Catling (2004) scattering by marine stratus clouds could have cooled the surface and delayed the run-away greenhouse effect for long time

Way et al. (2016): climate modeling indicating that oceans might have existed for 2 billion years

A History of Life on Venus?

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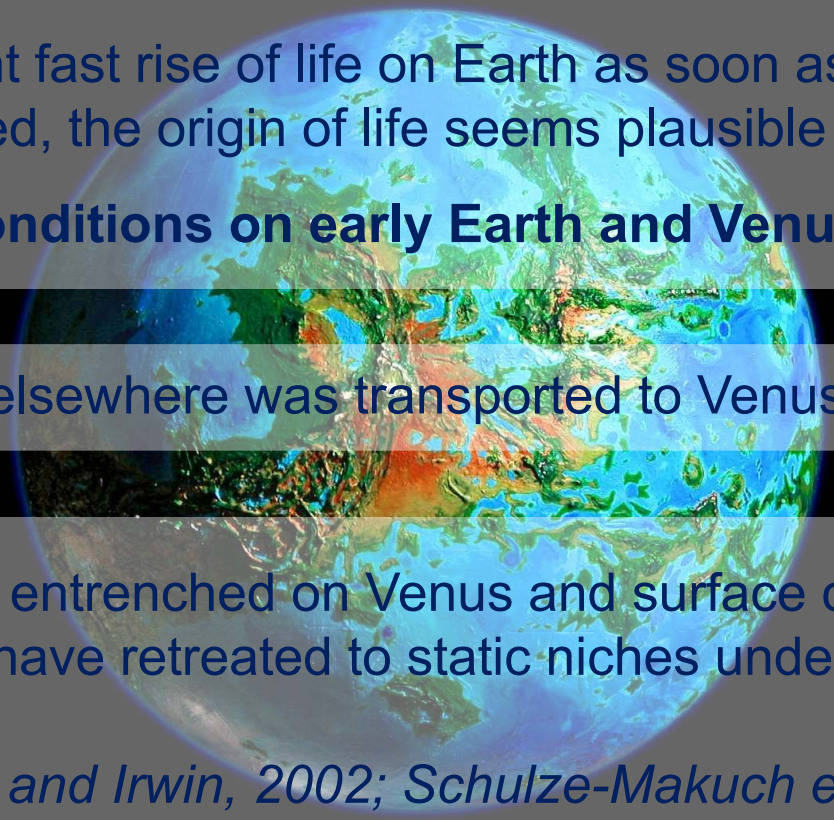

Given the apparent fast rise of life on Earth as soon as favorable conditions prevailed, the origin of life seems plausible

→ **very similar conditions on early Earth and Venus**

Or life originated elsewhere was transported to Venus (Panspermia)

Once life became entrenched on Venus and surface conditions became hostile, life could have retreated to static niches under stabilizing selection
(Schulze-Makuch and Irwin, 2002; Schulze-Makuch et al., 2004, 2013)

The Natural History Evolution of Venus

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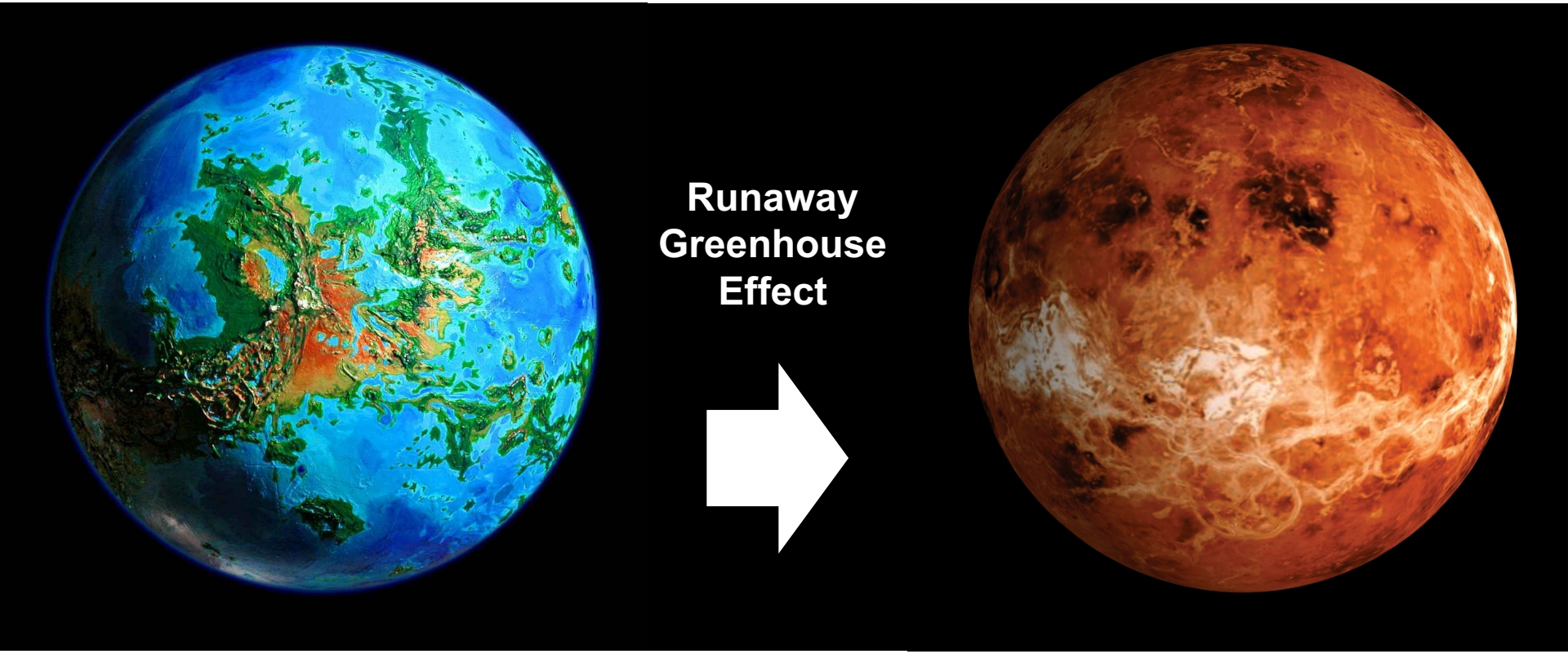

Water and Life ?

Surface: x
Subsurface: x
Atmosphere: ?

Atmospheric Properties

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- Present climate on Venus is controlled by an efficient greenhouse effect and by the radiative properties of its global cloud cover
- The average cloud base is at 48 km, where evaporation of H_2SO_4 occurs *(Bullock and Grinspoon, 2001)*
- Vigorous vertical motions, but not horizontally
- Atmospheric abundances of water, sulfur dioxide, and carbon dioxide change with

(1) exospheric escape of hydrogen
(2) outgassing from the Venusian interior
(3) reactions with surface minerals

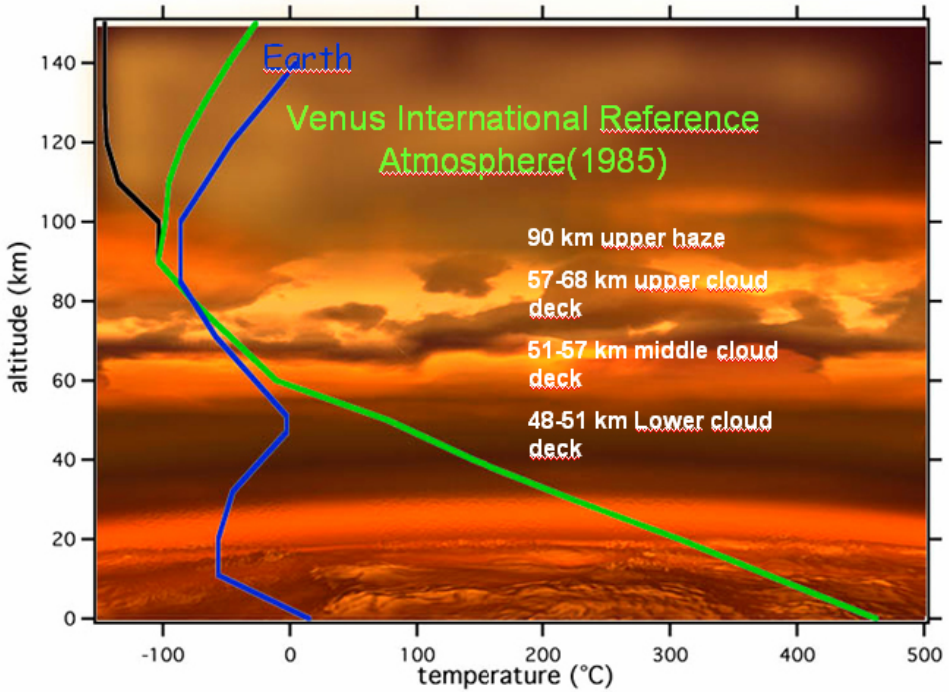
Cloud Particles

The Venusian clouds consist of an upper, middle and lower cloud layer, with the cloud layers including the following particles:

(1) mode 1 droplets (⌀ ~0.13 - 0.2 µm)

(2) mode 2 droplets (⌀ ~1.1 - 1.36 µm)

(3) mode 3 droplets (⌀ ~3.6 µm)



Mode 3 Particles (lower cloud deck only)

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- Photometric measurements from the Venera 9-14 probes: the mode 3 particles are distinctly different in origin from the other cloud particles *(Krasnopolsky, 1986)*
- Mode 3 particles are composed of non-absorbing material coated with sulfuric acid *(Cimino, 1982)* and are non-spherical *(Grinspoon et al., 1993)*
- Detailed infrared simulation indicate that mode 3 particles may be composed of an unknown non-absorbing core material that makes up 50 % by volume of the particles *(Grinspoon et al. ,1993)*

Lower Cloud Deck = Microbial Habitat?

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Pro-Arguments (1/3)

(1) The clouds of Venus are much larger, more continuous, and stable than the clouds on Earth

(2) The atmosphere is in disequilibrium, with H_2 and O_2, and H_2S and SO_2 co-existing

(3) The lower cloud layer contains non-spherical particle comparable in size to microbes on Earth (a few microns), the mode 3 particles are enriched at about 50 km altitude in the cloud layer

(4) While water is scarce on the surface, water vapor concentrations reach several hundred ppm in the lower cloud layer

Lower Cloud Deck = Microbial Habitat?

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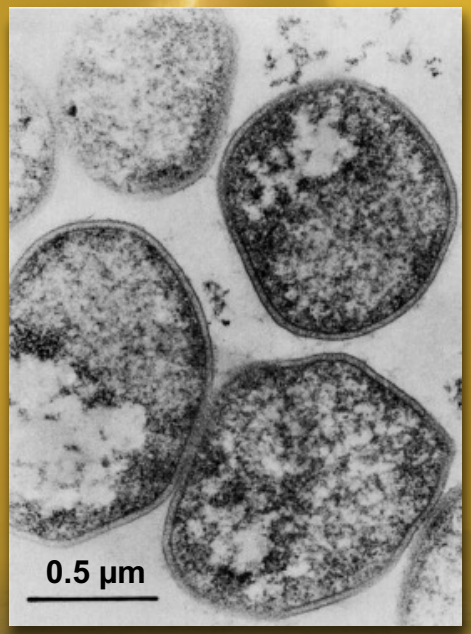
Pro-Arguments (2/3)

(5) Environmental conditions are extreme but manageable:
Temperature 30 – 80 °C; Pressure ~ 1 bar; pH: ~ 0

An example is the extreme thermoacidophile

Acidianus infernus

which grows optimally at 88 °C and a pH from 0.5 - 5.5
(Segerer et al.,1986)



Electron micrograph of a thin section of *A. infernus* *(Segerer et al.,1986)*

Lower Cloud Deck = Microbial Habitat?

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Pro-Arguments (3/3)

(6) The super-rotation of the atmosphere enhances the potential for photosynthetic reactions *(A day-night cycle of 4-6 Earth days compared with 117 Earth days on the surface)*

(7) An unknown absorber of UV radiation has been detected in the Venusian atmosphere

(8) If life arose or was transported to Venus, and gained a foothold, at a time when liquid water was available on the Venusian surface, then descendants of those early forms could have adapted to the increasingly warm, dry, and acidic conditions through directional selection *(Schulze-Makuch et al., 2013)*.

Lower Cloud Deck = Microbial Habitat?

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Counter-Arguments (1/3)

(1) Water is too scarce

The minimum water activity at Venus may be less than 0.6 – too less than for life on Earth

➡ However, Venusian microbes may assimilate water from hydrated sulfur compounds (H_2SO_4 x n(H_2O) or from the atmosphere, similar to the assimilation of carbon from CO_2 by microbes in Earth's atmosphere.
(Schulze-Makuch et al., 2004)

Lower Cloud Deck = Microbial Habitat?

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Counter-Arguments (2/3)

(2) Atmospheric life is not possible; there are no green clouds at Earth

- However, life is occurring in Earth's atmosphere, at least transient, and probably also growing and reproducing *(Dimmick, 1976, Sattler et al., 2001)*.
- The Venusian atmosphere is much more benign for life than Earth's atmosphere. Microbial reproduction cycles are well within the particle residence time of the lower cloud layer.

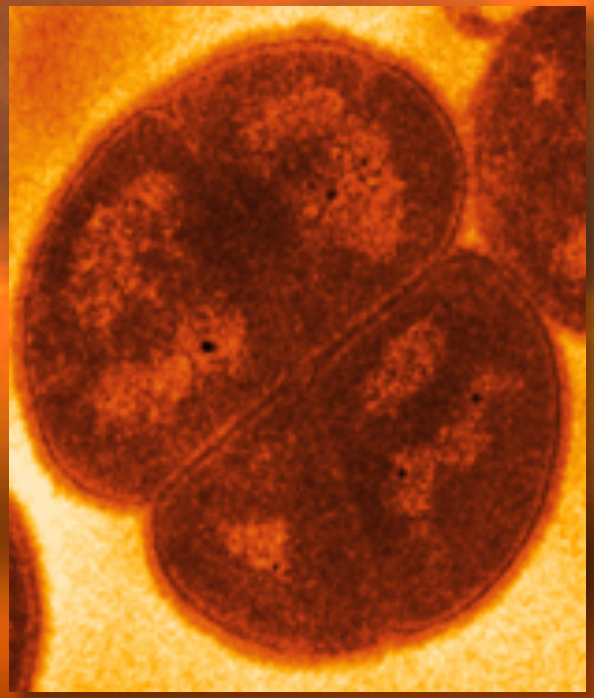
Lower Cloud Deck = Microbial Habitat?

Counter-Arguments (3/3)

(3) The UV radiation is too harmful

➡ Adaptations to UV radiation on Earth:

- Specialized organic pigments
- Multiple copies of DNA, large organelles, large nucleus and thick membrane, DNA in ring-like structure (e.g. *Deinococcus radiodurans)*
- Layer of water for protection
- Use of efficient repair mechanisms



Deinococcus radiodurans (Brookes and Murray, 1981)
(image: www.microbe.org)

Adaptation to UV–Radiation: Venus

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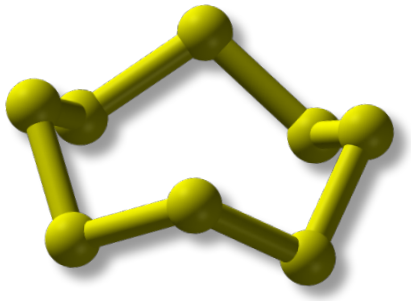
Cycloocta Sulfur (S_8) ?



- Thermally very stable and does not react with sulfuric acid
- Absorbs strongly in the UV wavelengths and re-emits in the visible wavelengths
- Venusian microbes could deposit elemental sulfur on their cell to convert UV radiation to EM frequencies usable for photosynthesis

➡ On Earth, some purple sulfur bacteria deposit elemental sulfur granules inside the cell, while some green sulfur bacteria deposit elemental sulfur granules outside of the cell

(Schulze-Makuch et al., 2004, 2013)

Presence of S8 in the Venusian Clouds

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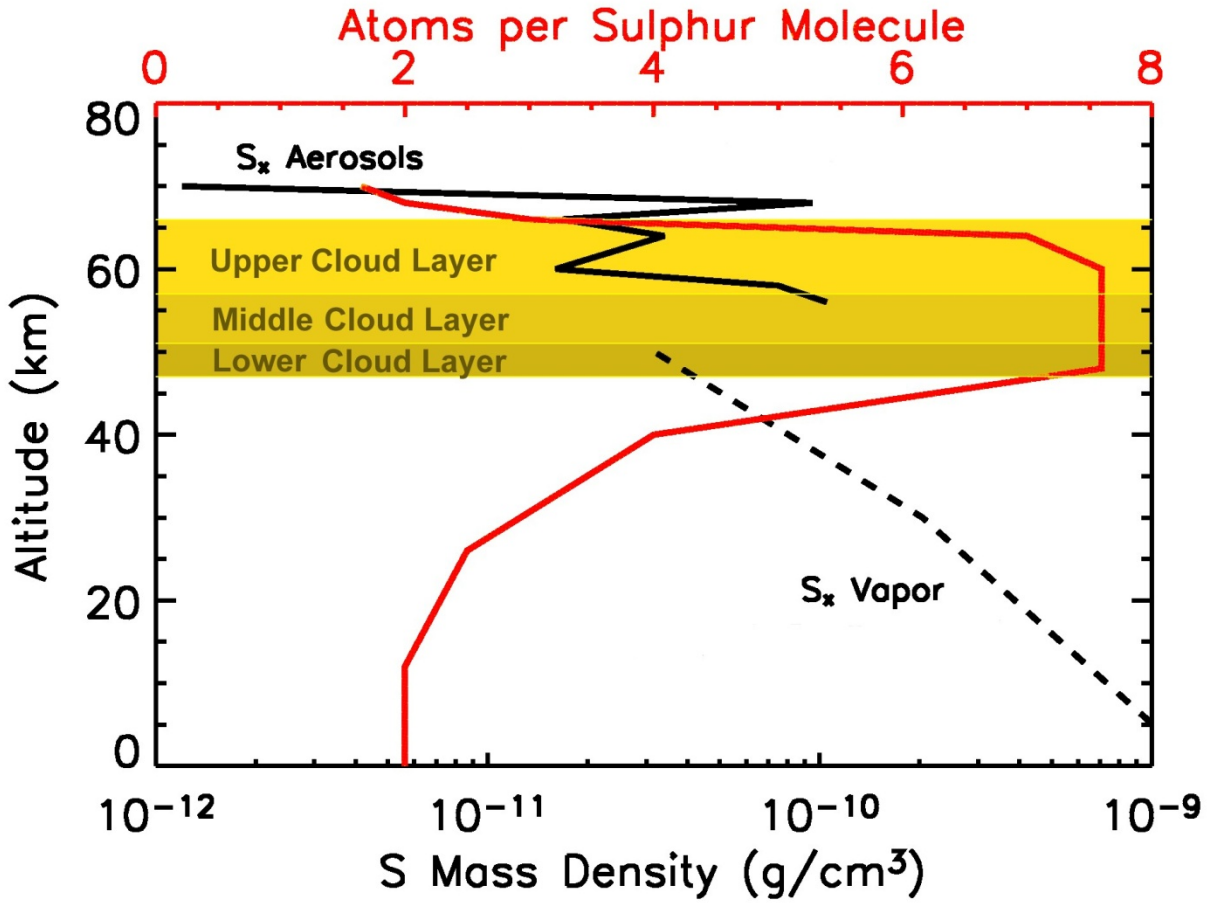

Composite Figure based on data from
Toon et al (1982), San'ko (1980) in Schulze-Makuch et al (2004)

The Venus Express Mission (2006-2014)

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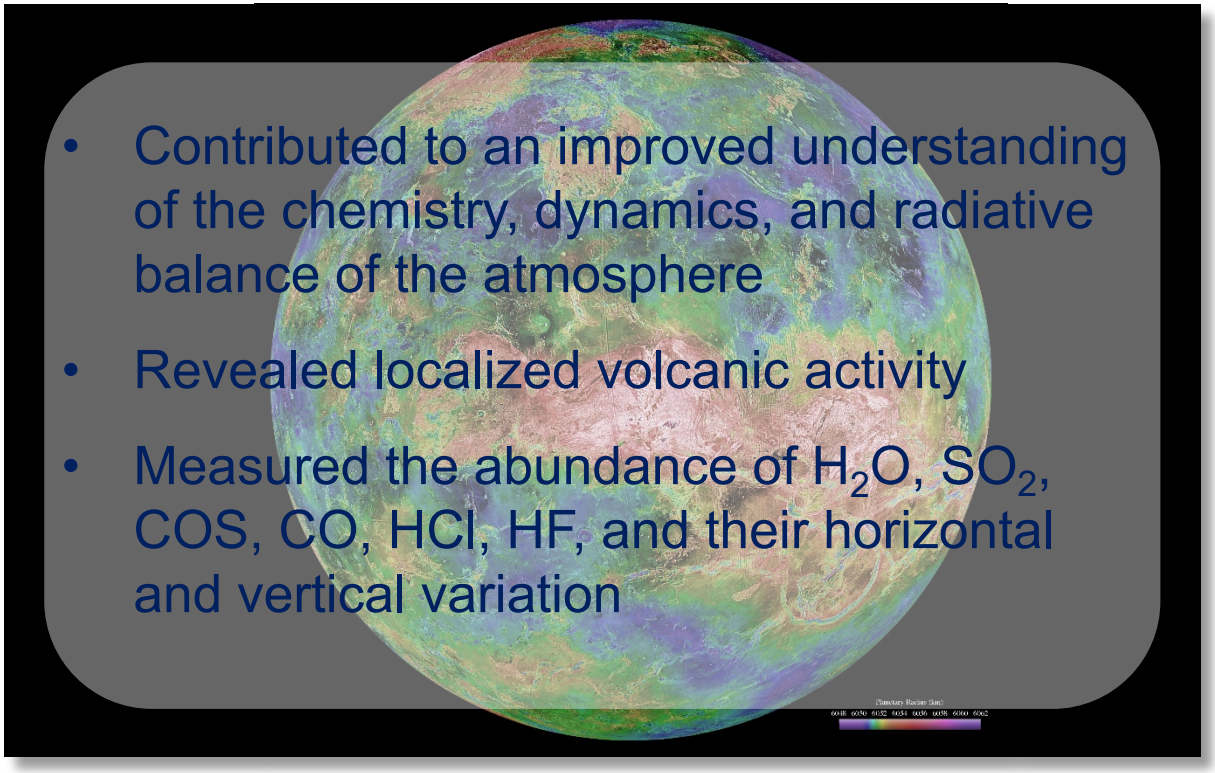

- Contributed to an improved understanding of the chemistry, dynamics, and radiative balance of the atmosphere
- Revealed localized volcanic activity
- Measured the abundance of H_2O, SO_2, COS, CO, HCl, HF, and their horizontal and vertical variation

Venus Express

But the case is likely not settled before the interior of the mode 3 particles can be analyzed

Missing was also: analysis of sulfur isotopes and habitat characterization of the lower cloud deck

Conclusions

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(1) Liquid water and environmental conditions favorable to the origin or transplantation of life existed on early Venus

(2) Once life got established on the surface of Venus, it could have retreated to the atmospheric habitat under directional selection

(3) Life in the lower cloud should in principle be manageable for microbial organisms

(4) The strong UV radiation can be overcome with S_8 as sunscreen and even aid in the conversion of UV to visible wavelengths.
S_8 is present in the atmosphere and can form as by-product of anaerobic photosynthesis, and is precipitated by some purple and green sulfur bacteria on Earth

Conclusions

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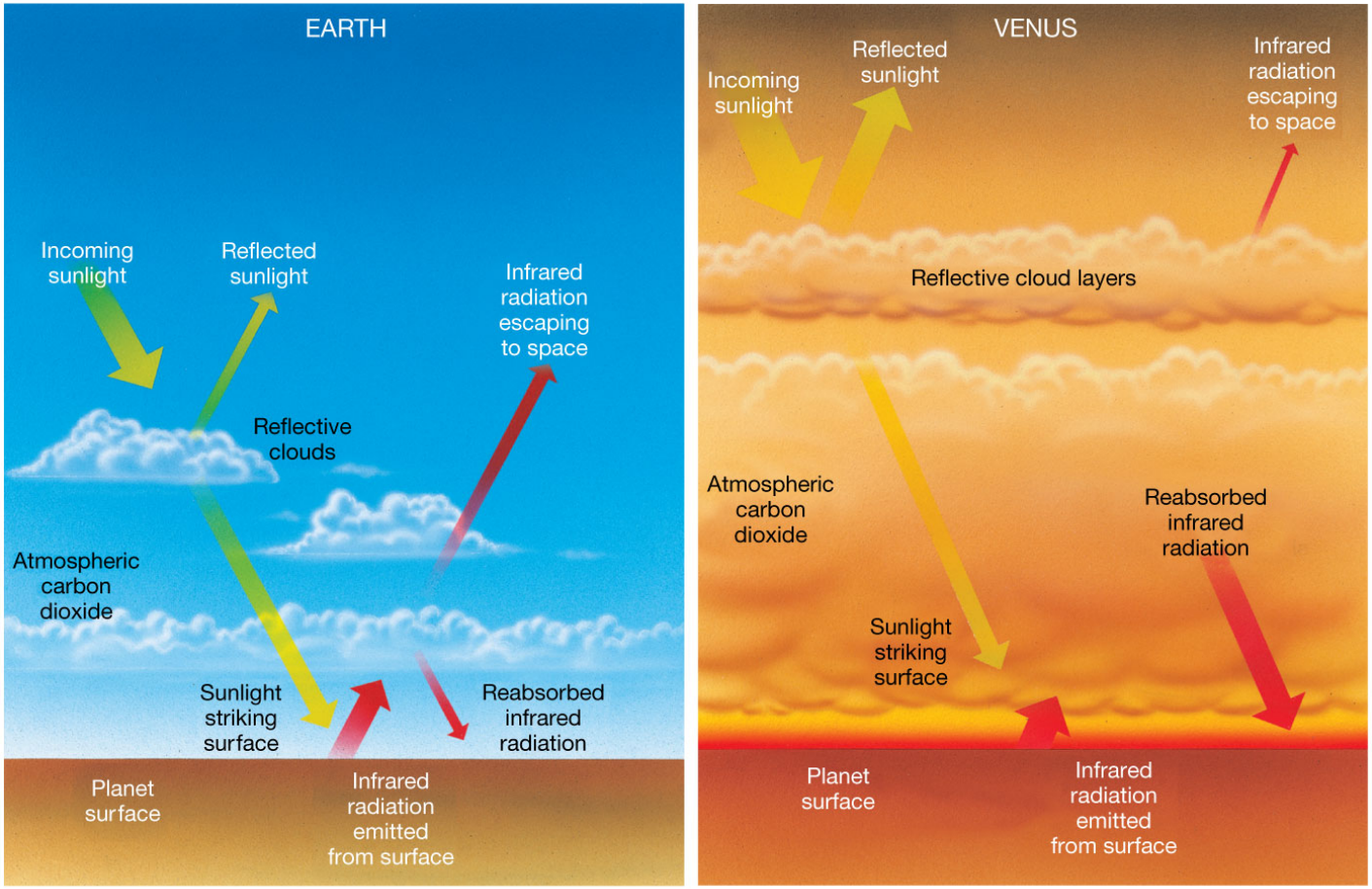
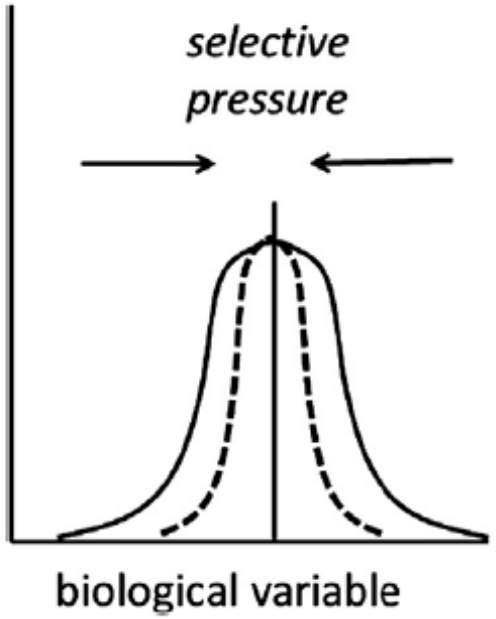
Runaway Greenhouse Effect



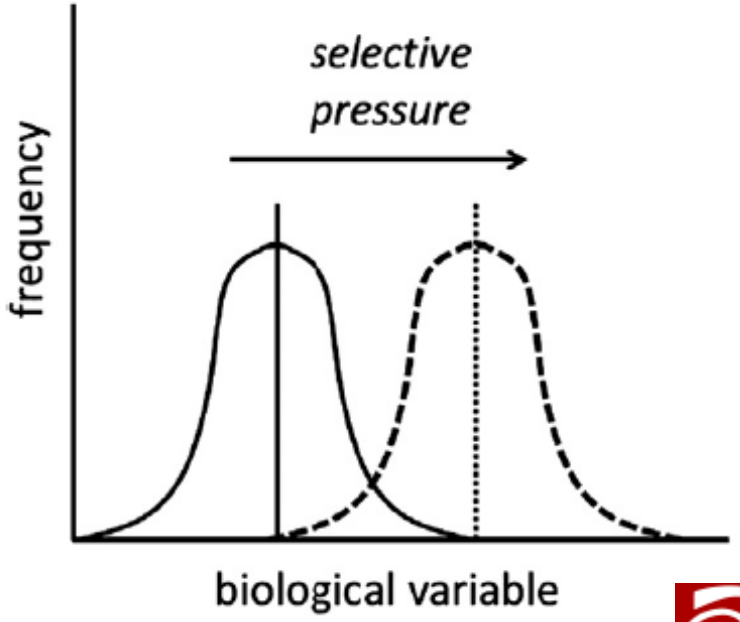
Natural Selection

Effect depends on the nature of the environmental change:

Constant environment
→*STABILIZING SELECTION*



Changing environment
→ *DIRECTIONAL SELECTION*

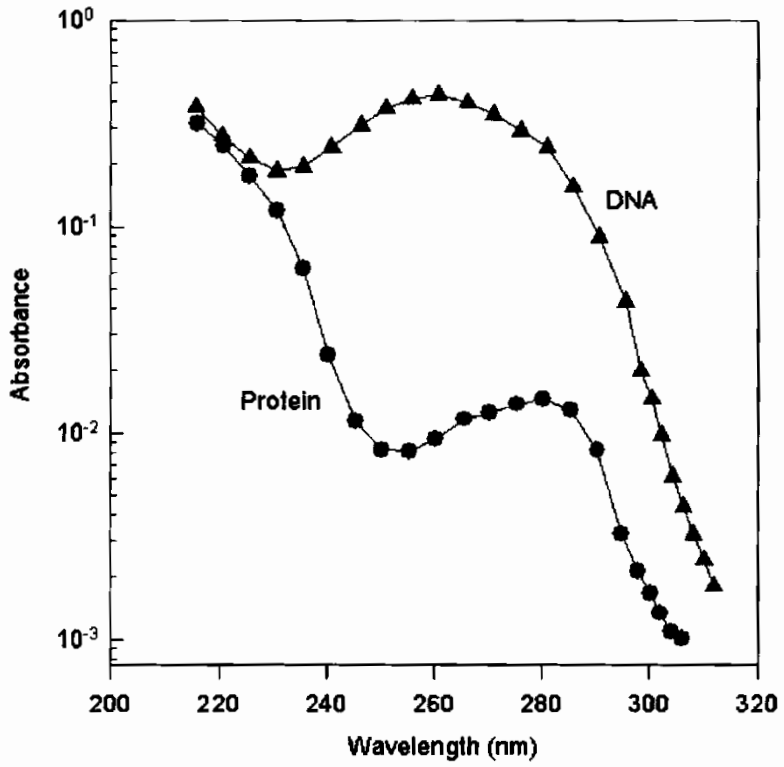


(Schulze-Makuch et al., 2013)

Lower Cloud Deck = Microbial Habitat?

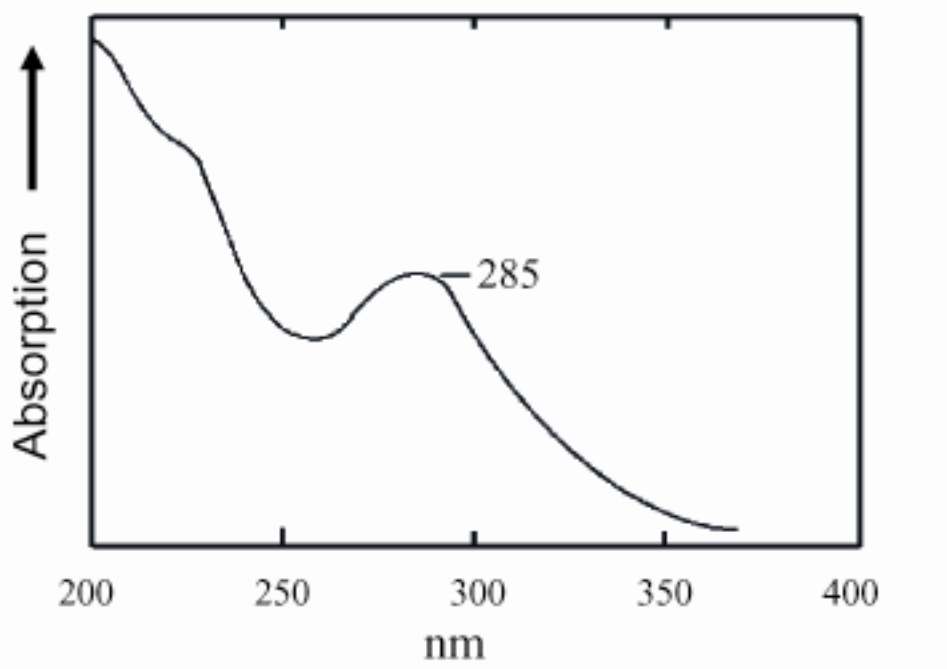
Counter-Arguments (4/4)

(4) The UV radiation is too harmful



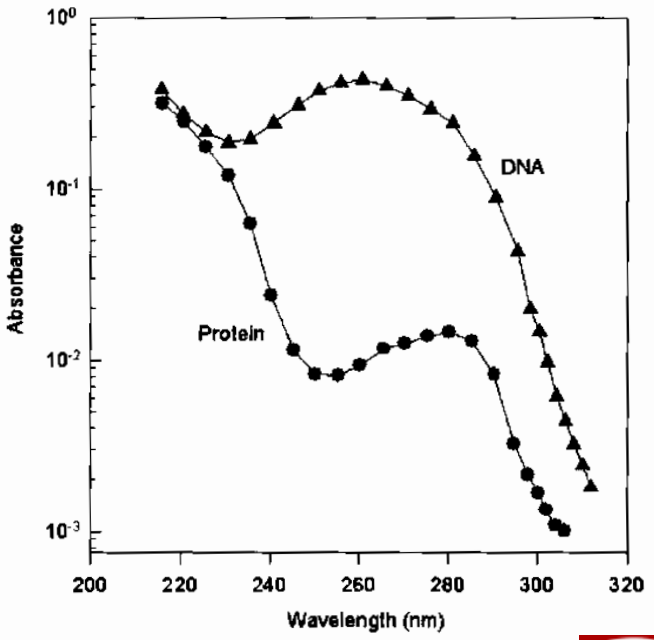
Absorption spectra of DNA and a protein at identical concentrations
(Rettberg and Rothschild, 2002)

UV Absorbance of a thin film of S8 at 298 K



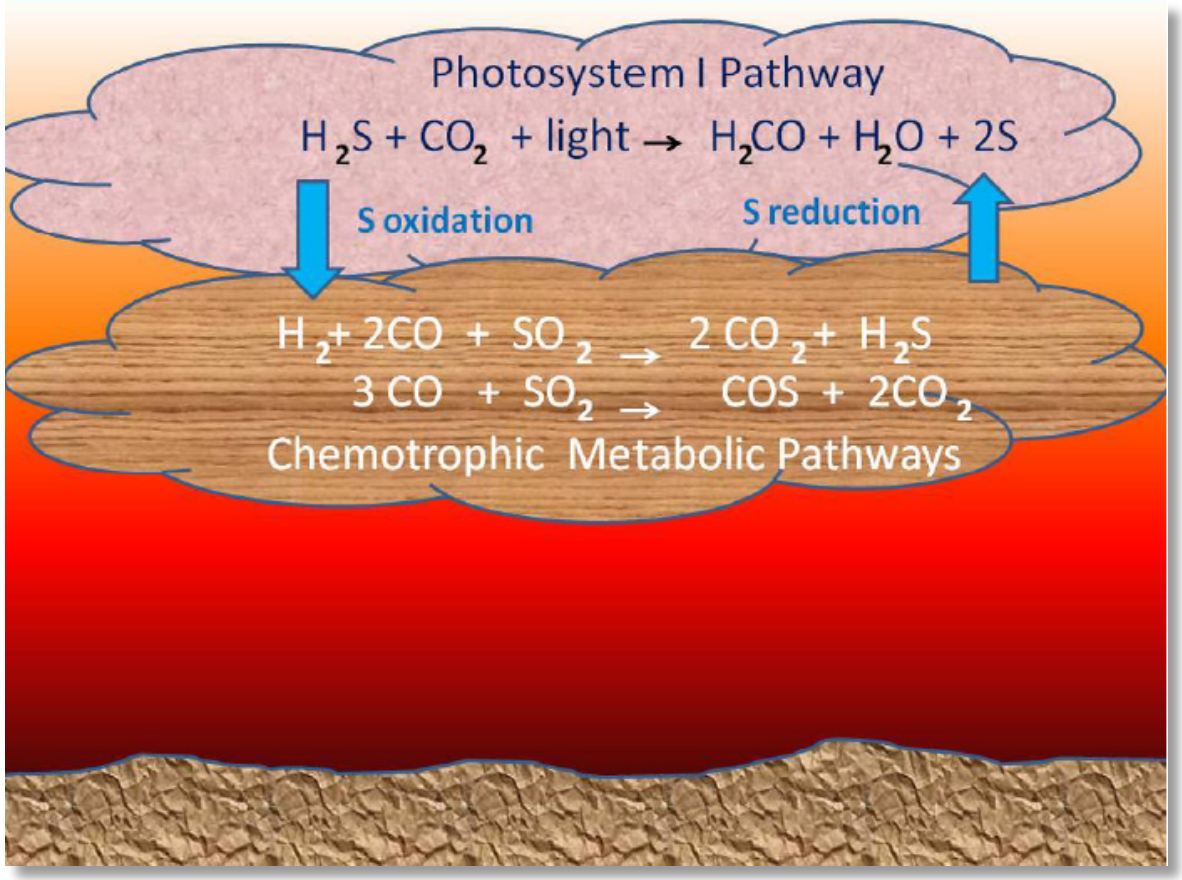
(Clark, 1963)

Compared to DNA and protein absorbance:



(Rettberg and Rothschild, 2002)

Putative metabolic ecosystem in the Venusian lower cloud layer



Schulze-Makuch et al., 2013