Habitability of Exoplanets

(ExoClimes mtg., Exeter, September 2010)

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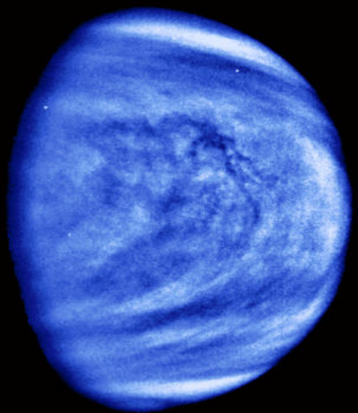
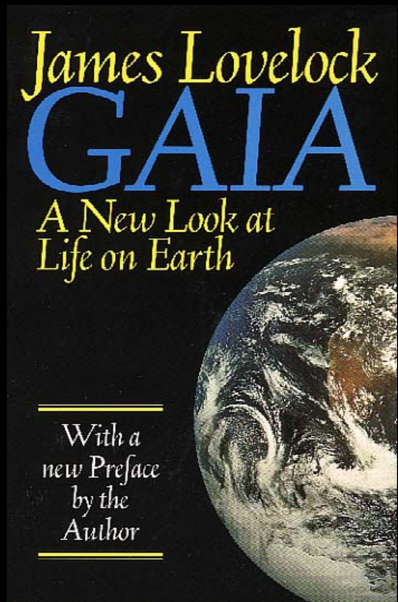


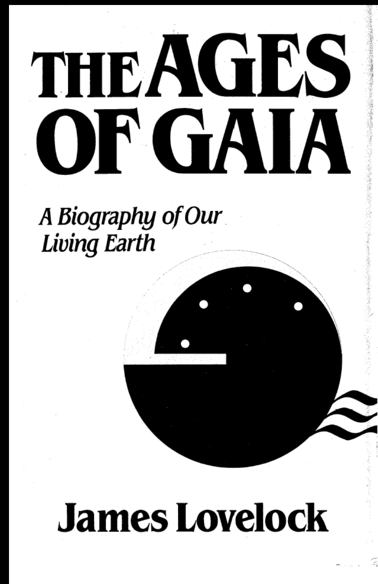
Brief book review: What makes a planet habitable?

The Gaia hypothesis

First presented in the 1970s by James Lovelock



1979

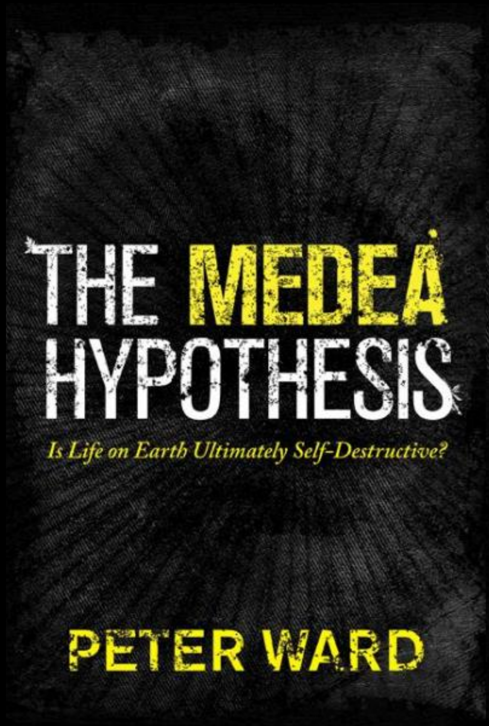


1988

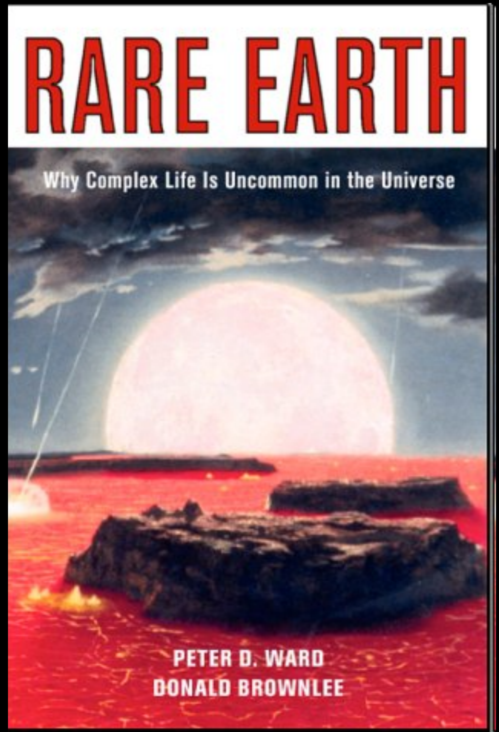
- Life itself keeps a planet habitable

The Medea and Rare Earth hypotheses

Peter Ward



2009



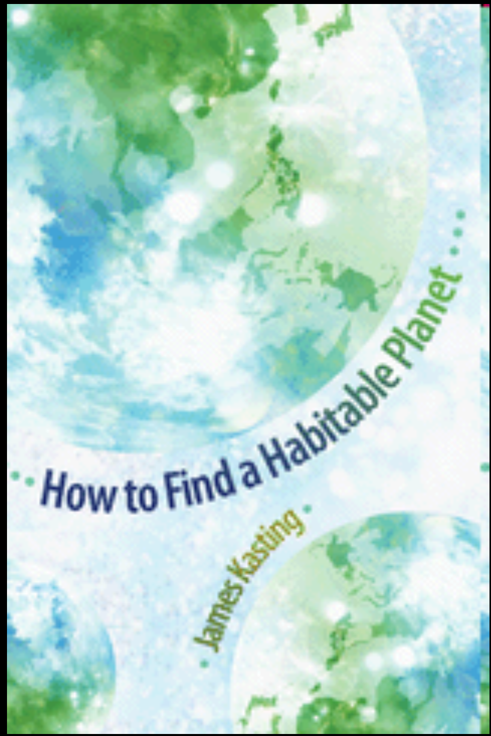
2000

<u>Medea hypothesis</u>: Life is *harmful* to the Earth!

<u>Rare Earth hypothesis</u>: Complex life (animals, including humans) is rare in the universe

The latest addition to this literature

Me



My new book
(Princeton University
Press, 2010)

- Habitable planets and (maybe) life are probably common in the universe, as Carl Sagan suggested a long time ago

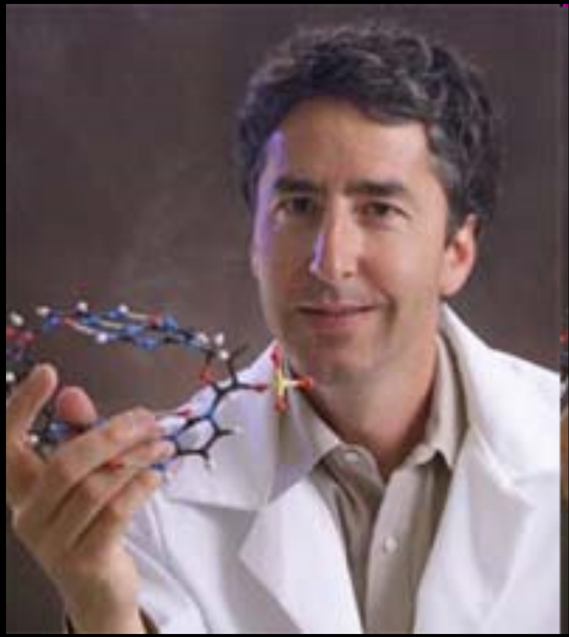
Talk outline

- Introduction (which you heard already)
- What makes Earth unique, and what is life?
- How did Earth remain habitable over time (the faint young Sun problem)?
- How does plate tectonics influence our ideas about the habitable zone?
- What are the implications of the new climate results for early Mars?

What is life?

- If we are going to search for life on other planets, we first need to decide what we are looking for
- One definition: "Life is a self-sustained chemical system capable of undergoing Darwinian evolution"

  --*Jerry Joyce*
- This definition, however, is better suited to looking for life in a laboratory experiment than for searching remotely on planets around other stars

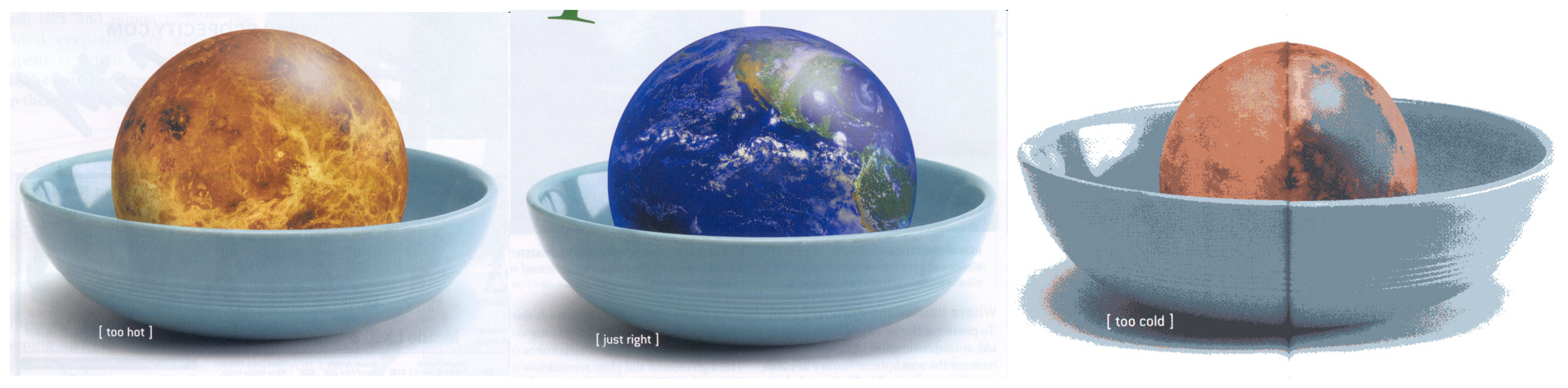


Jerry Joyce, Salk Institute

Liquid water is essential for life
(as we know it)

- Life on Earth is carbon-based (DNA, RNA, and proteins) and requires liquid water
- So, our first choice is to look for other planets like Earth
- *Subsurface water* is not relevant for remote life detection because it is unlikely that a subsurface biota could significantly modify a planetary atmosphere

The Goldilocks paradox

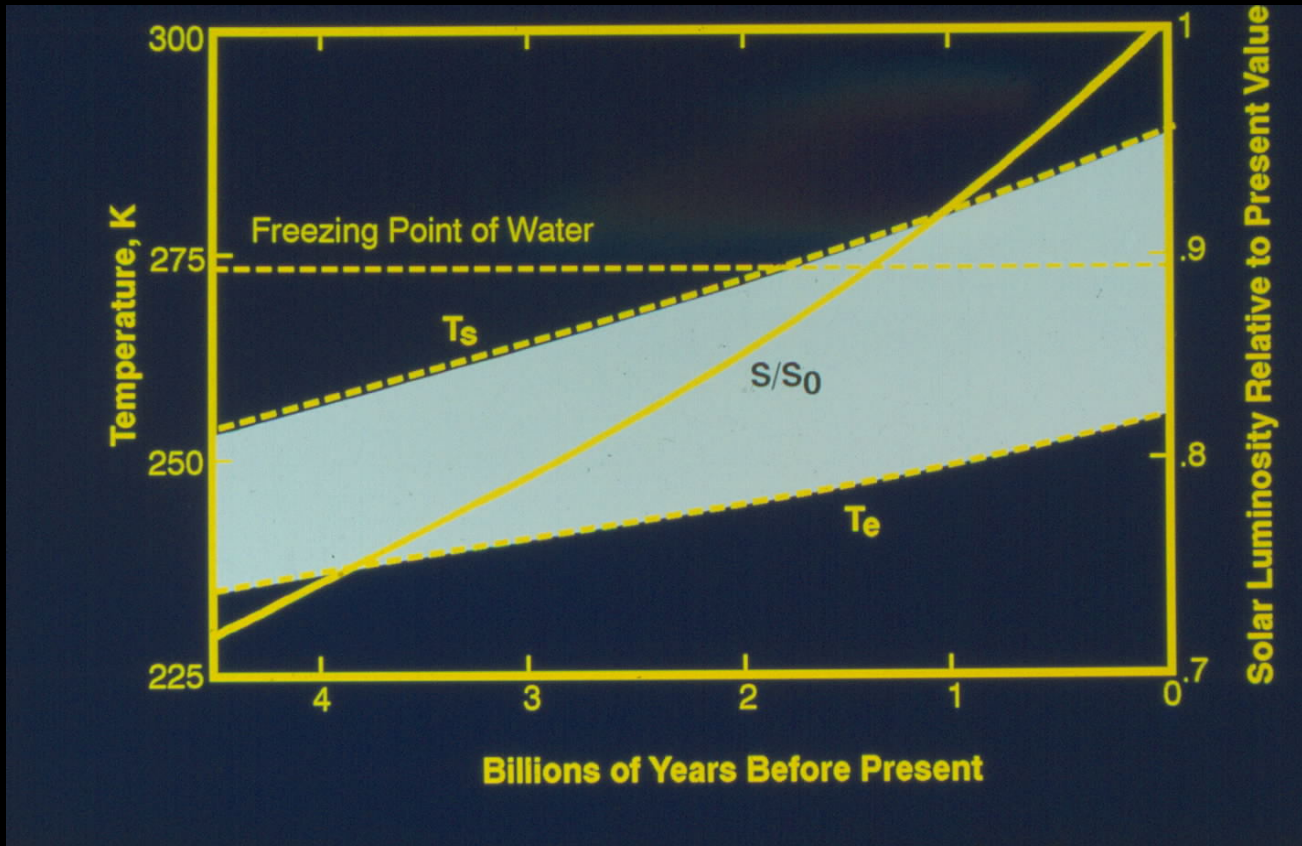


- Why is Venus too hot, Mars too cold, while Earth is just right?

  Lynn Margulis

- The obvious answer concerns their relative distances from the Sun
- However, it turns out that this is only part of the story…

The faint young Sun problem



- Earth's surface temperature would have been below the freezing point of water prior to 2 b.y. ago if its atmosphere was the same as today
- The problem can be resolved if the early atmosphere was rich in *greenhouse gases* such as CO_2, CH_4, and NH_3

Kasting et al., *Scientific American* (1988)

Sagan and Mullen, Science (1972)

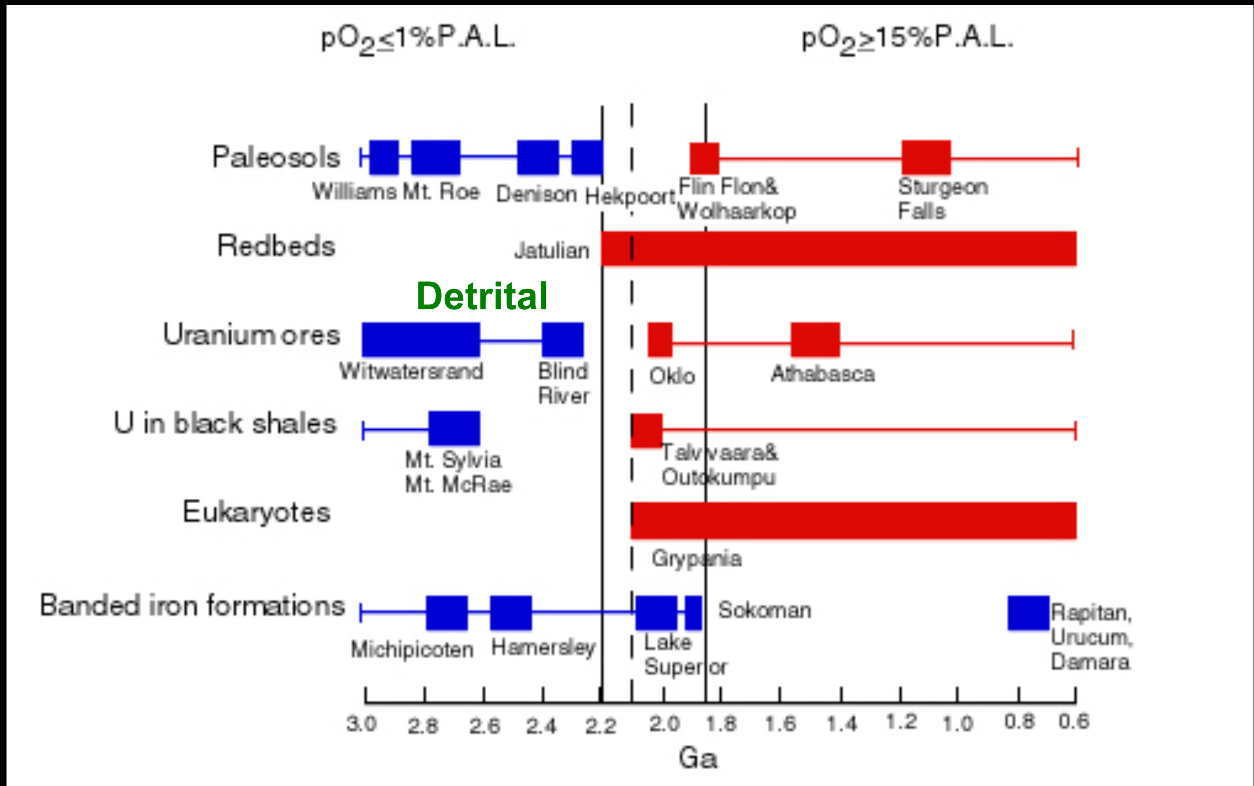
Reports

Earth and Mars: Evolution of Atmospheres and Surface Temperatures

Abstract. *Solar evolution implies, for contemporary albedos and atmospheric composition, global mean temperatures below the freezing point of seawater less than 2.3 aeons ago, contrary to geologic and paleontological evidence. Ammonia mixing ratios of the order of a few parts per million in the middle Precambrian atmosphere resolve this and other problems. Possible temperature evolutionary tracks for Earth and Mars are described. A runaway greenhouse effect will occur on Earth about 4.5 aeons from now, when clement conditions will prevail on Mars.*

- Sagan and Mullen liked *ammonia (NH_3)* as an Archean greenhouse gas
- They were aware that atmospheric O_2 was low on the early Earth ⇒

- “Conventional” geologic indicators show that atmospheric O_2 was low prior to ~2.2 Ga



H.D. Holland (1994)

- Mass-independently fractionated S isotopes strongly support this conclusion

Banded iron-formation or BIF (>1.8 b.y ago)

- Fe^{+2} is soluble, while Fe^{+3} is not
- BIFs require long-range transport of iron

⇒ The deep ocean was anoxic when BIFs formed

Problems with Sagan and Mullen's hypothesis

- Ammonia is *photochemically unstable* with respect to conversion to N_2 and H_2 (Kuhn and Atreya, 1979)

(R70) $$NH_3 + h\nu \rightarrow NH_2 + H$$

(R75) $$NH_2 + NH_2 + M \rightarrow N_2H_4 + M$$

(R81) $$N_2H_4 + H \rightarrow N_2H_3 + H_2$$

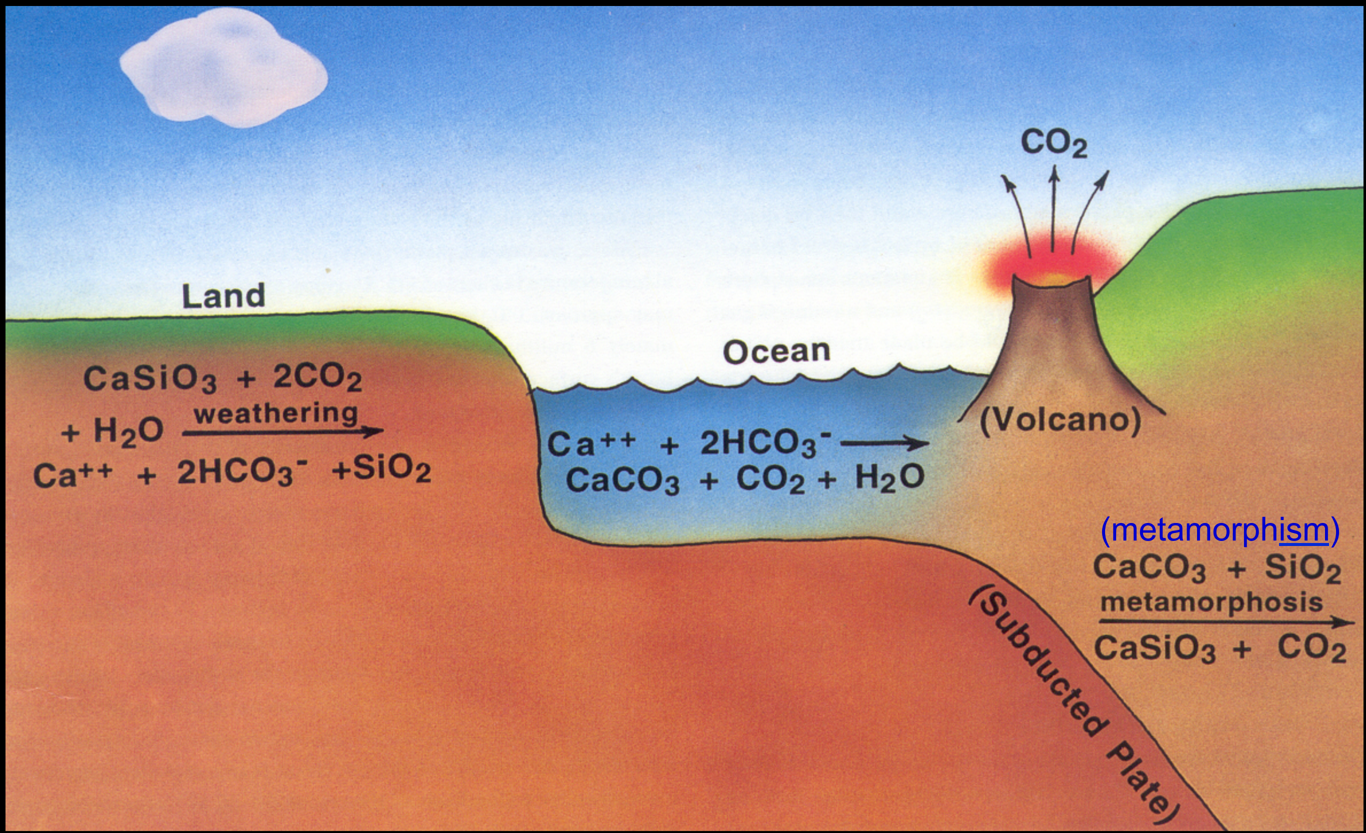
(R80) $$N_2H_4 + h\nu \rightarrow N_2H_3 + H$$

(R83) $$N_2H_3 + N_2H_3 \rightarrow N_2H_4 + N_2H_2$$

$$\rightarrow N_2H_4 + N_2 + H_2$$

- The apparent failure of the NH_3 greenhouse led to other models that depended on higher concentrations of CO_2 $\Rightarrow$

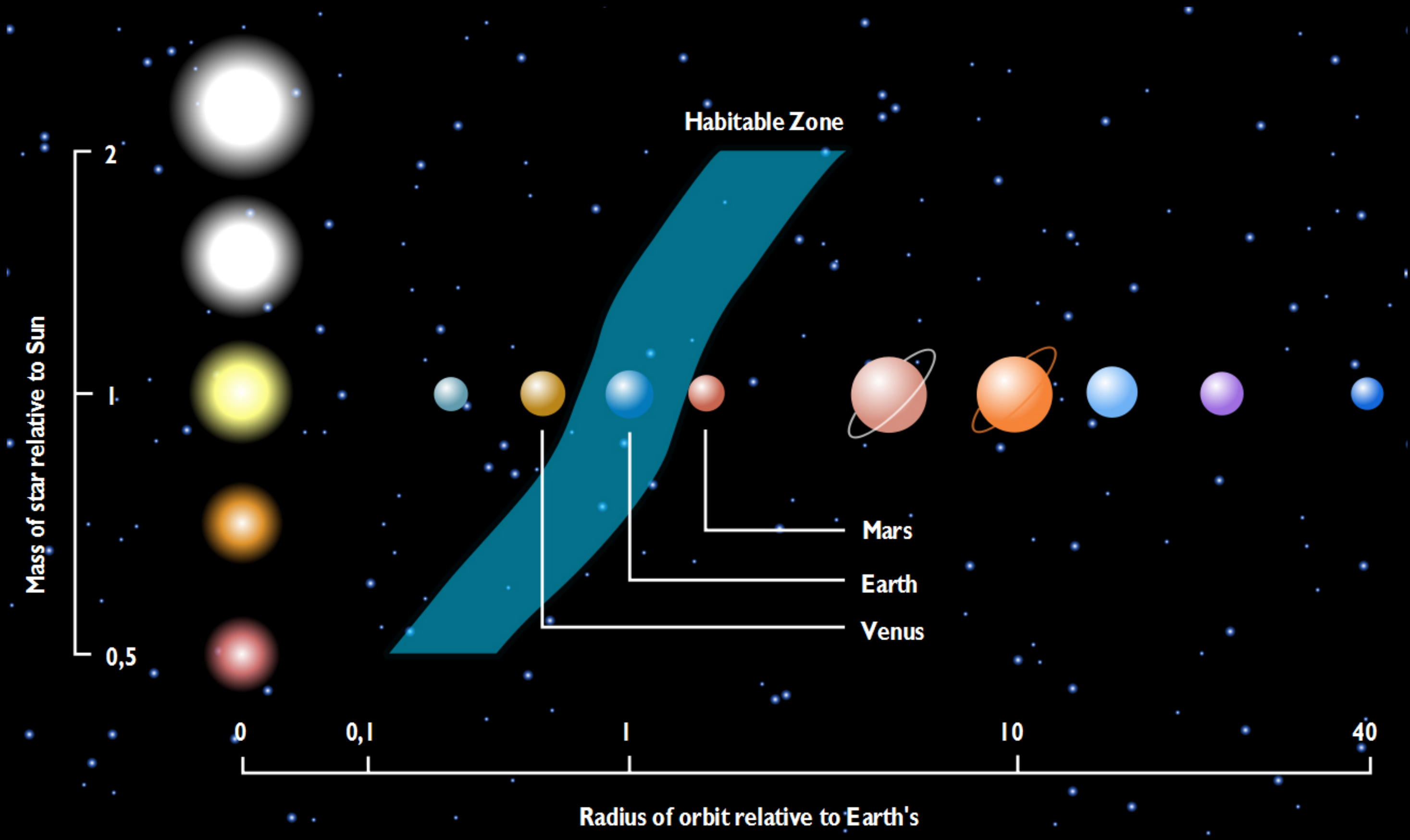
The carbonate-silicate cycle



- Atmospheric CO_2 should build up as the planet cools
- This cycle regulates Earth's atmospheric CO_2 level over long time scales and has acted as a planetary *thermostat* during much of Earth's history
- Biology affects this cycle, but the feedback should still operate on an abiotic planet ⇒ doesn't require Gaia!

- Aside: The CO_2-climate feedback is also the key to our current theory of the habitable zone ⇒

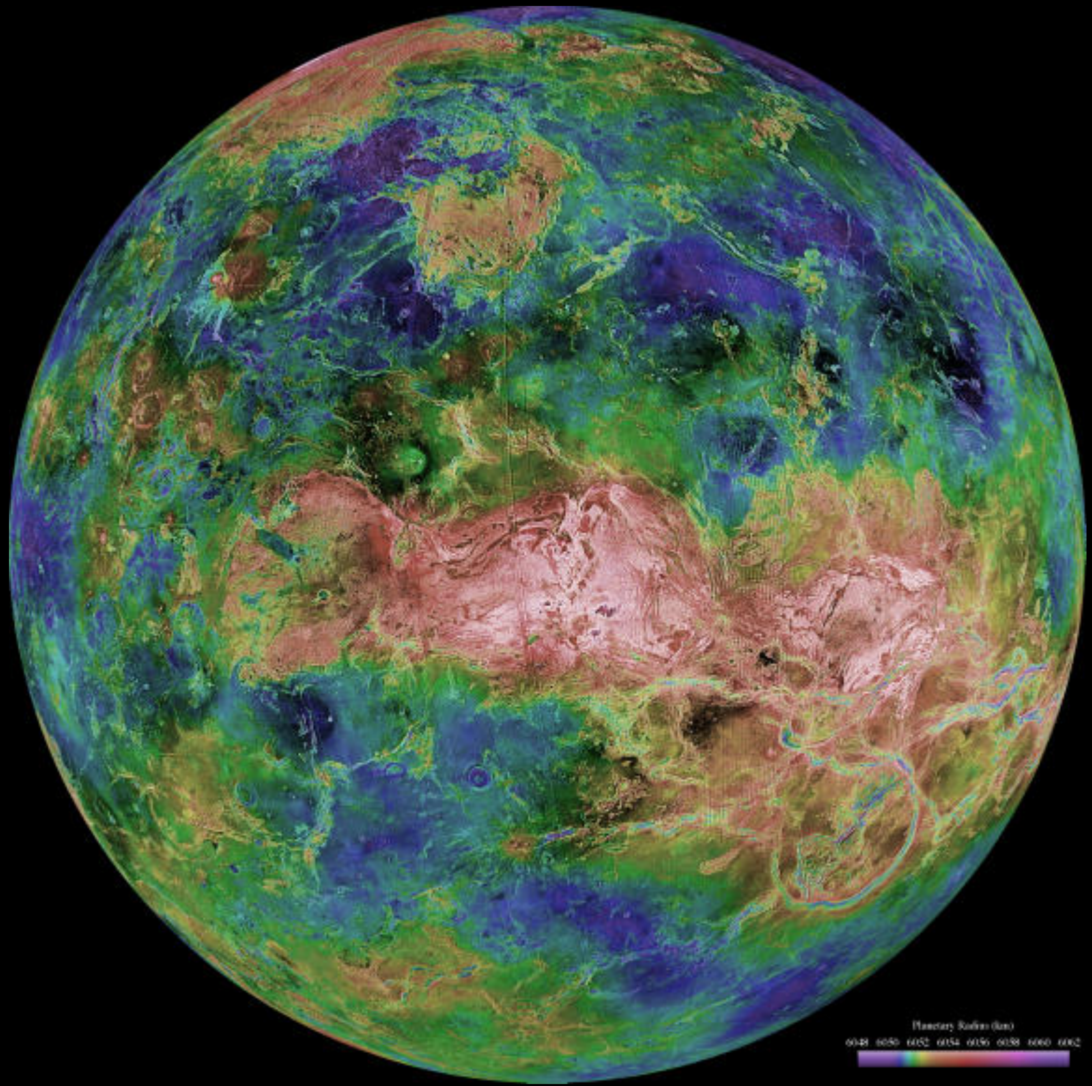
The (liquid water) habitable zone



- The habitable zone is relative *wide* because of the negative feedback provided by the carbonate-silicate cycle
- In previous models (Hart, 1978, 1979), the habitable zone extended only from about 0.95-1.01 AU

http://www.dlr.de/en/desktopdefault.aspx/tabid-5170/8702_read-15322/8702_page-2/

- Related aside: This is also why plate tectonics, or something equivalent, is a key issue for habitability of Earth-like planets



Venus as seen by Magellan

- Does Venus have plate tectonics?

Image made using *synthetic aperture radar* (SAR)

http://www.crystalinks.com/venus703.jpg

Earth topography

- Earth’s topography shows tectonic features such as *midocean ridges*

http://www.kidsgeo.com/geography-for-kids/0012-is-the-earth-round.php

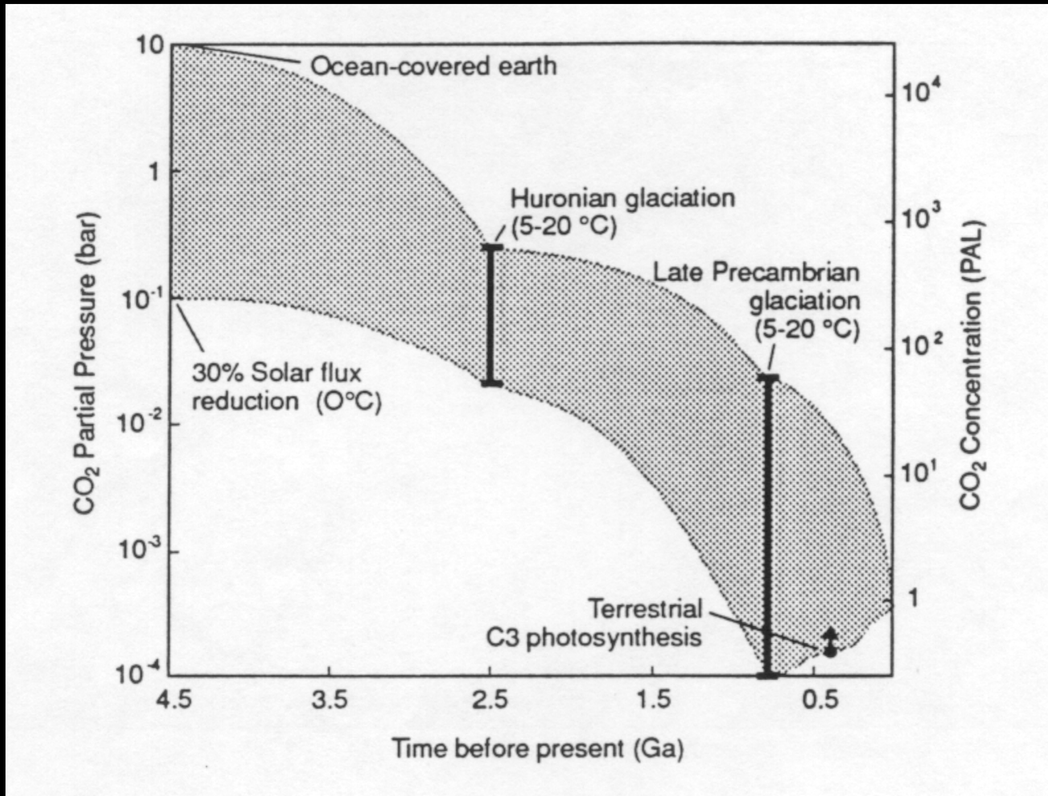
http://sos.noaa.gov/download/dataset
_table.html

Earth topography

- *Linear mountain chains* are also observed
- As mentioned by Fred Taylor, many geophysi-cists attribute the lack of plate tectonic on Venus to lack of water

- Back to the faint young Sun problem…

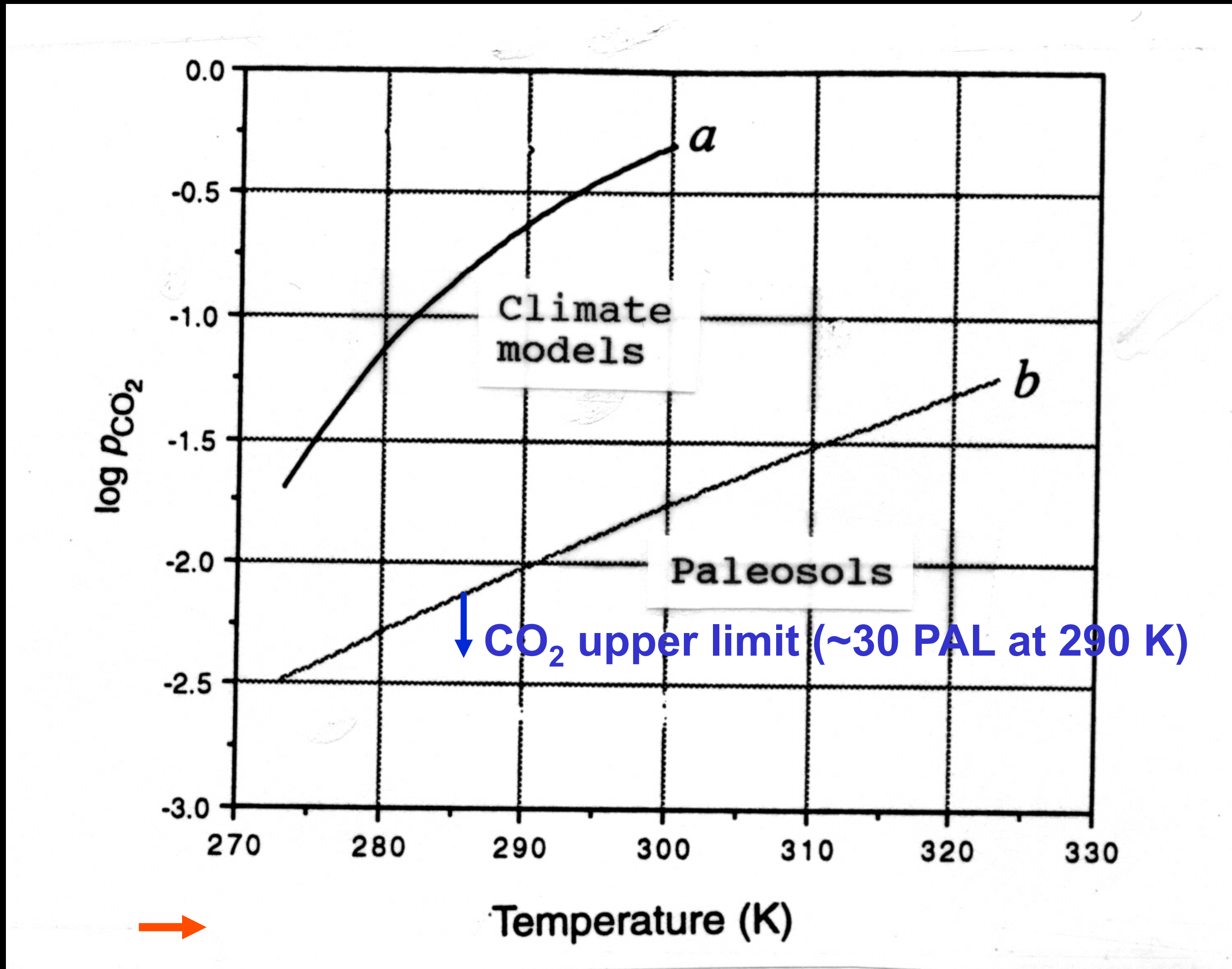
CO_2 vs. time *if* no other greenhouse gases (besides H_2O)



J. F. Kasting, *Science* (1993)

- In the simplest story, atmospheric CO_2 levels should have declined monotonically with time as solar luminosity increased
- *But*, there are reasons to believe that this simple story may not be correct!

pCO_2 from paleosols (2.8 Ga)

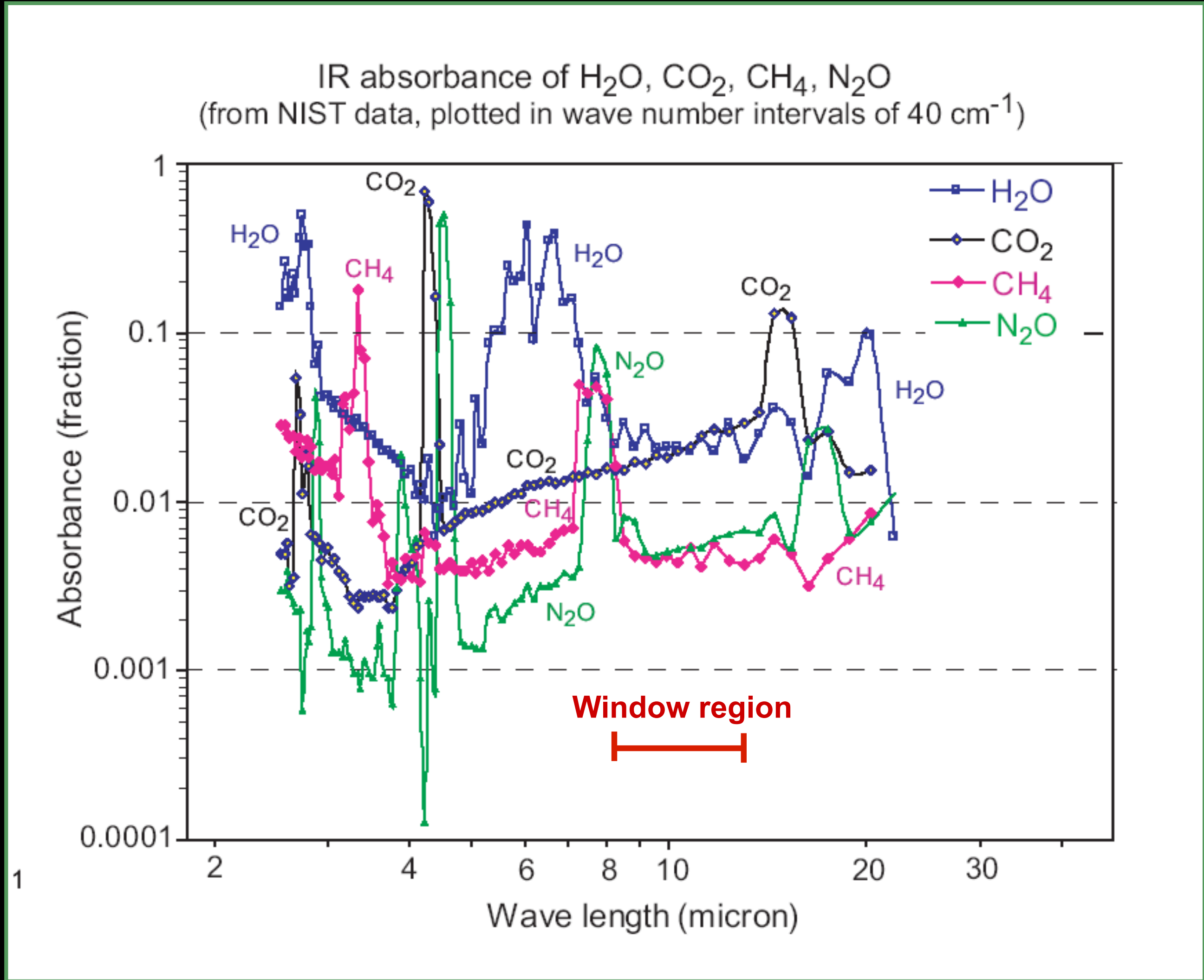


Today's CO_2 level (3×10^{-4} atm)

Rye et al., *Nature* (1995)

Absence of siderite ($FeCO_3$) places upper bound on pCO_2

⇒ May need other green-house gases (CH_4?)



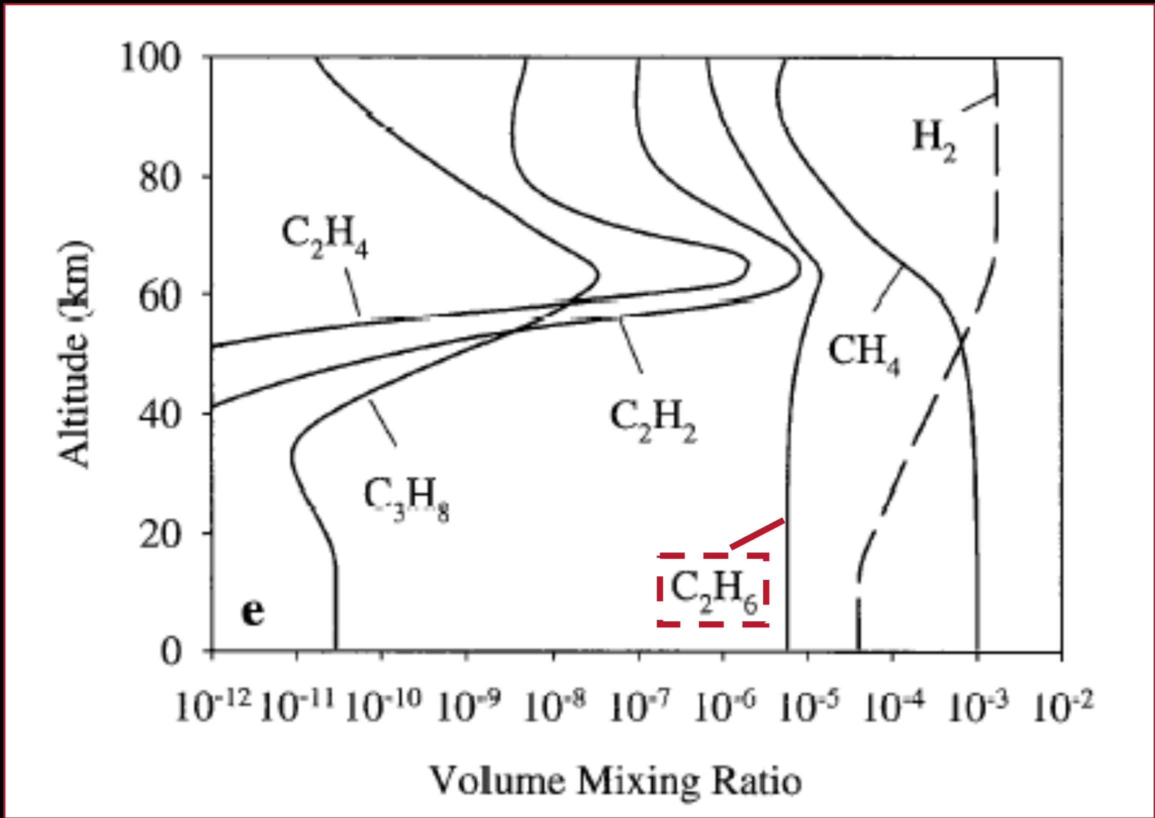
- CH_4 has a strong absorption band at 7.7 μm, right in the edge of the 8-12 μm "window" region where H_2O and CO_2 have weak absorption
- So, methane is a reasonably strong greenhouse gas

Figure courtesy of Abe Lerman, Northwestern Univ.

- Today, CH_4 is produced mainly in restricted, *anaerobic* environments, such as the intestines of cows and the water-logged soils underlying rice paddies
- Methanogenic bacteria (*methanogens*) are responsible for most methane production
- Methanogens are probably evolutionarily ancient

- The greenhouse effect of CH_4 is limited, though, because CH_4 *polymerizes* in atmospheres with $CH_4/CO_2 > 0.1$ $\Rightarrow$

Low-O_2 atmospheric model



Ethane formation:

1) $CH_4 + h\nu \rightarrow CH_3 + H$

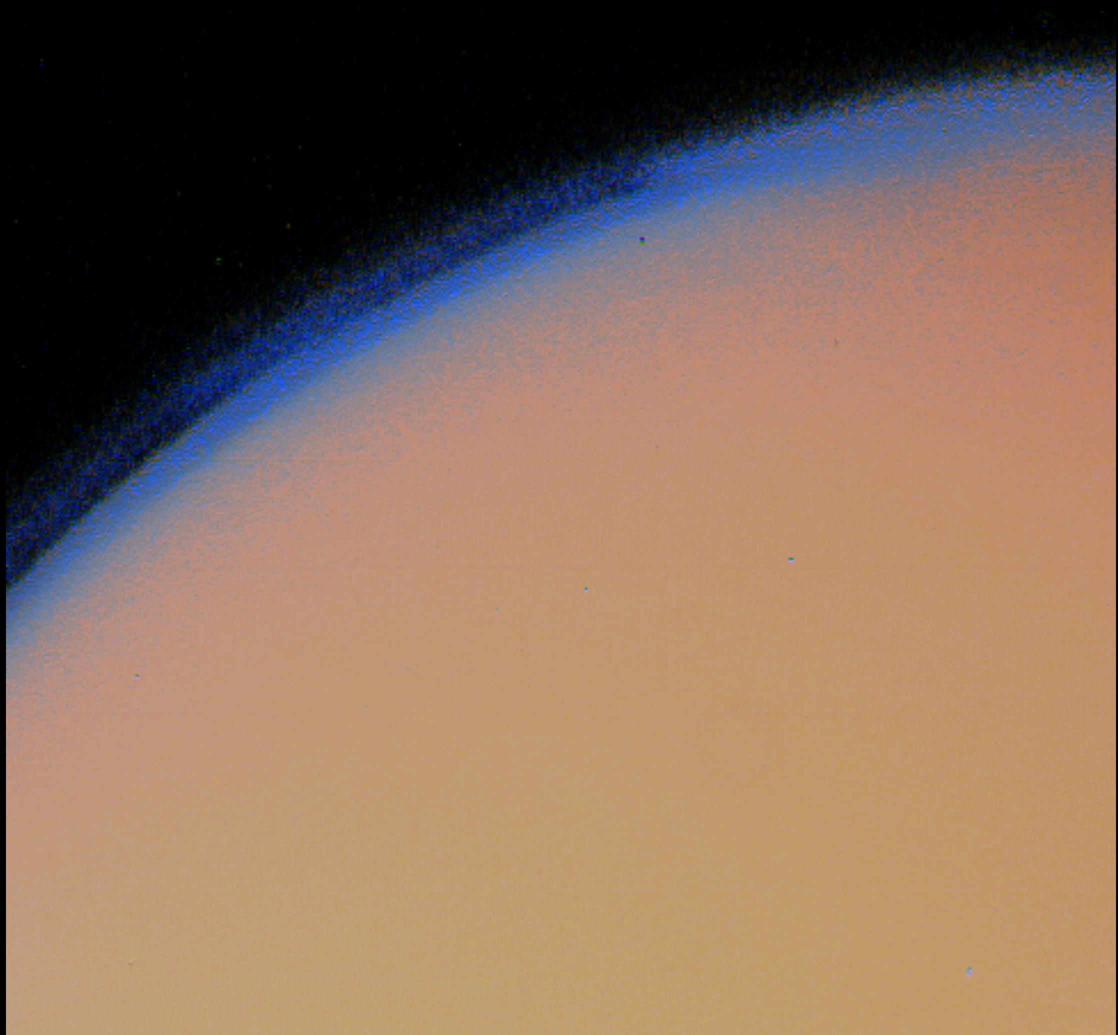
or

2) $CH_4 + OH \rightarrow CH_3 + H_2O$
3) $CH_3 + CH_3 + M \rightarrow C_2H_6 + M$

--Further reactions lead to polyacetylenes and eventually to smog

- "Standard", low-O_2 model from Pavlov et al. (*JGR*, 2001)
- 2500 ppmv CO_2, 1000 ppmv CH_4 $\Rightarrow$ 8 ppmv C_2H_6

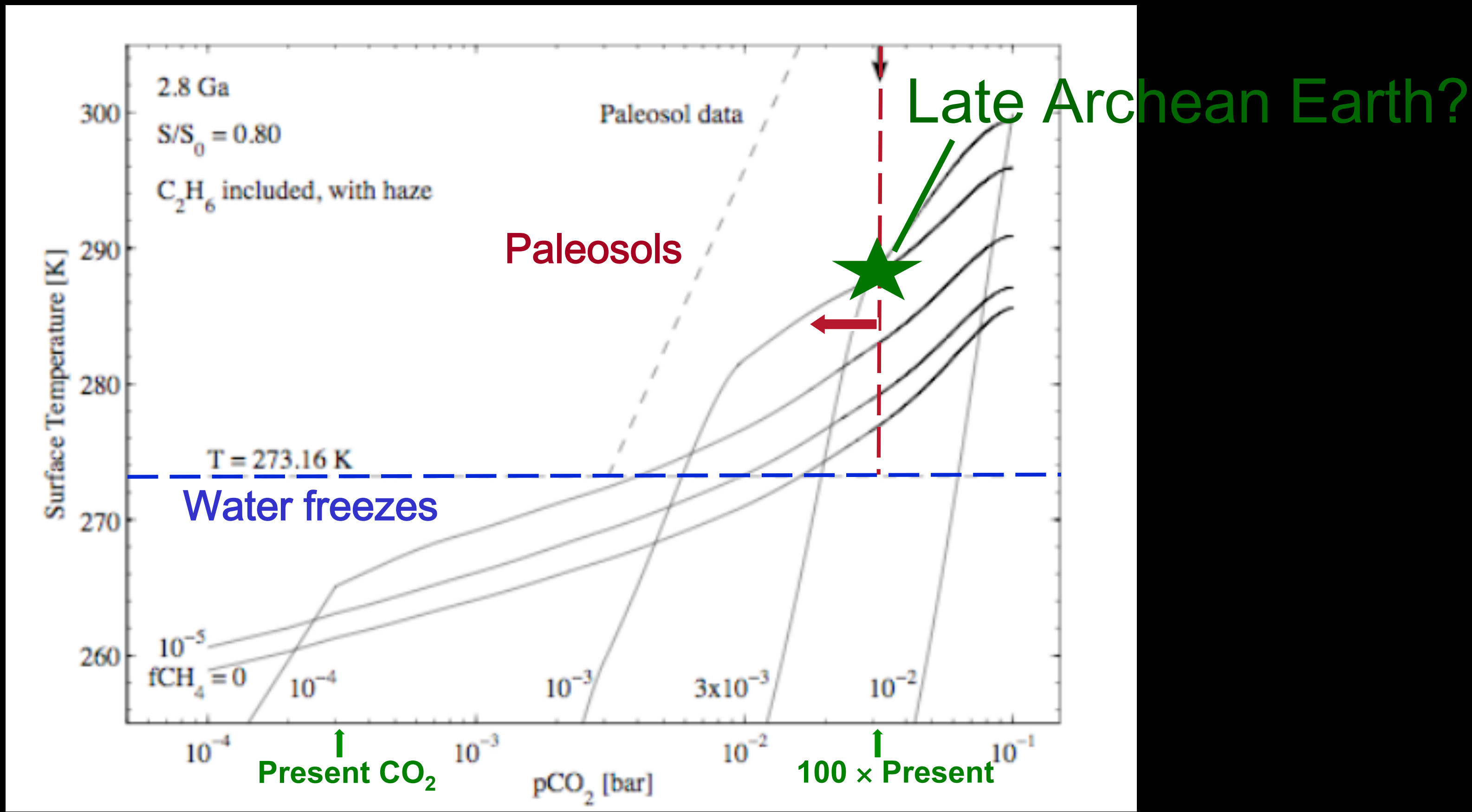
Titan's organic haze layer



- Haze is thought to form from photolysis (and charged particle irradiation) of CH_4
- It can produce an *anti-greenhouse effect* by absorbing incoming sunlight high up in the atmosphere and re-radiating it to space

(Picture from Voyager 2)

$CH_4/CO_2/C_2H_6$ greenhouse with haze



- Bottom line: One can generate Late Archean surface temperatures near modern values, but only if CO_2 levels are ~100 PAL

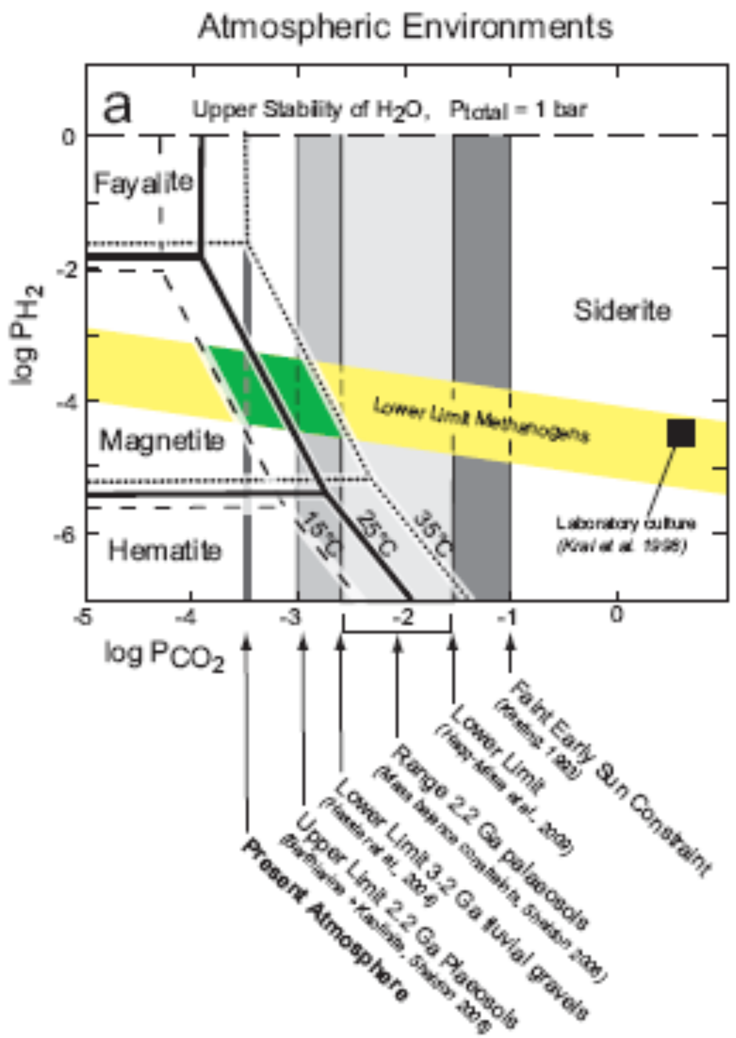
nature Vol 464|1 April 2010|doi:10.1038/nature08955

LETTERS

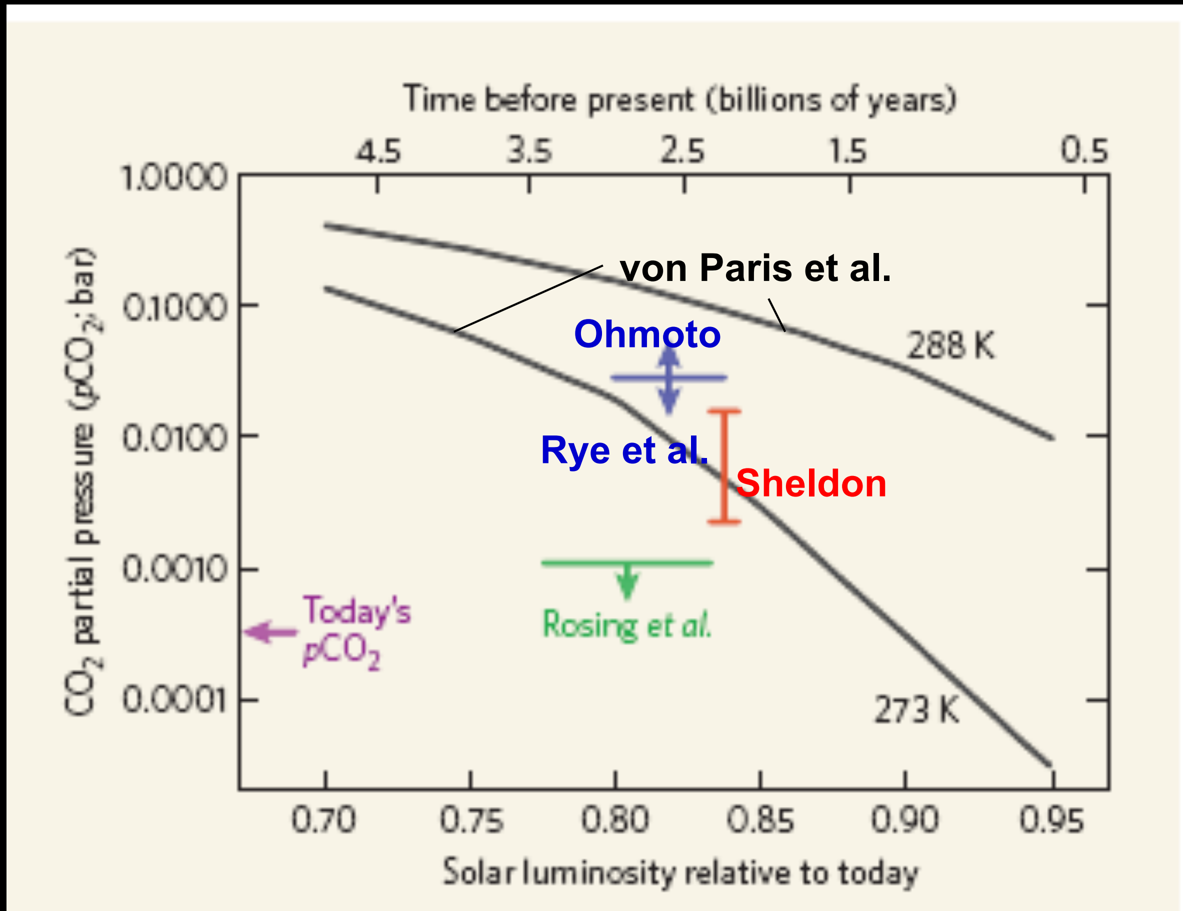
No climate paradox under the faint early Sun

Minik T. Rosing[1,2,4], Dennis K. Bird[1,4], Norman H. Sleep[5] & Christian J. Bjerrum[1,3]

- Rosing et al. place constraints on pCO_2 based on the mineralogy of *banded iron-formations*, or BIFs
- Siderite ($FeCO_3$) and magnetite (Fe_3O_4) are found within the same units ⇒ pCO_2 should lie near the phase boundary
- The implied atmospheric CO_2 concentrations are really low: ~ 10^{-3} bar, or 3 PAL



Rosing et al.: CO_2 from BIFs



- If the new CO_2 constraints are correct, then other warming mechanisms are clearly needed
- Rosing et al. suggest a reduced *cloud albedo* caused by the absence of biogenic sulfur gases, but this isn't sufficient if the climate was as warm or warmer than today

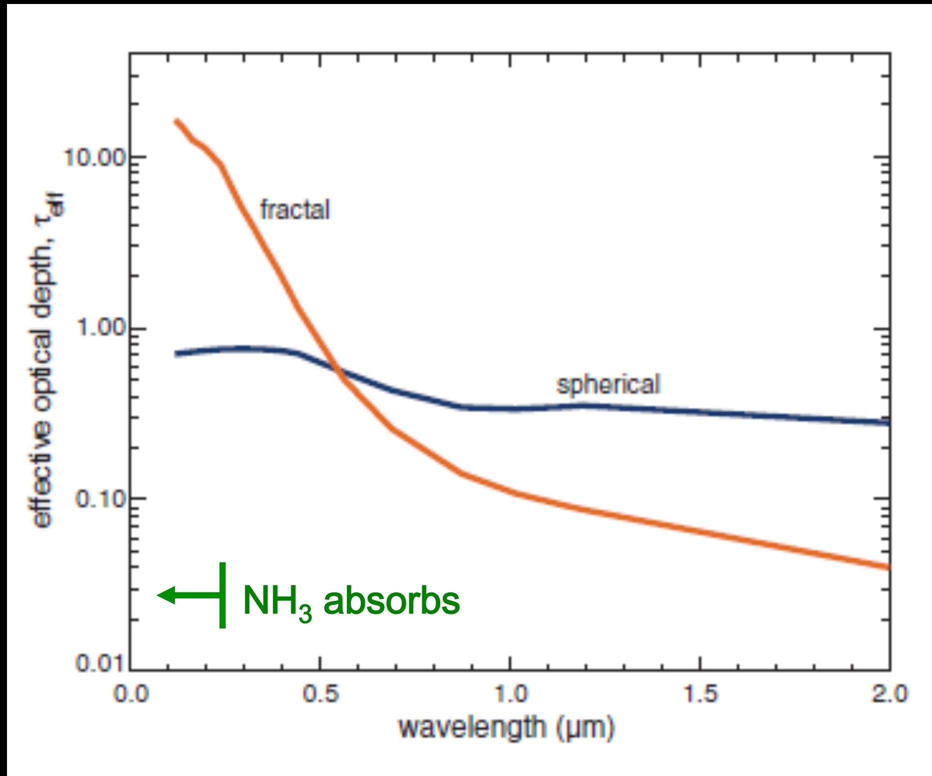
J. F. Kasting, Nature, Apr. 1

Fractal Organic Hazes Provided an Ultraviolet Shield for Early Earth

E. T. Wolf and O. B. Toon

Science (2010)

- The ratio of UV/visible optical depth is much greater for fractal particles than for spheres
- Fractal haze models produce a better fit to *Titan's albedo spectrum* than do standard Mie sphere models
- This allows the possibility of creating an effective UV shield for NH_3 without causing a large anti-greenhouse effect

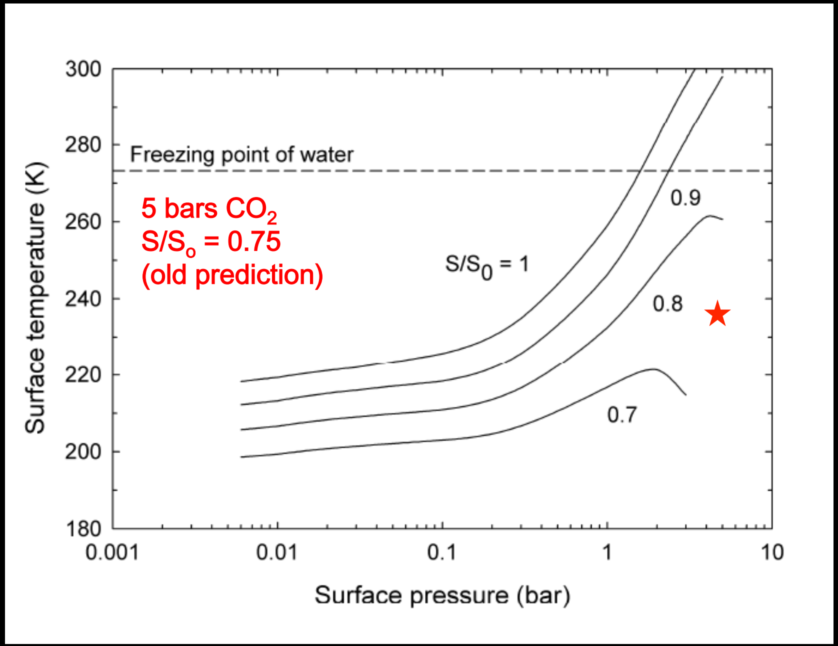


Why isn't Mars habitable?

- The problem with Mars is its small *size* compared to Earth
  - Mar's has half Earth's diameter and 1/10th its mass
- Volcanism and plate tectonics (?) ended early, and the carbonate-silicate cycle feedback didn't work
- Also, Mars' small size allowed it to lose heavy elements (C, N, and O) to *space*

Recent Mars calculations

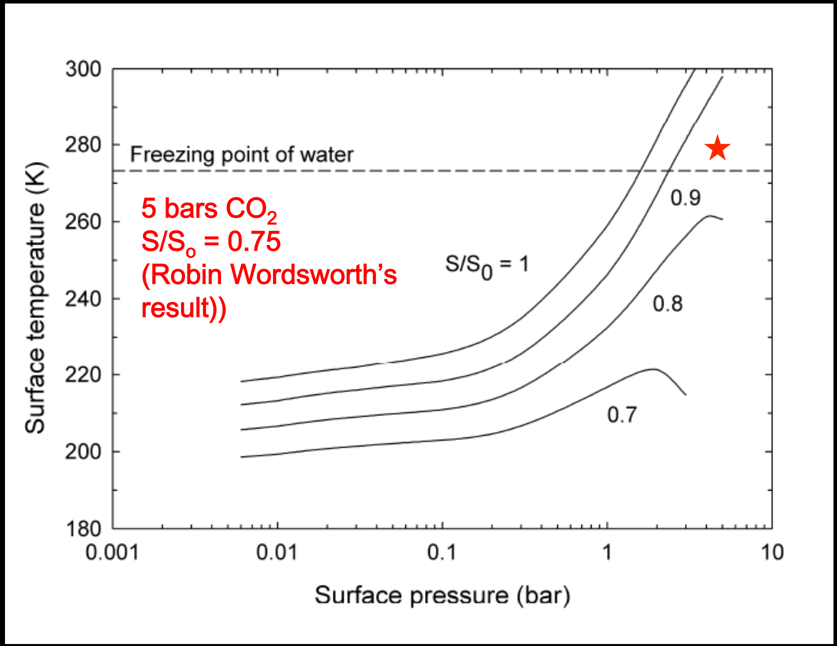
- 1-D calculations have repeatedly failed to explain how early Mars could have remained warm in the face of low solar luminosity



F. Tian, J. F. Kasting, J. D. Haqq-Misra, and M. Claire, EPSL (2010)

Recent Mars calculations

- The new calculations that we heard about on Tuesday show that early Mars could have been warmed by CO_2 and H_2O
- This also implies (as Peter Read suggested) that the outer edge of the habitable zone is further out than has been thought



F. Tian, J. F. Kasting, J. D. Haqq-Misra, and M. Claire, EPSL (2010)

Conclusions

- Liquid water is probably required for life $\Rightarrow$ we should be searching for planets in the habitable zones of their stars
  - The good news: The habitable zone is wide because of negative feedbacks provided by the carbonate-silicate cycle
- We still do not understand climate evolution on our own planet, Earth
  - We need to reach agreement on geological constraints on CO_2
  - The same can be said about constraints on surface temperatures derived from O isotopes (not discussed)
- We also need a better theory for plate tectonics (or lack thereof) on Earths and super-Earths
- Understanding early Mars is also important for our theories of terrestrial planet evolution