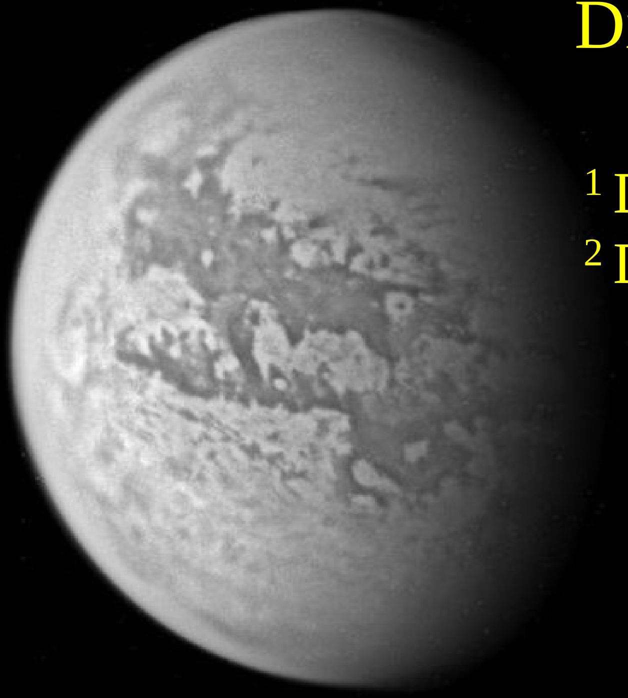
The Possibility of Alien Life in Exotic Forms on Other Worlds

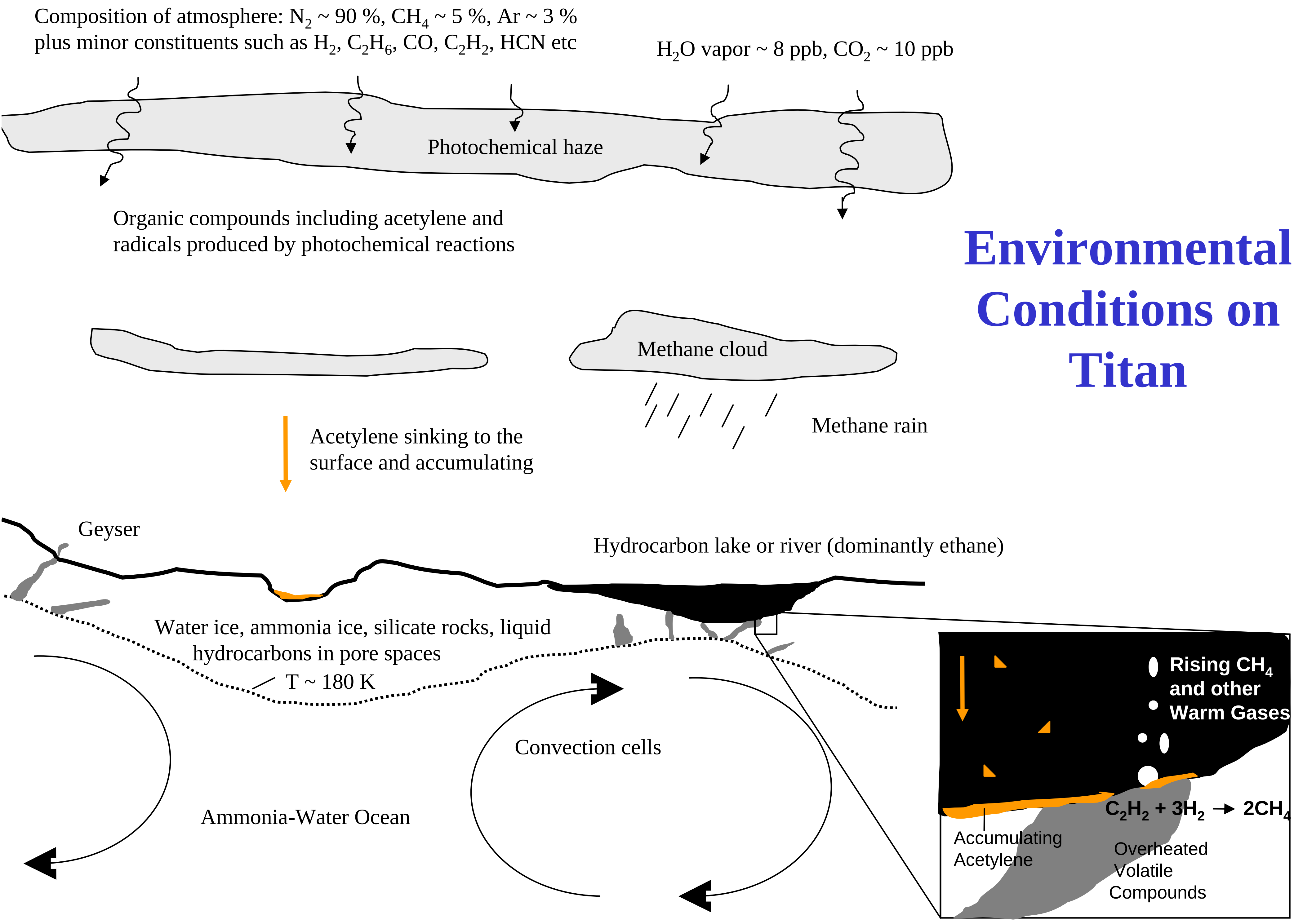
Dirk Schulze-Makuch[1] and Louis Irwin[2]

[1] Department of Geology, Washington State University
[2] Department of Biological Sciences, Univ. of Texas at El Paso



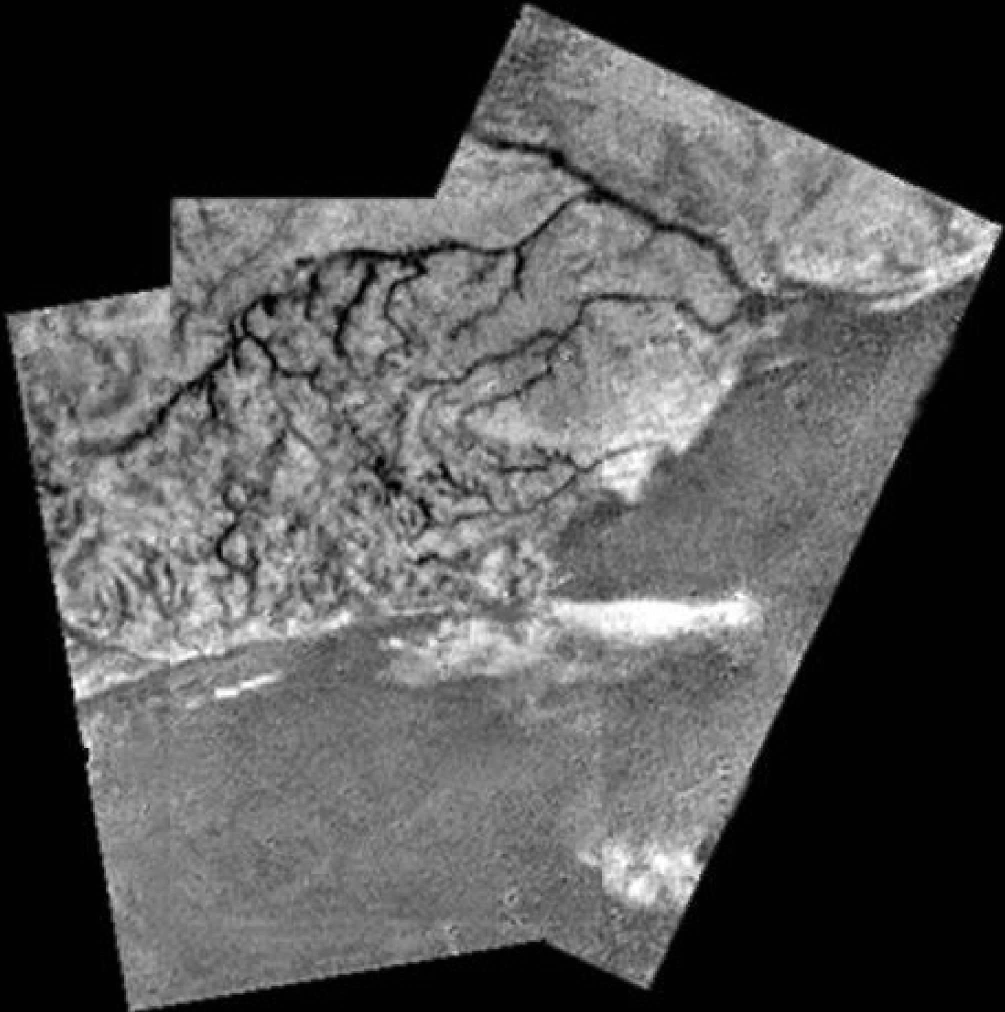
Titan: Some (may) like it cold

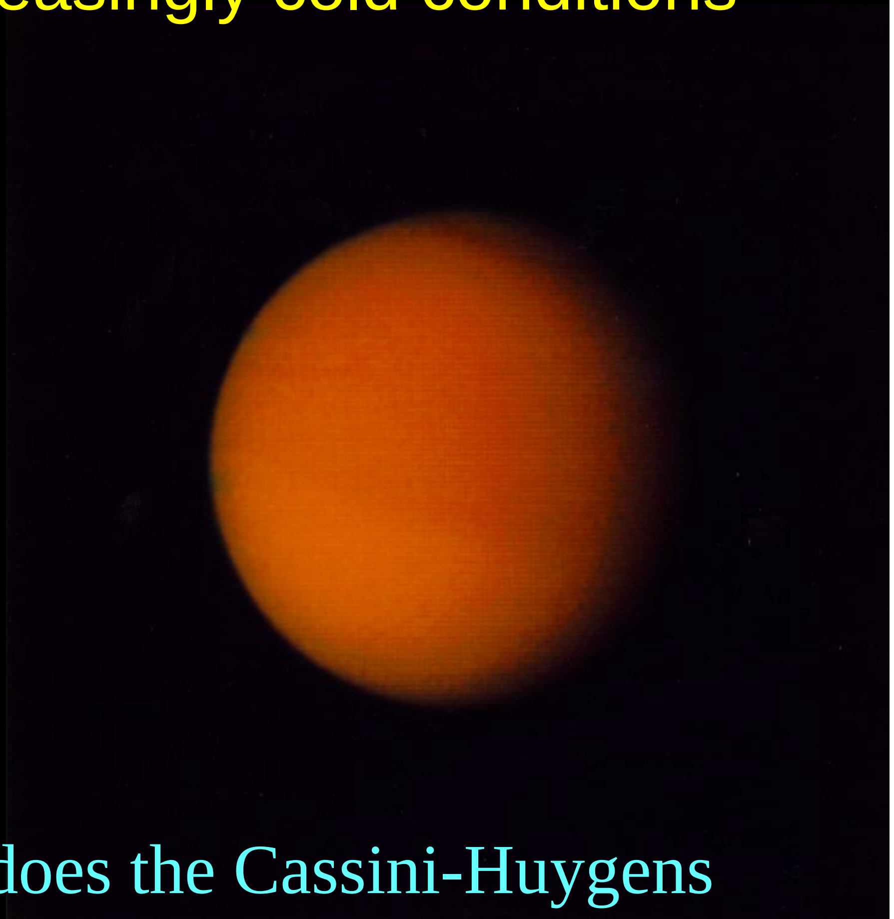
Venus: Some (may) like it hot



Environmental Conditions on Titan
Composition of atmosphere: N_2 ~ 90 %, CH_4 ~ 5 %, Ar ~ 3 % plus minor constituents such as H_2, C_2H_6, CO, C_2H_2, HCN etc
H_2O vapor ~ 8 ppb, CO_2 ~ 10 ppb
Photochemical haze
Organic compounds including acetylene and radicals produced by photochemical reactions
Methane cloud
Methane rain
Acetylene sinking to the surface and accumulating
Geyser
Hydrocarbon lake or river (dominantly ethane)
Water ice, ammonia ice, silicate rocks, liquid hydrocarbons in pore spaces
T ~ 180 K
Convection cells
Ammonia-Water Ocean
Rising CH_4 and other Warm Gases
$C_2H_2 + 3H_2 \rightarrow 2CH_4$
Accumulating Acetylene
Overheated Volatile Compounds

Life may have originated on Titan during its warmer early history and then adapted to cope with the increasingly cold conditions





But, does the Cassini-Huygens Mission support the notion of possible life on Titan?

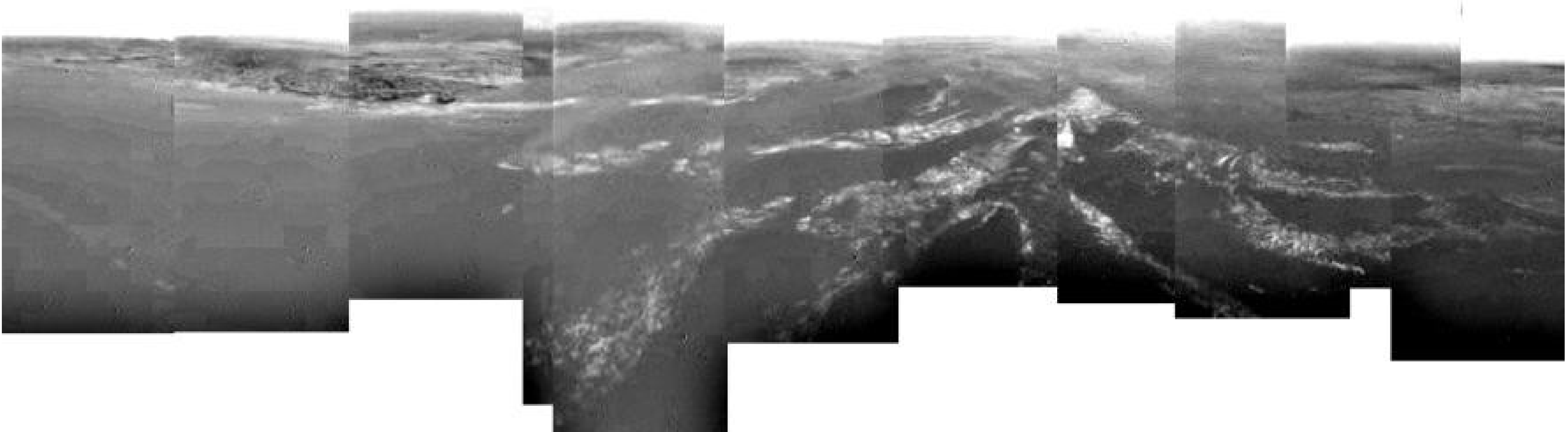
Mission Results in Favor of Possible Life

(1) Titan's smooth surface $\Rightarrow$ endogenic activity

(2) Liquid ethane and methane on the surface

(3) Flow channels $\Rightarrow$ temporary surface liquid (+ near surface reservoirs?)
(dark and bright $\Rightarrow$ ethane/methane and ammonia-water?)

And we know about the presence of many organic compounds….

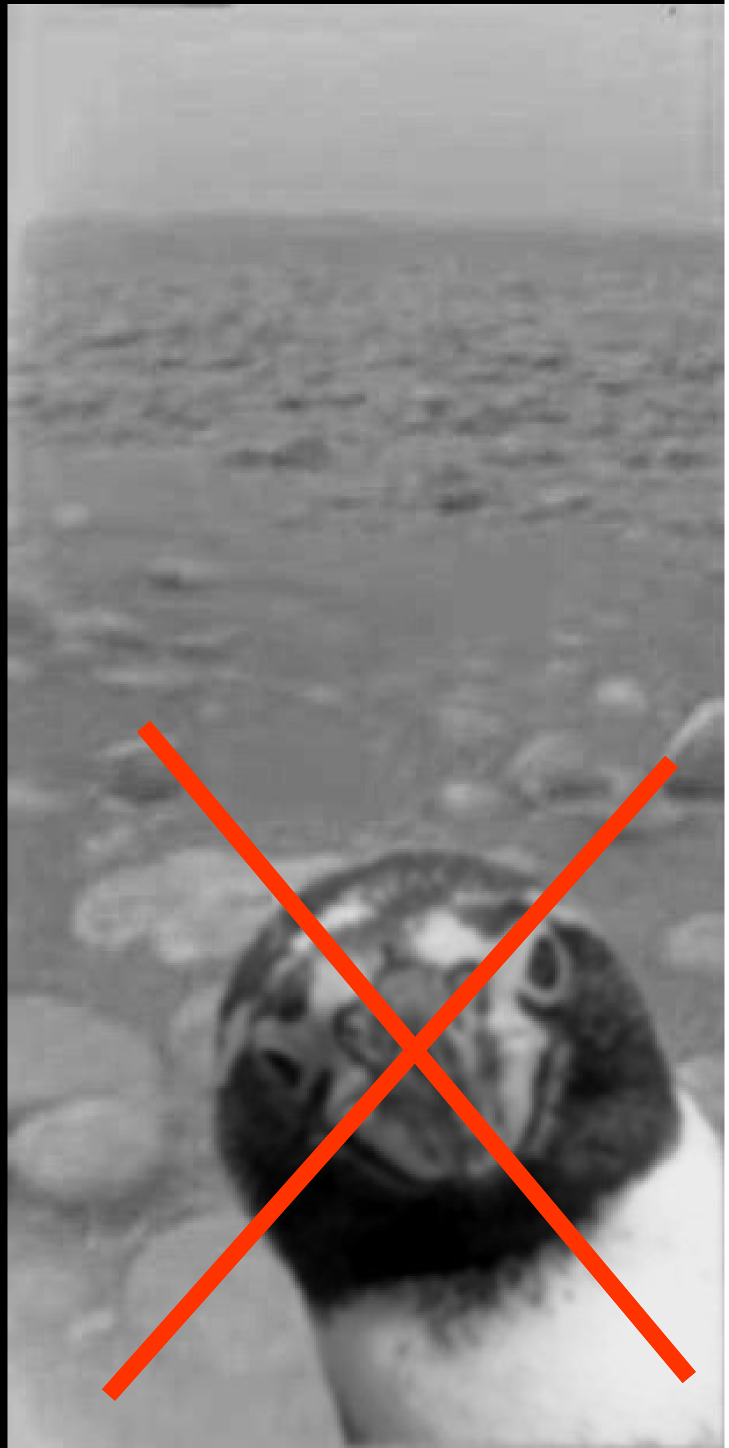


Mission Results Against Possible Life

- Absence of any large standing surface liquids
  (e.g. latest discovery of dunes by Lorenz et al.,2006)

- Carbon isotope fractionation rate as from Huygens GC/MS

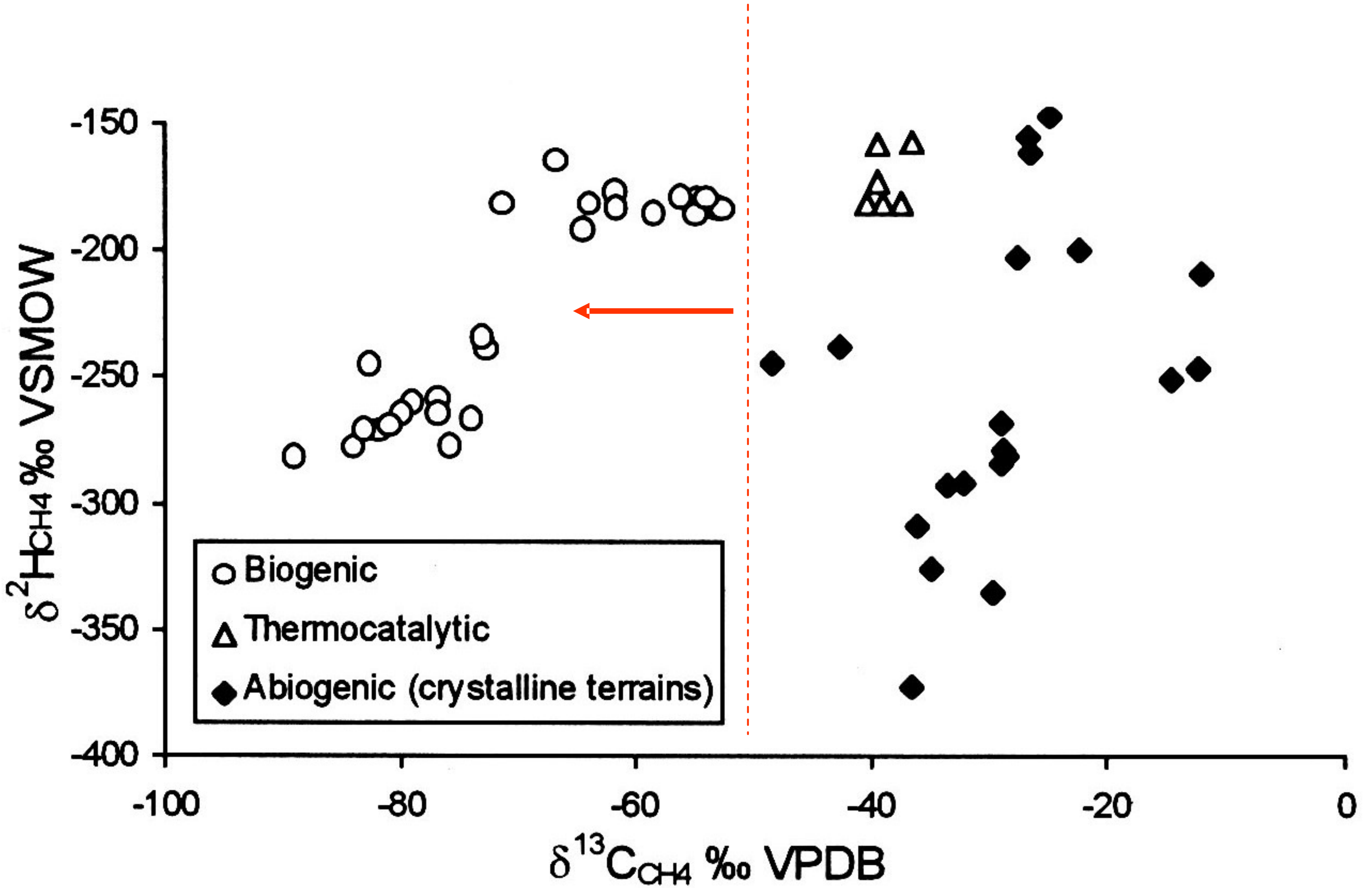
However, the carbon isotope fractionation rate is far from conclusive



The Argument Against Possible Life
(e.g. Niemann et al., 2005)

$^{12}C/^{13}C$ Titan by Huygens GC/MS:	82.3 +/- 1
Solar $^{12}C/^{13}C$ ratio **(Anders and Grevesse, 1989)**	89.91
Inorganic Earth Rocks (**Eichmann et al., 1997: δ -3.6 to -9 ‰**)	~ 90.4
Biological Fractionation consistent with methanotrophic affiliation of Archaea on Earth) **(δ ~ -37 ‰)**	~ 93.4
Typical bacterial methanogenesis **(δ = -60 to - 90‰)**	> 95

Typical Methanogenesis



Origin of methane in water from many sources (Clark and Fritz, 1997)

What is Wrong with this Interpretation?

Too simplistic:

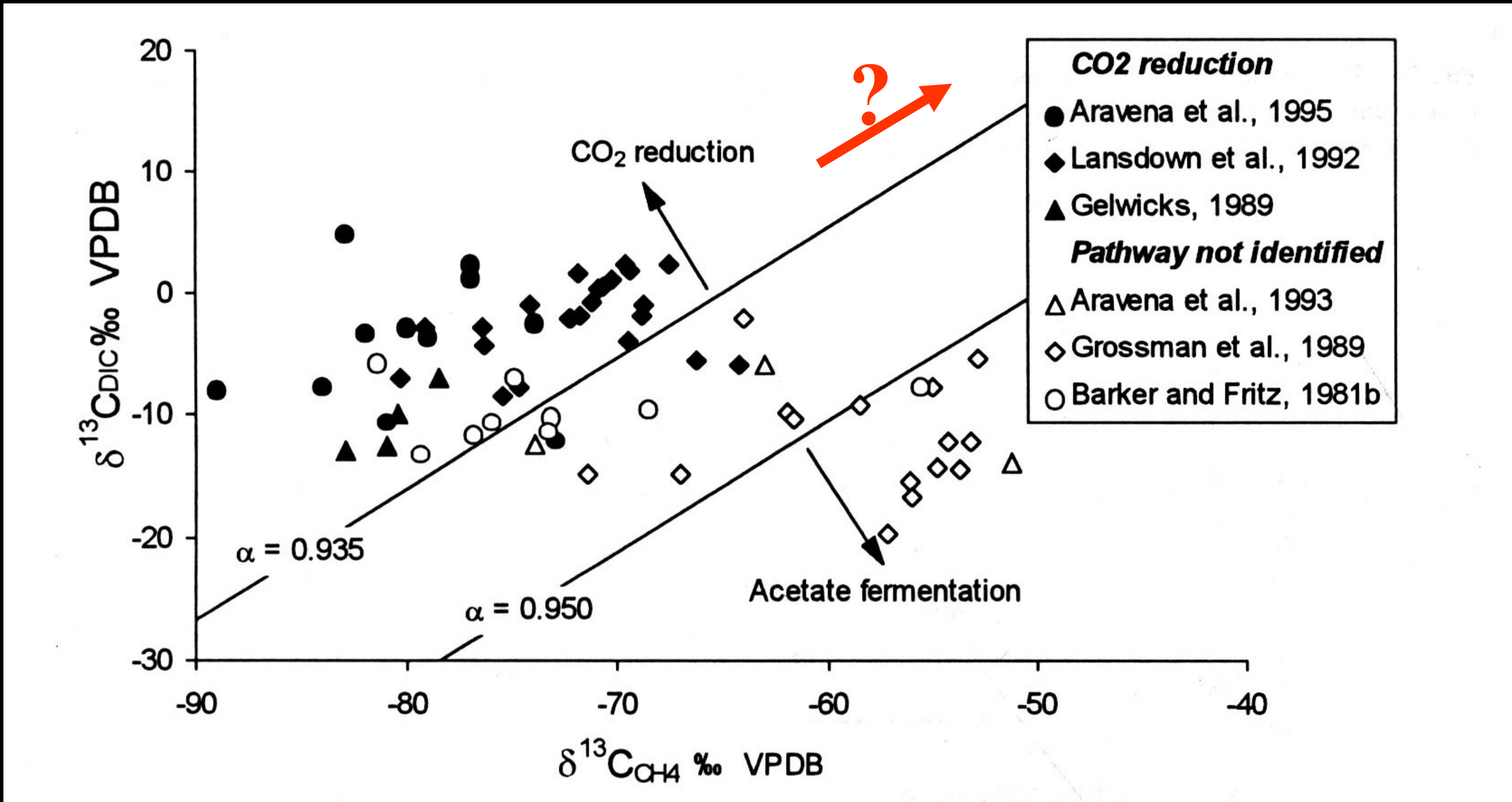
1. **The educt is greatly enriched by photochemistry, as suggested by $^{14}N/^{15}N$ isotope ratio of 183 ± 5** **(Niemann et al., 2005)**

2. **Independent origin and different biochemistry ⇒ "exotic" life , hence may not follow Earth isotope fractionation rules** (e.g. Archaea vs Bacteria)

3. **$^{12}C/^{13}C$ isotope ratio of 95 ± 1 in upper atmosphere** **(Waite et al. 2005 with the Cassini INMS instrument)**
   ⇒ ***we don't understand the processes involved***

Most of All: The Educt Problem?

If methanogenesis is occuring on Titan, photochemistry would ↑ ^{13}C isotopes; and this would affect the $^{13}C/^{12}C$ ratio of the product, methane



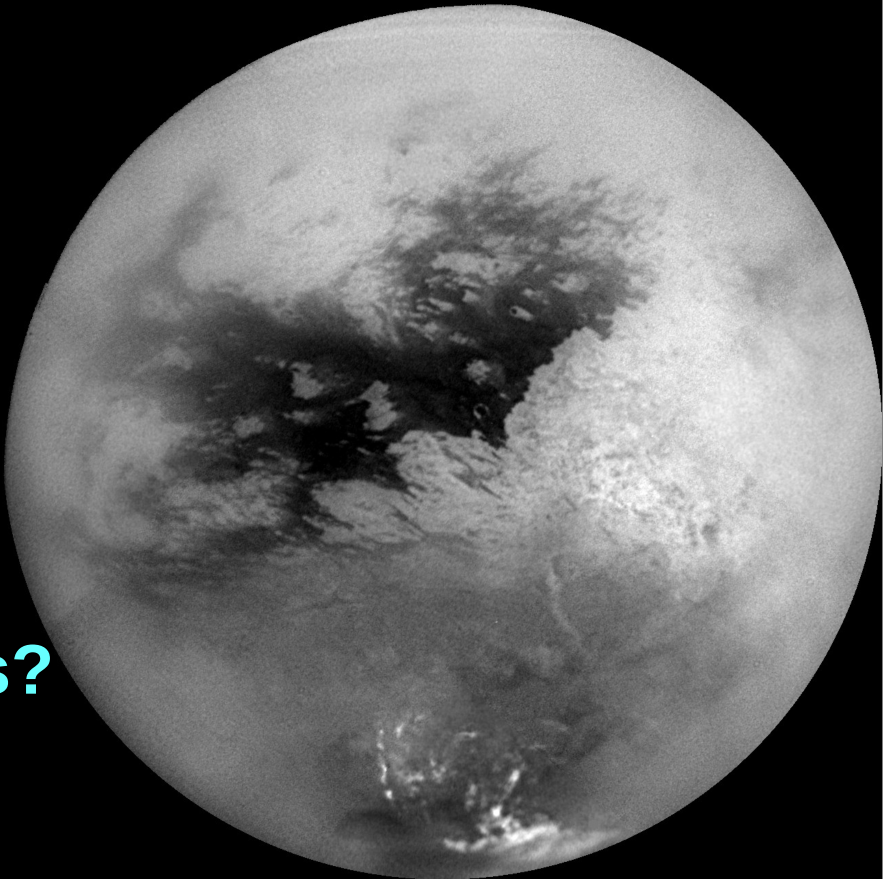
The $\delta^{13}C$ composition of biogenic methane. Notice the fractionation lines!

Our Recommendation

- Determine $^{13}C/^{12}C$ ratios of possible educts

- Quantify extent of carbon photochemical fractionation to resolve whether Titan's methane falls within fractionation lines from methanogenesis on Earth

What could be some of these educts?



We have suggested other possible metabolisms

(e.g. Schulze-Makuch and Grinspoon, 2005, in *Astrobiology*)

Catalytic hydrogenation of acetylene

$$C_2H_2 + 3H_2 \rightarrow 2CH_4 \qquad \Delta G = -107.7 \text{ kJ/mol} \qquad (1)$$

supported by:

- atmospheric CH radicals —*photochemical* produced acetylene
- abundant atmospheric H_2
- continuous methane (should be destroyed within ~ 10^7 years)

Example 1 of Exotic Life:

Metabolic Pathways involving Radicals

CH_2 radical + N_2 radical $\rightarrow$ CN_2H_2 (2)

2 CH radicals + N_2 radical $\rightarrow$ 2 HCN (3)

All reactants have been detected in Titan’s environment

Metabolic Pathways Involving Radicals

On Earth, reactions involving radicals

- are difficult to control
- cause internal damage to the organisms

- But on Titan at < 100 K, these reactions
  - may be controllable
  - proceed at a reasonable pace
  - may constitute feasible energy-yielding reactions

- Note that reactions (2) and (3) produce biologically important cyanamide and HCN

Methane Metabolism and Biomass Calculations

1. Methane highly reactive -- photolyzed in Titan's atmosphere by solar UV radiation over short time scale of ~10^7 years (Lorenz, 2000)

2. Methane should be lacking, unless re-supplied

3. But methane conc. of ~ 5 % is observed.

4. Assuming a biogenic formation of methane, 2.2×10^{21} kJ are produced over 10 Myr to keep observed [methane] constant.

5. Estimated free energy of formation for one unit carbon formula weight (UCFW = 24 g/mol) for the yeast *Saccharomyces cerevisiae* = 76.89 kJ (Battley, 1987), => 3.2 kJ/g

Methane Metabolism and Biomass Calculations *(cont.)*

6. Biomass turnover of 6.8×10^{13} g/year would keep [methane] stable (1 year assumed due to slower kinetics in cold environment).

7. Typical size of microorganisms on Earth $\Rightarrow$ dry mass of 2×10^{-14} g (Whitman, 1998). Spread evenly over upper 1 m of Titan's surface => ~ 4.1×10^{13} microbes / m^3 (comparable to a slightly nutrient deprived environment on Earth).

8. Since cells may be larger (cold and hydrophobic solvent), cellular densities could be lower, but biomass densities may be the same or even larger.

9. Also, since organisms would likely not be evenly distributed, some local habitats would be highly populated, while plain surface ice would be very sparsely populated if at all.

Biothermal Melting?

What percentage of metabolic energy might go into keeping ammonia-water liquid?

Where energy is plentiful but liquid is rare, it may be beneficial to use energy for melting.

(Like recycling waste heat of car engine into interior of car for heat.)

Where energy is plentiful but liquid is rare, natural selection may favor organisms that can melt their surroundings.

(Schulze-Makuch and Grinspoon, 2005)

Could Biological Heating Contribute to Melting in Cold Places?

<u>Examples</u>: Glacial melting by algal metabolism. Marine microorganisms contribute to melting of Arctic pack ice. Microbial colonization in cryoconite holes on glaciers, and in basal glacial melt waters (some of which release CH_4).

Apparent youth and smoothness of Titan's surface and likely evidence for active cryovolcanism, is "surprising" (Stofan et al. 2005)…

…or not (Lunine, 2005 and earlier)

Biothermal Heating Calculations

1. Energy needed for melting = heat capacity of the water-ammonia mixture + enthalpy = 11.5 kJ/mol (T_{Titan}=94 K, $T_{NH3\text{-}H2Oeutectic}$=175 K)

2. Energy gain from $C_2H_2 + 3H_2 \rightarrow 2CH_4$ = ~ 100 kJ/mol
   S. cerevisae would need 76.89 kJ/mol;
   the rest could go to melting the surrounding ice.

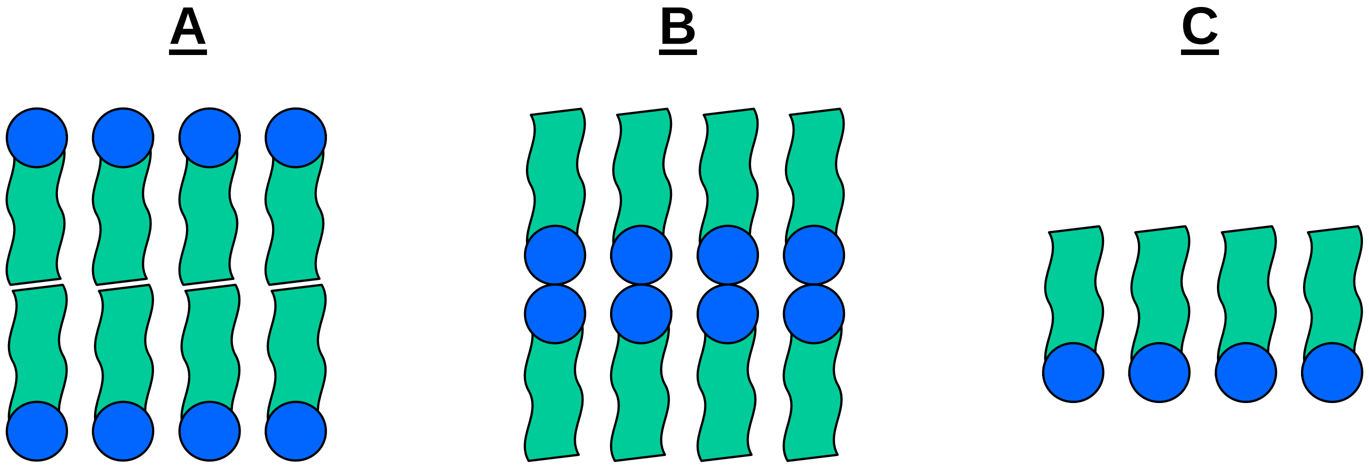
3. Assuming 2.2 x 10^{21} kJ of biological energy was produced / 10 million years to keep the observed methane constant, the remaining energy could melt 7.9 x 10^{10} kg of water-ammonia ice per year.

4. *Thus,* Biothermal Heating is a possible process.

<u>Example 2 of Exotic Life</u>:

Alternative Cell Boundaries

- In a water-ammonia mix, bi-lipid layers, hydrophilic heads toward outside(**A**).



- In organic solvent (ethane or methane), bi-lipid layers, hydrophilic heads toward inside (**B**).

- Or an ampophilic monolayer separating hydrophobic outside (ethane or methane), from hydrophilic (water-ammonia) inside (**C**).

Example 3 of Exotic Life: Silicon Biochemistry

- Membranes could incorporate silanes as building blocks.
- Silanes are liquid while polysilanes are solid at Titan surface conditions (Table 1).

Table 1. Melting and boiling points of some silanes

Physical Property	SiH_4	Si_2H_6	Si_3H_8	n-Si_4H_{10}
Melting Point ($^oC/^oK$)	-185/88	-133/140	-117/156	-90/183
Boiling Point ($^oC/^oK$)	-112/161	-14.3/259	53.1/326	108/381

Also, Bains (2004) suggested the possibility of photosynthesis based on silicon (bio)chemistry:

- sp3 silicon can delocalize electrons via s-orbital overlap
- Electron delocalization could therefore occur readily in appropriate silicon compounds
- Light- activated electronic effects (basis of photosynthesis) could also occur.
- Layered silanes, $(SiH)_n$, are electroluminescent.

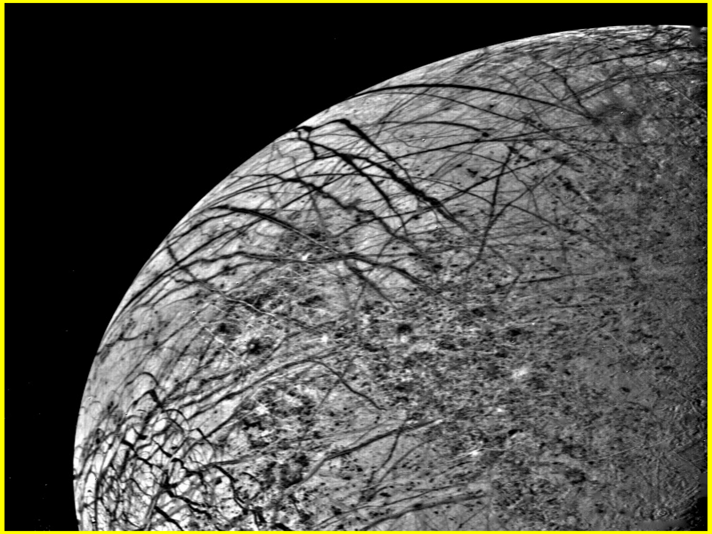
Example 4 of Exotic Life:

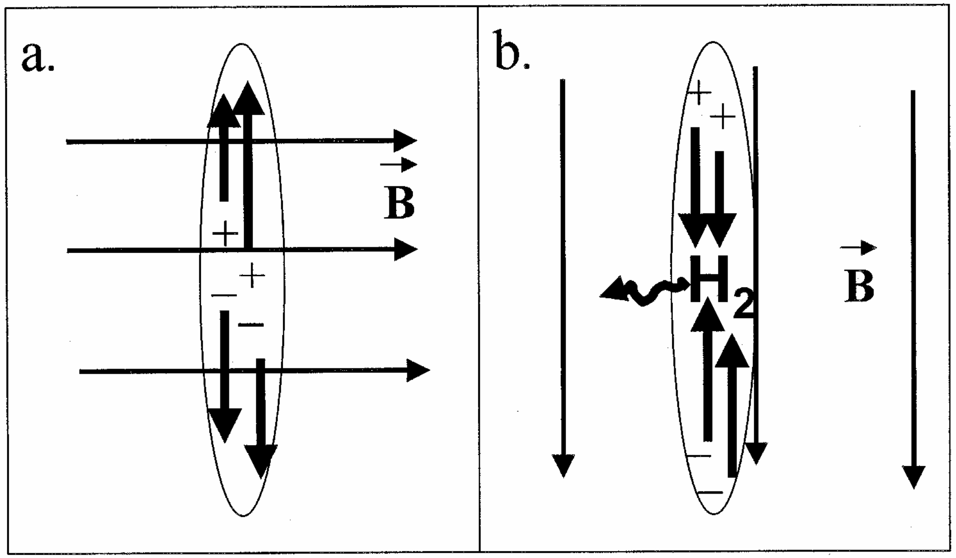
Alternative Energy Sources for Life

On Earth, only chemical and light energy are utilized as biological energy sources. But this may be so, because under Earth conditions these energy sources are readily available and accessible.

In putative subsurface liquid reservoirs of Titan (and Europa for example), light is not available, so other energy sources must be be utilized.

Europa





a. Lorentz force separates protons and electrons,
b. Microbe orients itself parallel to magnetic field lines
c. protons and electrons form molecular hydrogen: energy is harvested

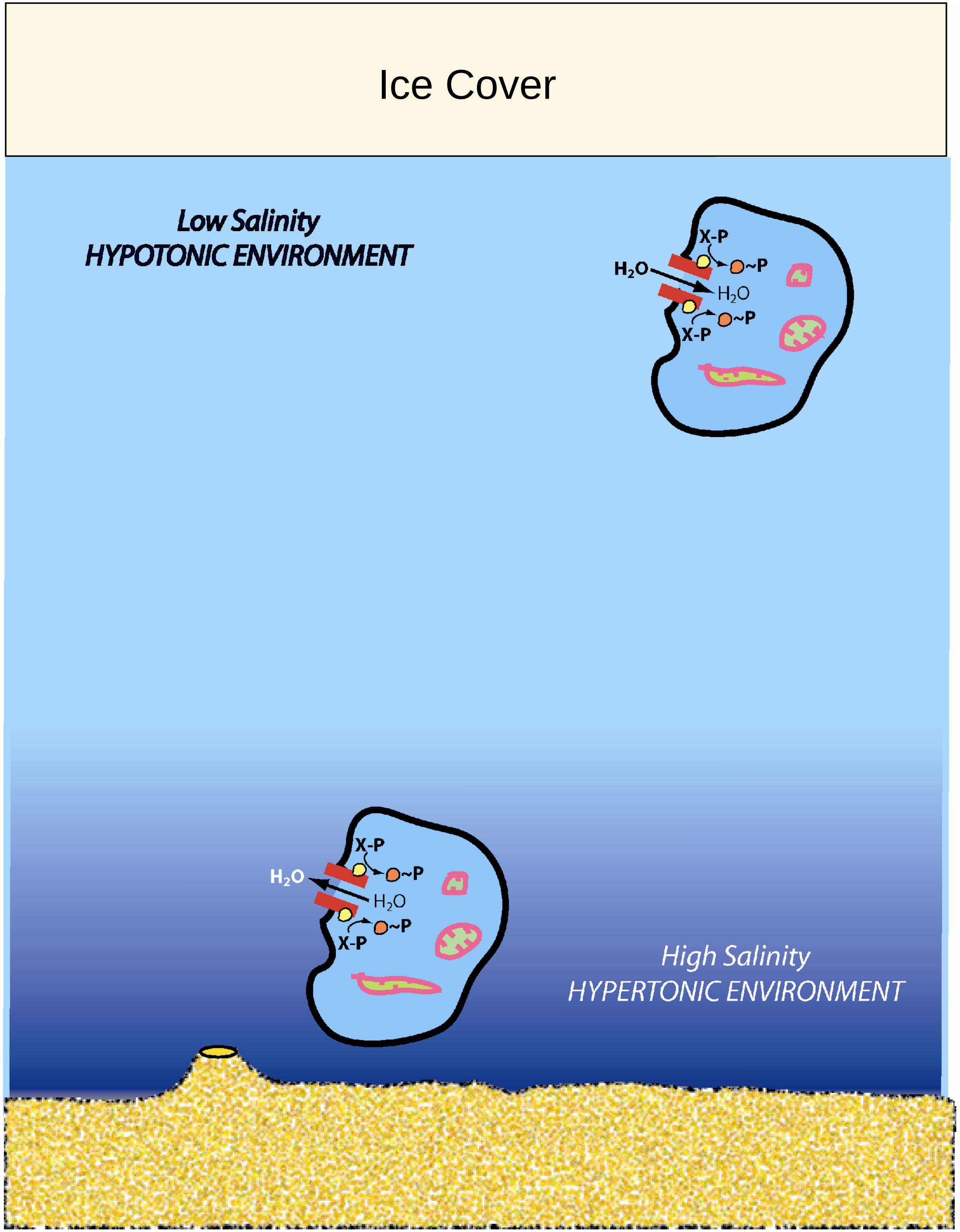
(from Schulze-Makuch and Irwin 2004)

Or,

Osmotrophism?

Osmotrophs could harvest energy from salinity gradients, by coupling water flux to a reaction that forms a high-energy covalent bond (~P) by a membrane molecular complex

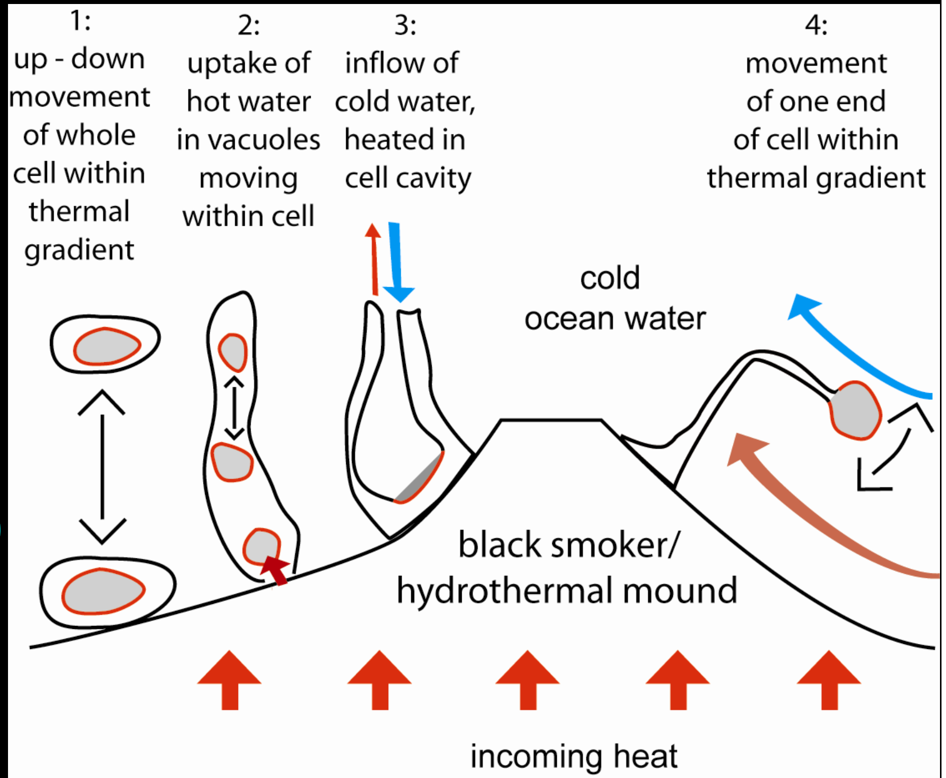
(Schulze-Makuch & Irwin, 2006)



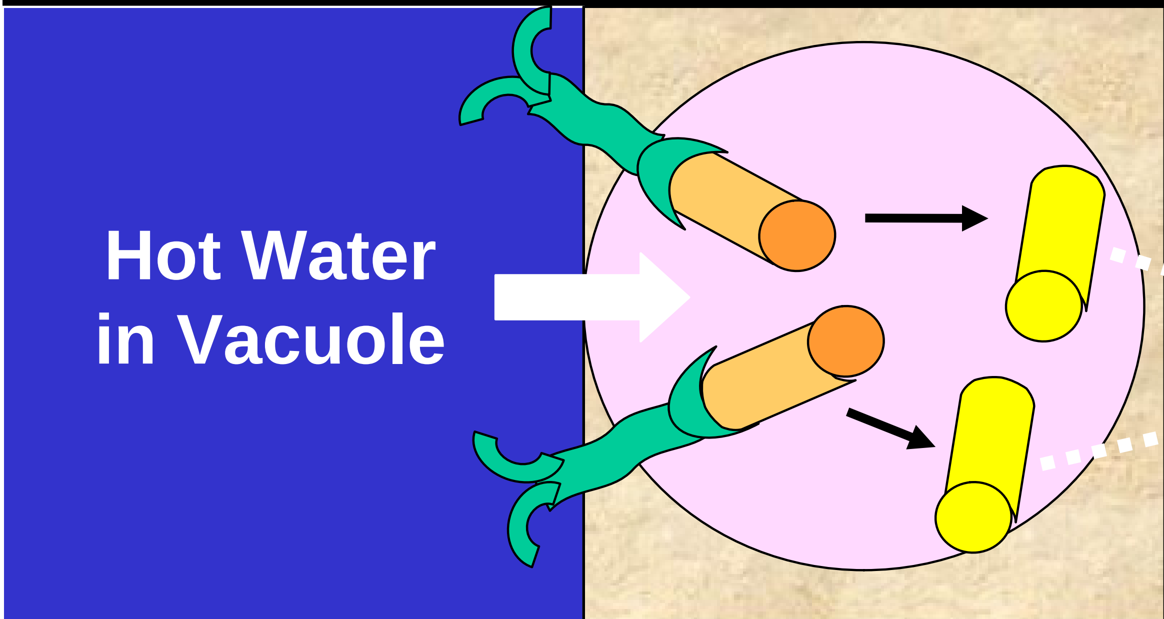
* **Using thermal gradients via the process of thermosynthesis**
(for more info see paper in *OLEB* by Muller and Schulze-Makuch, 2006, on "Thermal Energy and the Origin of Life")

Or,

Thermal Energy?



* **Using the high heat capacity of water and conformational changes**
(e.g., Schulze-Makuch and Irwin, 2002, 2004)



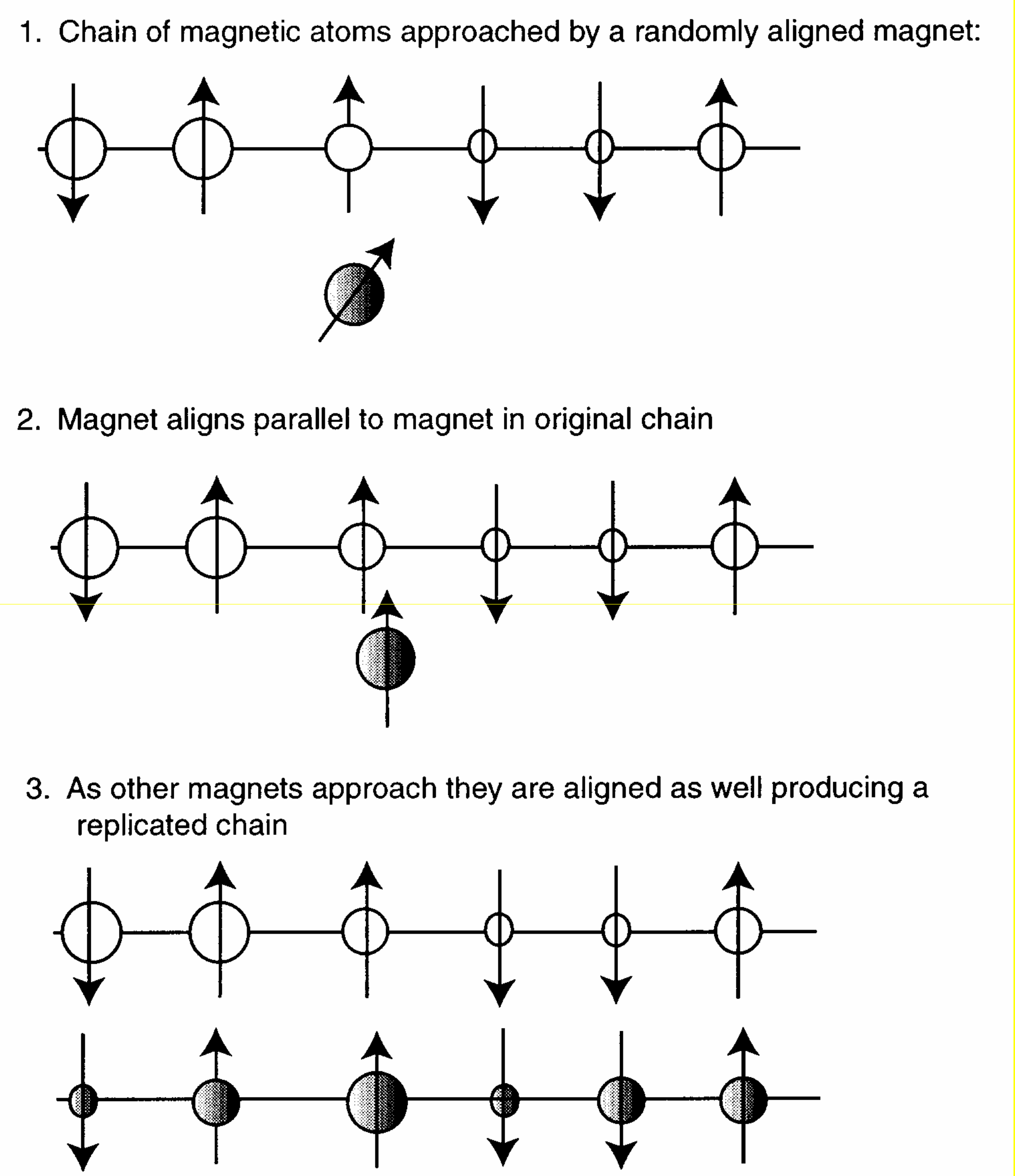
High-energy metabolites

<u>Example 5 of Exotic Life:</u>
Alternative Genetic Code

Based on alignment of magnetic moments in variable directions.

(1) Randomly directed magnet approaching the chain lines up parallel to nearest magnet.

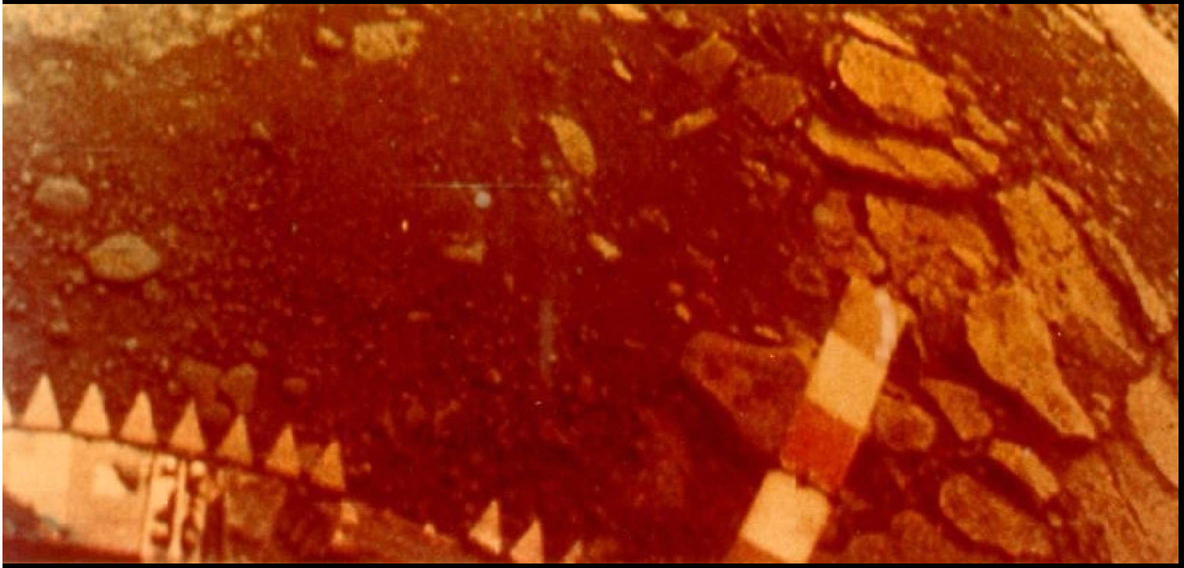
(2) Continuation for many magnets → formation of new chain that duplicates original chain

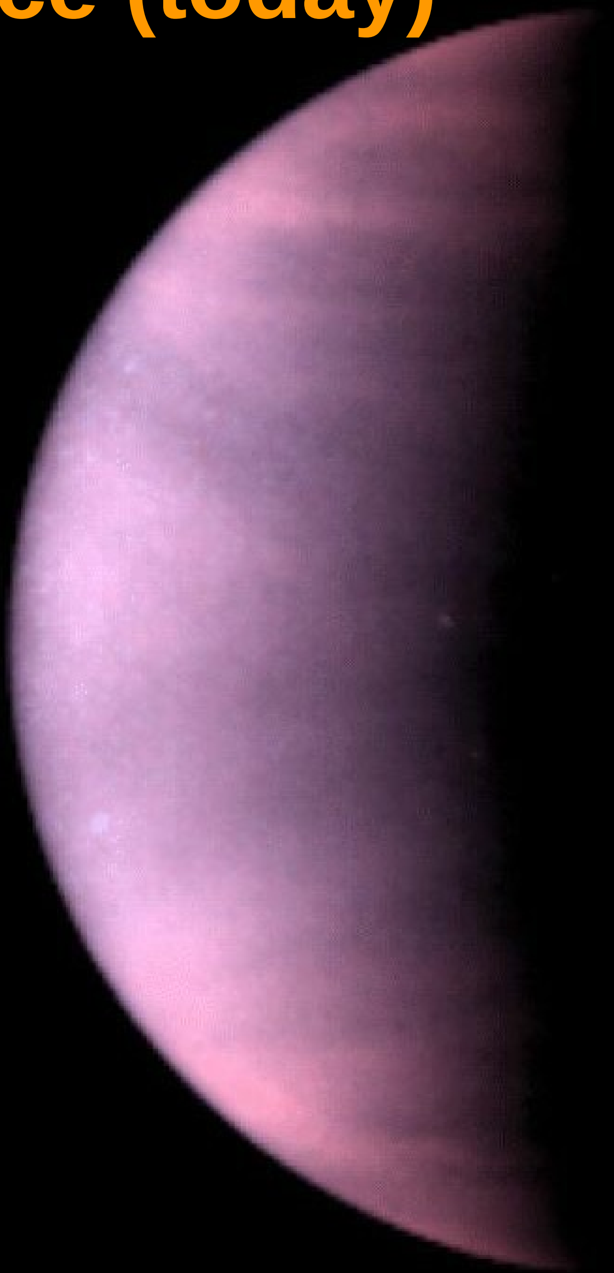


Notice that replicated components are (1) identical rather than complimentary, and (2) sensitive only to direction, not to magnet size *(modified from Feinberg and Shapiro, 1980).*

Possible Life on Venus ? – just not on the surface (today)

Average Surface Temperature:
~ 450^{o}C, Pressure: ~ 92 bar





The Lower Cloud Deck as Microbial Habitat ?

Arguments in Favor (1/4)

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

(2) Atmosphere is in disequilibrium: H_2 and O_2, and H_2S and SO_2 co-exist

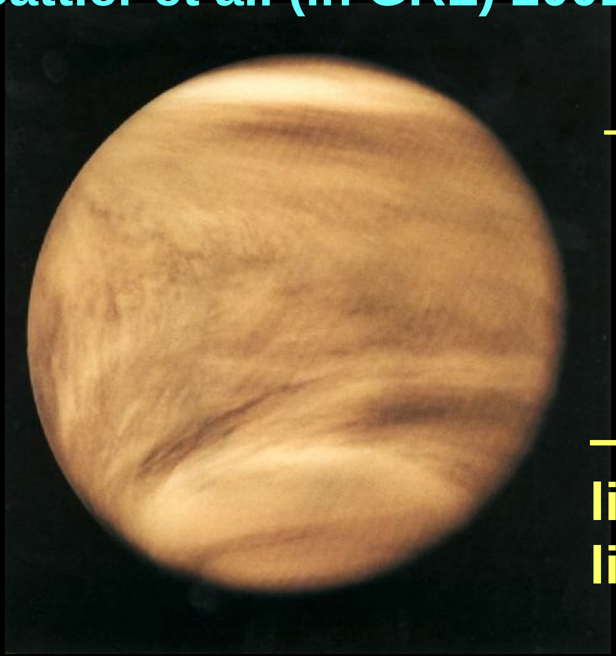
(3) Lower cloud layer (50 km alt.) has non-spherical mode 3 particles comparable in size to microbes on Earth (a few microns)

Pioneer probe

Clouds as Refugium of Life ?

Earth's atmosphere is used as microbial habitat (growth and reproduction, not only transport; **e.g. Sattler et al., 2001)**

If limitation to atmospheric habitation is residence time in atmosphere (Sattler et al. (in GRL) 2001), then



Source NSSDC

– the Venusian atmosphere would be a much more suitable habitat with particle residence time of months rather than days (Esposito et al., 1983, James et al., 1997).

– the lower clouds of Venus are attractive sites for life in terms of elemental (C,N,P) requirements for life (Cockell (1999)

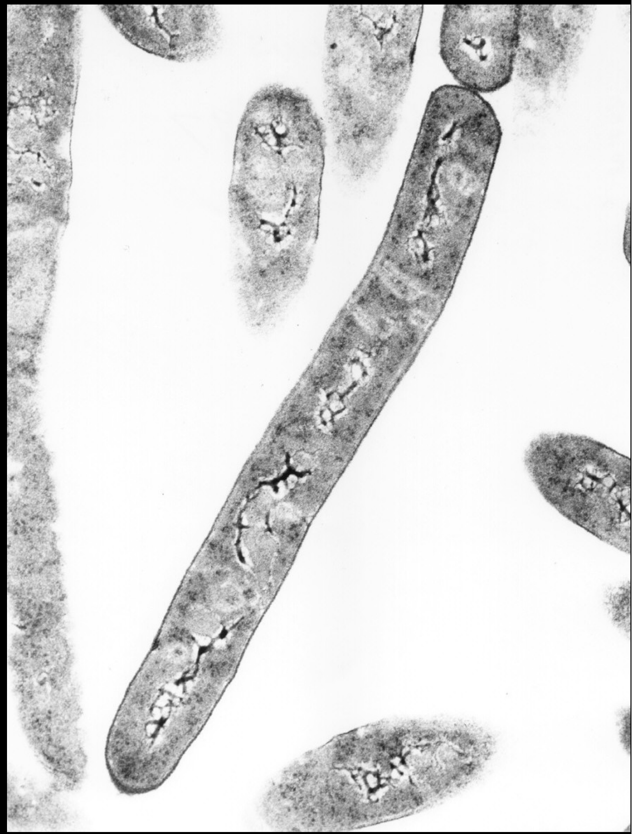
Also, from Earth it is known that fogs are very nutrient-rich (e.g. Gislen, 1948, Fuzzi, 2002)

The Lower Cloud Deck as Microbial Habitat ?

Arguments in Favor (2/4)

(4) Extreme but Tolerable Environmental Conditions

a. Temperature: 30 – 80^{o}C
b. Pressure: ~ 1bar
c. pH: ~ 0



Bacillus infernus, from Henry Aldrich

Tolerance of acidity and high temperature is possible in a single organism

The extreme thermoacidophile, *Acidianus infernus*, grows optimally at 88^{o}C and a pH range from 0.5 to 5.5 **(Cockell, 1999)**

The Lower Cloud Deck as Microbial Habitat ?

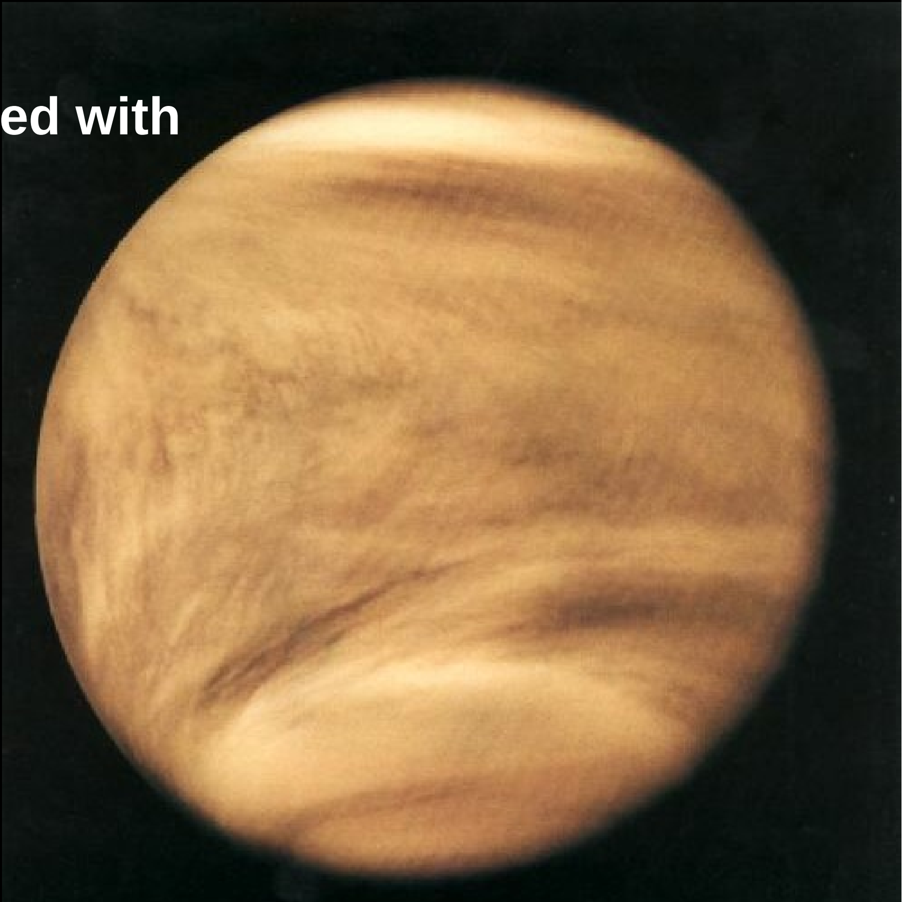
Arguments in Favor (3/4)

(5) Super-rotation of the atmosphere enhances the potential for photosynthetic reactions by reducing dark period

A day-night cycle of 4-6 Earth days compared with 117 Earth days on the surface

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

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



Ultraviolet image of Venus' clouds as seen by the Pioneer Venus Orbiter (Feb. 5, 1979). Source NSSDC

The Lower Cloud Deck as Microbial Habitat ?

Arguments in Favor (4/4)

(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 and Irwin, 2004).**

Evidence for a Past 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

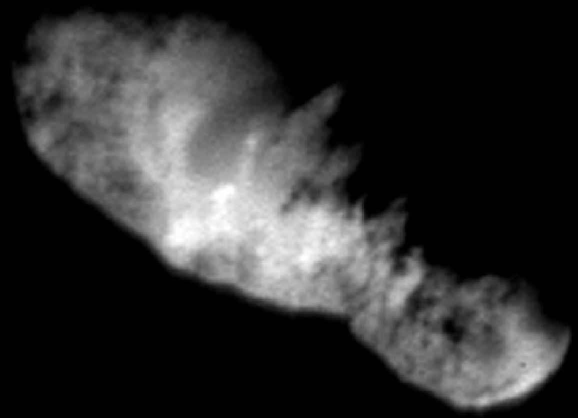
•Matsui and Tajika (1991) based on comparative analyses of the similar amounts of CO_2 and N_2 in near-surface volatile reservoirs of Venus and Earth

A History of Life on Venus?

- The origin of life on Venus seems plausible (given similar conditions as on early Earth , where life appeared relatively soon)

- Once life became entrenched on Venus and surface conditions became hostile, retreating to the atmosphere would have been favored by natural selection
  (Schulze-Makuch and Irwin, 2002, 2004)

Or, organisms could have been delivered by meteorites from early Earth or Mars (recent studies indicate that bacteria can survive space travel for millions of years given minimal shielding)
(Davies, 1996; Horneck and Rettberg, 2002)



Microbes Could Live in the Atmosphere of Venus Today

Energy Cycling between Phototrophs and Chemotrophs ?

Chemotrophic Metabolic Pathways:

$H_2 + 2\,CO + SO_2 \rightarrow 2\,CO_2 + H_2S$ (1)

$3\,CO + SO2 \rightarrow COS + 2\,CO2$ (2)

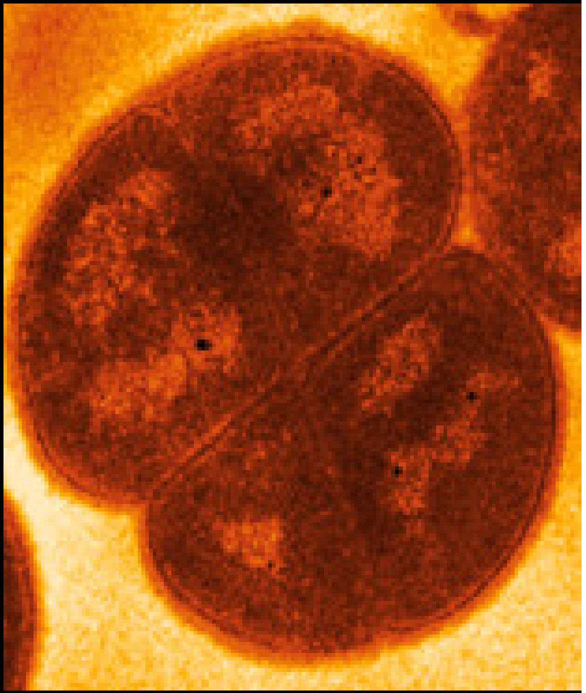
Produce reduced sulfur

Produce reduced carbon and water

Photosystem I Pathway:

$H_2S + CO_2 + \text{light} \rightarrow CH_2O + H_2O + 2S$ (3)

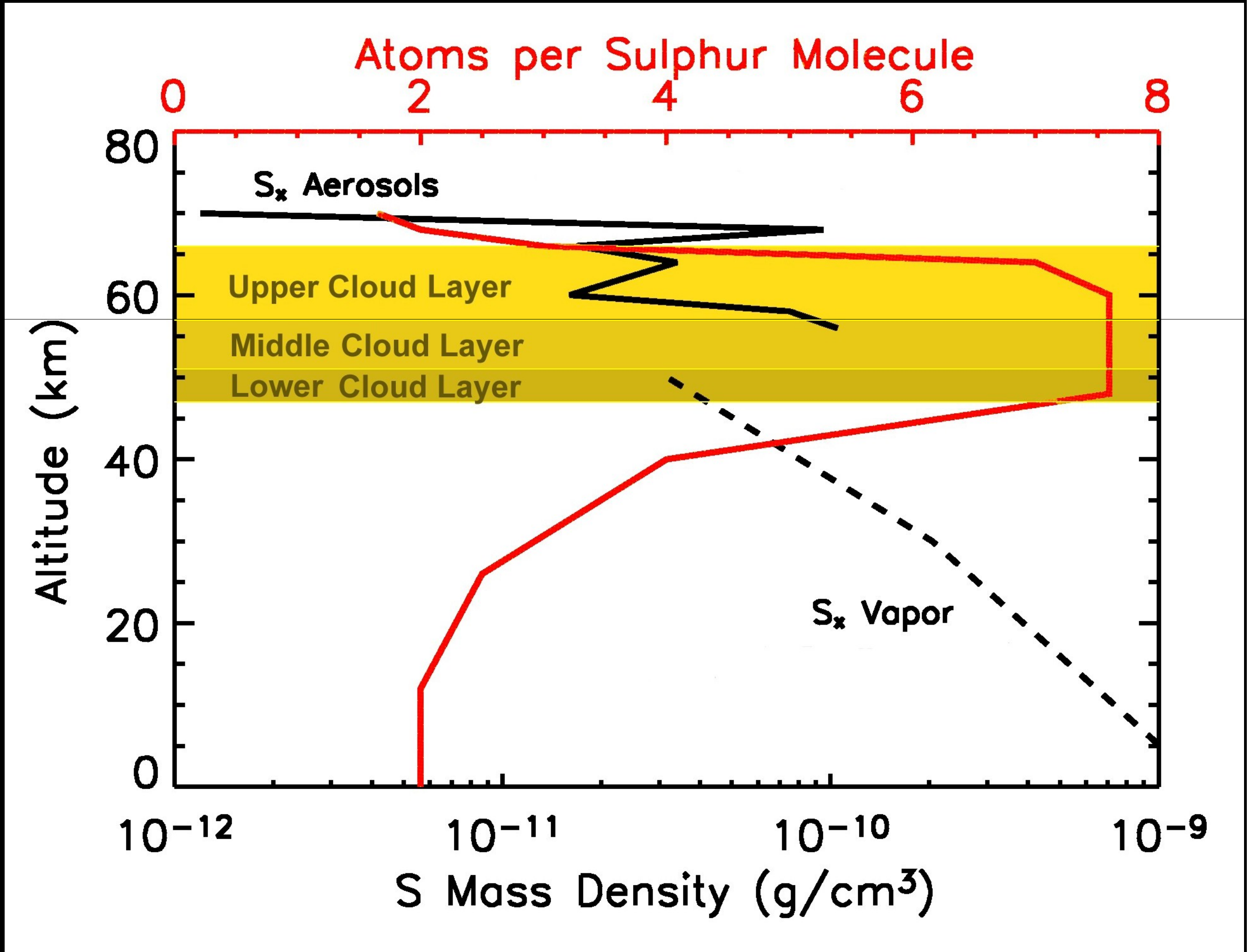
Note that on Venus COS is a common gas – on Earth COS is typically only found in association with biological activity **(Kasting and Siefert, 2002)**



Deinococcus radiodurans

Adaptation to UV –Radiation at Venus

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, purple sulfur bacteria deposit elemental sulfur granules inside the cell, while green sulfur bacteria deposit elemental sulfur granules outside of the cell)

(Schulze-Makuch et al., 2004)

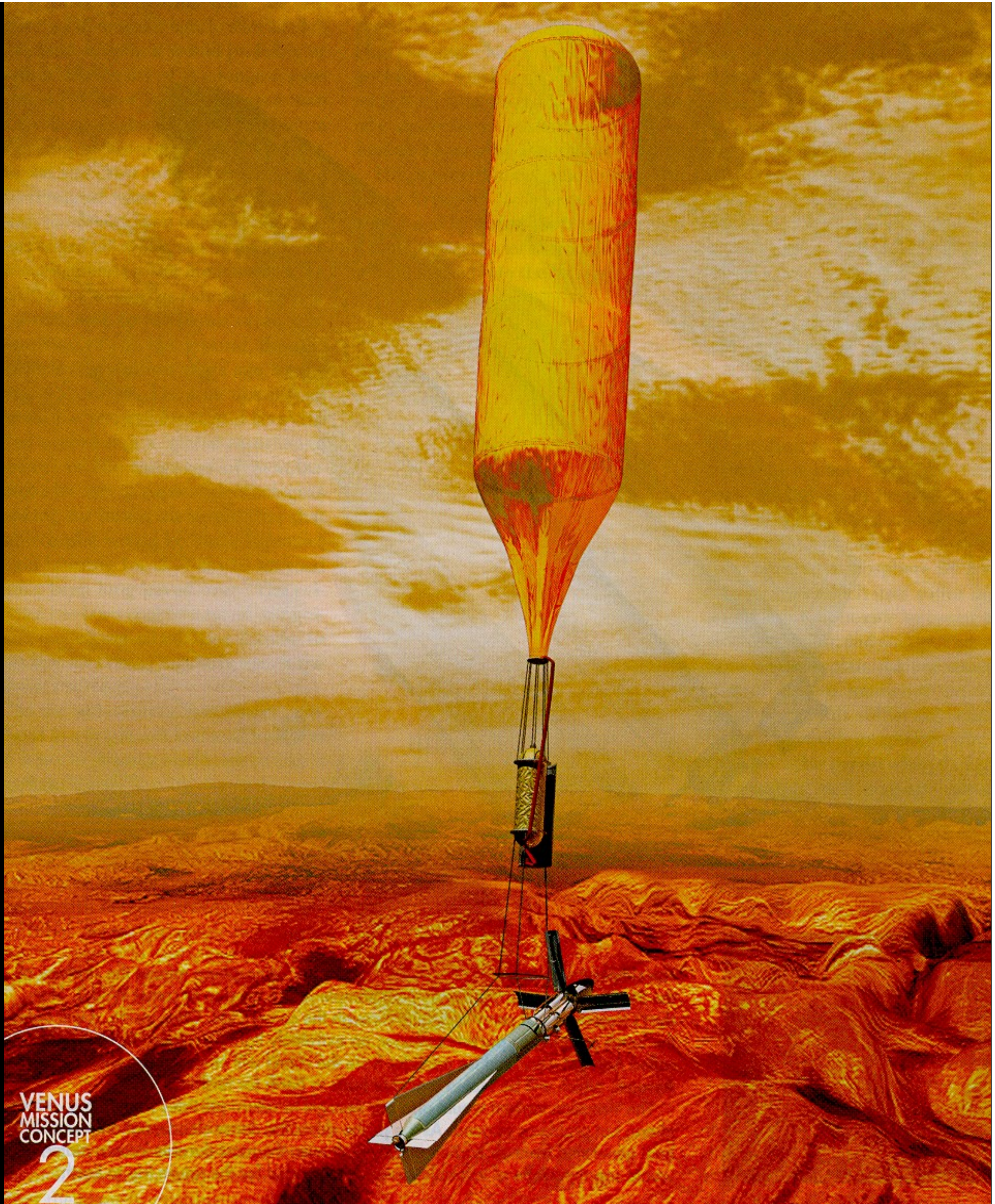
We propose a

Mode 3 Particle Retrieval Mission to Venus

To resolve this
Open Question

Parachute Drop with Balloon Floatation

(Schulze-Makuch et al., 2002; Schulze-Makuch et al., 2005)



From Popular Science (Feb 2003)

SUMMARY

1. Life on Earth provides a singular example of carbon-based, water-borne, photosynthesis driven life.

2. Alien life could be based on very different chemistries, solvents, and energy sources.

3. Two possible habitats for life:
   - Titan's surface environment
   - lower cloud layer of the Venus

4. Life could be possible in any of these environments,
   using a very different tool set from that provided by Earth biology,
   but one entirely consistent with known chemical and physical laws

For More Examples on “Exotic Life”, see:

Bains W (2004) Many chemistries could be used to build living systems. *Astrobiology* 4: 137-167.

Benner SA et al. (2004) Is there a common chemical model for life in the universe? *Current Opinion in Chemical Biology* 8: 672-689.

Schulze-Makuch D & Irwin LN (2004) *Life in the Universe: Expectations and Constraints*, Springer.

Schulze-Makuch D & Irwin LN (2006) The prospect of alien life in exotic forms on other worlds, *Naturwissenschaften*, vol. 93, no. 4, p. 155-172.