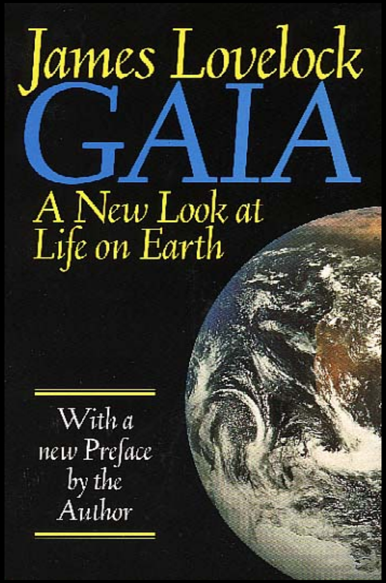
Evolution of Earth's Atmosphere and Climate

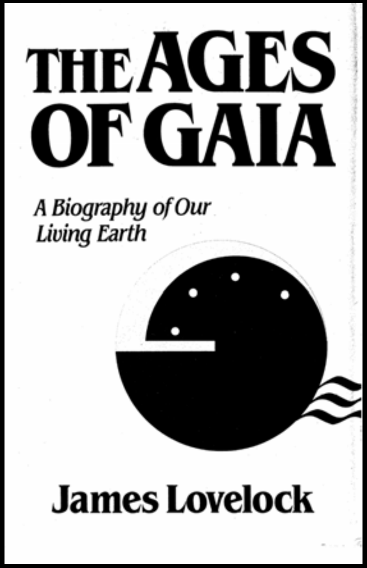
James F. Kasting
Department of Geosciences
Penn State University

The Gaia hypothesis

First presented in the 1970s by James Lovelock



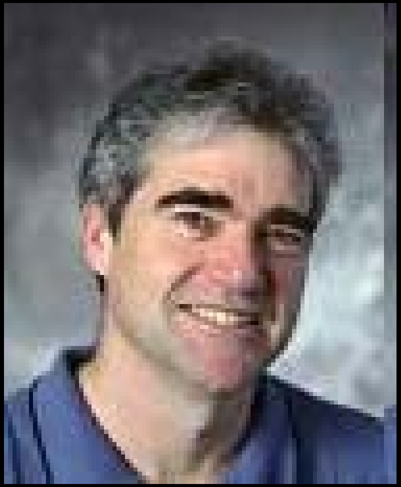
1979



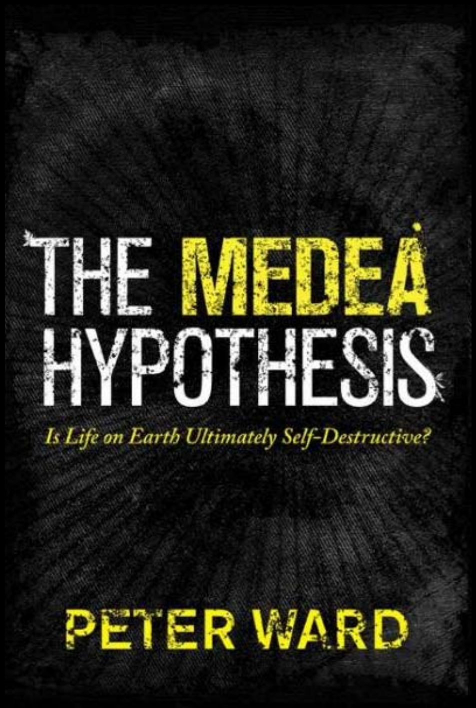
1988

http://www.ecolo.org/lovelock

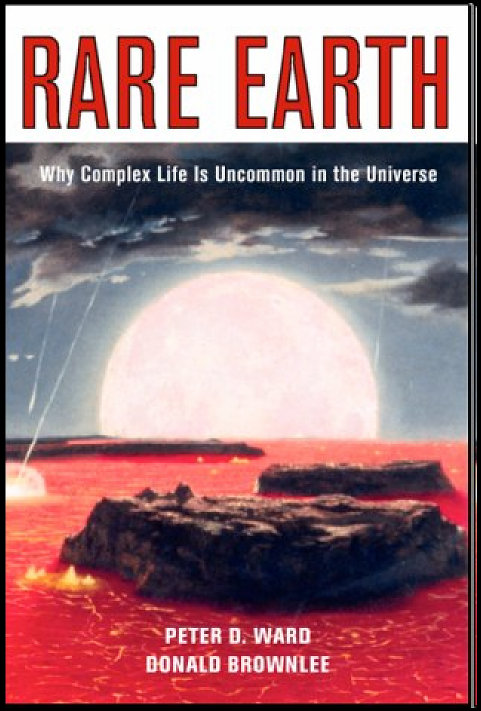
The Medea and Rare Earth hypotheses



Peter Ward



2009



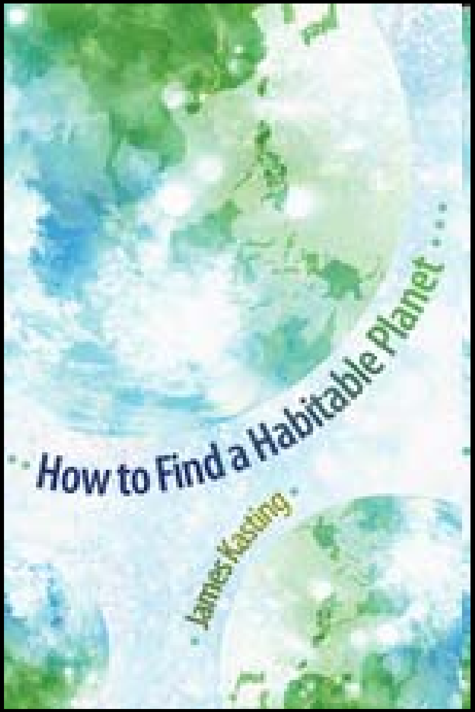
2000

<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)

- As you will see, I am more optimistic than either Peter Ward or Jim Lovelock

Phanerozoic Time

Era	Period	Epoch	Duration in millions of years	Millions of years ago
CENOZOIC	Quaternary	Holocene	0.01	0.01
		Pleistocene	1.8	1.8
	Tertiary	Pliocene	3.5	5.3
		Miocene	18.5	23.8
		Oligocene	9.9	33.7
		Eocene	21.1	54.8
		Paleocene	10.2	65
MESOZOIC	Cretaceous		79	144
	Jurassic		62	206
	Triassic		42	248
PALEOZOIC	Permian		42	290
	Carboniferous	Pennsylvanian	33	323
		Mississippian	31	354
	Devonian		63	417
	Silurian		26	443
	Ordovician		47	490
	Cambrian		53	543
PRECAMBRIAN				

s, based on the principles of

Ice age (Pleistocene)

← Dinosaurs go extinct

Warm

← First dinosaurs

Ice age

← First vascular plants on land

← Ice age

← Age of fish

Warm

← First shelly fossils

Geologic time

EON		ERA	Duration in millions of years	Millions of years ago
PHANEROZOIC		CENOZOIC	65	65
PHANEROZOIC		MESOZOIC	183	248
PHANEROZOIC		PALEOZOIC	295	543
PRECAMBRIAN	PROTEROZOIC	LATE	357	900
PRECAMBRIAN	PROTEROZOIC	MIDDLE	700	1600
PRECAMBRIAN	PROTEROZOIC	EARLY	900	2500
PRECAMBRIAN	ARCHEAN	LATE	500	3000
PRECAMBRIAN	ARCHEAN	MIDDLE	400	3400
PRECAMBRIAN	ARCHEAN	EARLY	400	3800
PRECAMBRIAN	HADEAN		800	4600

← First shelly fossils (Cambrian explosion)

← Snowball Earth ice ages

Warm

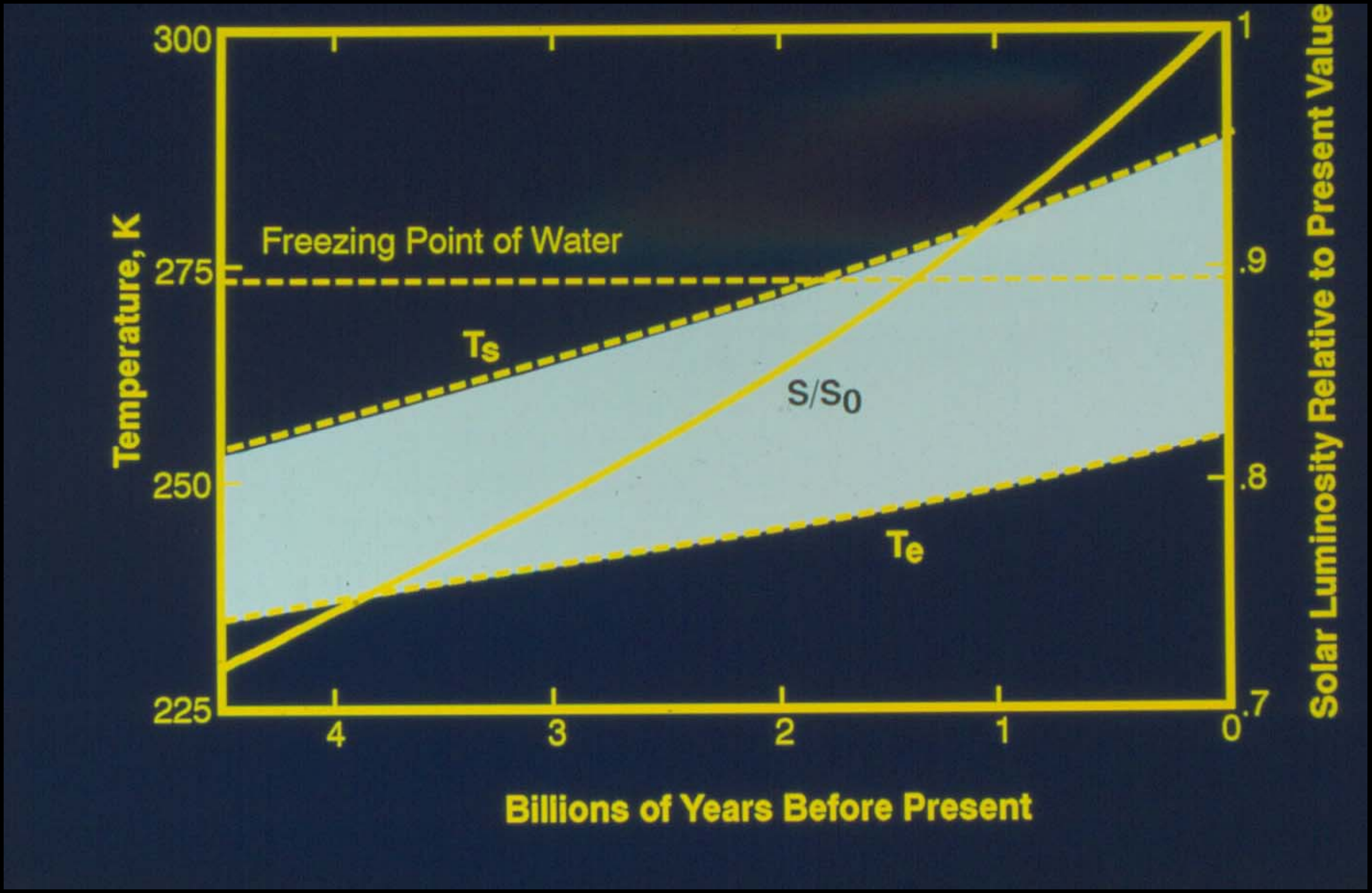
← Rise of atmospheric O_2 (Ice age)

← Ice age

Warm (?)

Origin of life

The faint young Sun problem



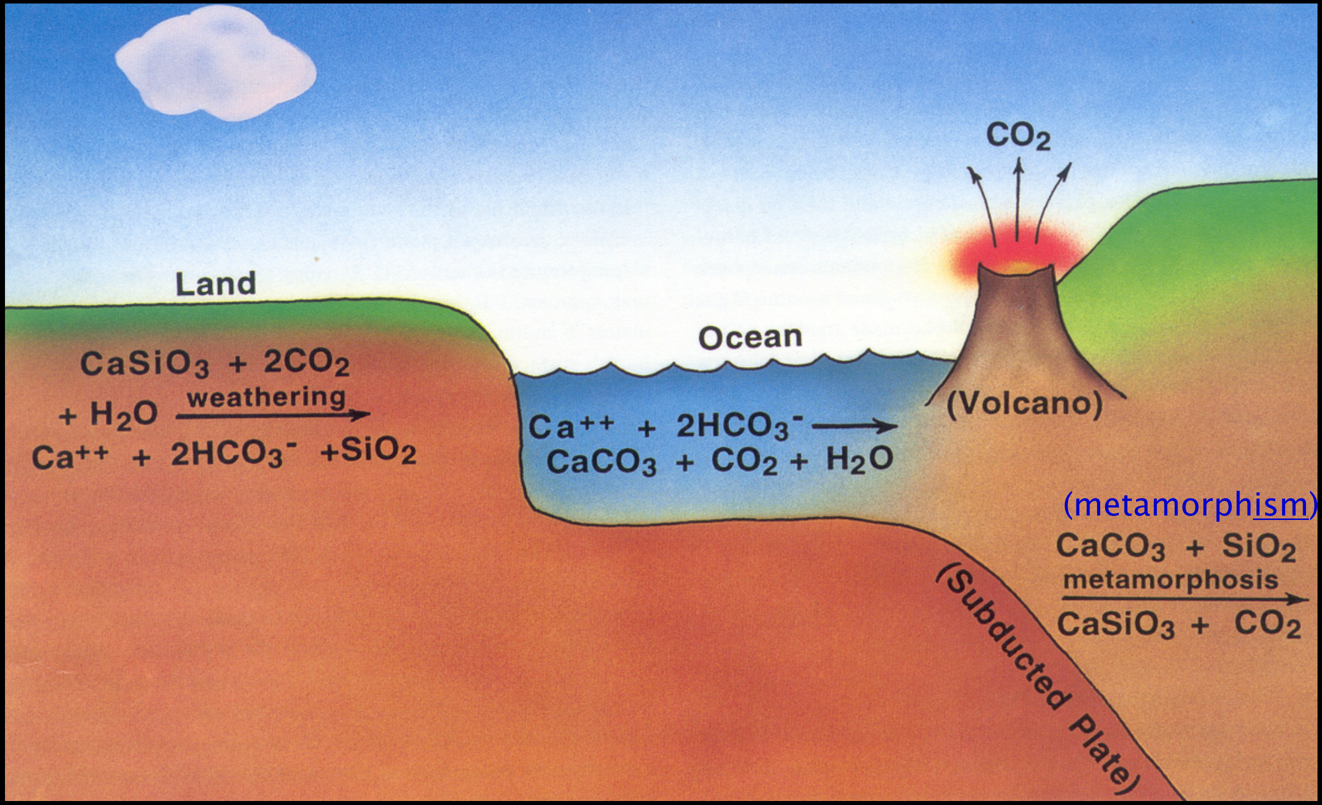
- The Sun was less bright back in the distant past. If nothing else changed, Earth's oceans should have been entirely frozen. Kasting et al., *Scientific American* (1988)

- The best (but not the only!) way to address this problem is to have higher *greenhouse gas* concentrations on the early Earth $\Rightarrow$

Greenhouse gases

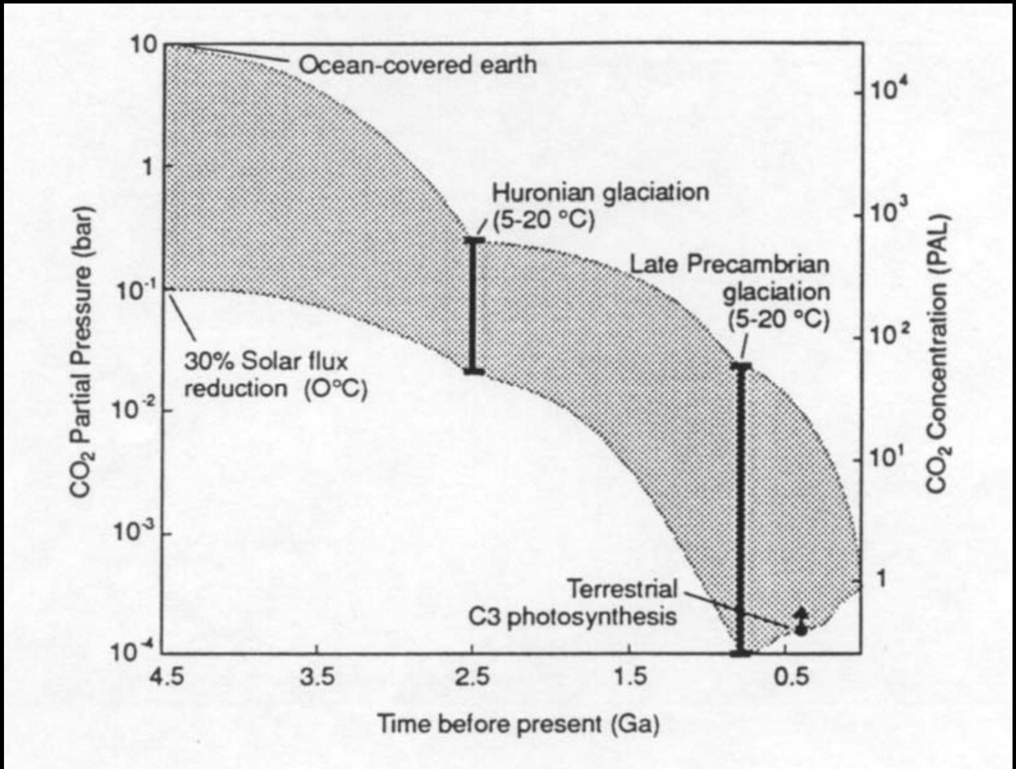
- Greenhouse gases are gases that let most of the incoming visible solar radiation in, but absorb and re-radiate much of the outgoing infrared radiation
- Important greenhouse gases on Earth are CO_2, H_2O, and CH_4
  - H_2O, though, is always near its condensation temperature; hence, it acts as a *feedback* on climate rather than as a *forcing* mechanism
- The decrease in solar luminosity in the distant past could have been offset either by higher CO_2 or by reduced gases, such as NH_3 and CH_4

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

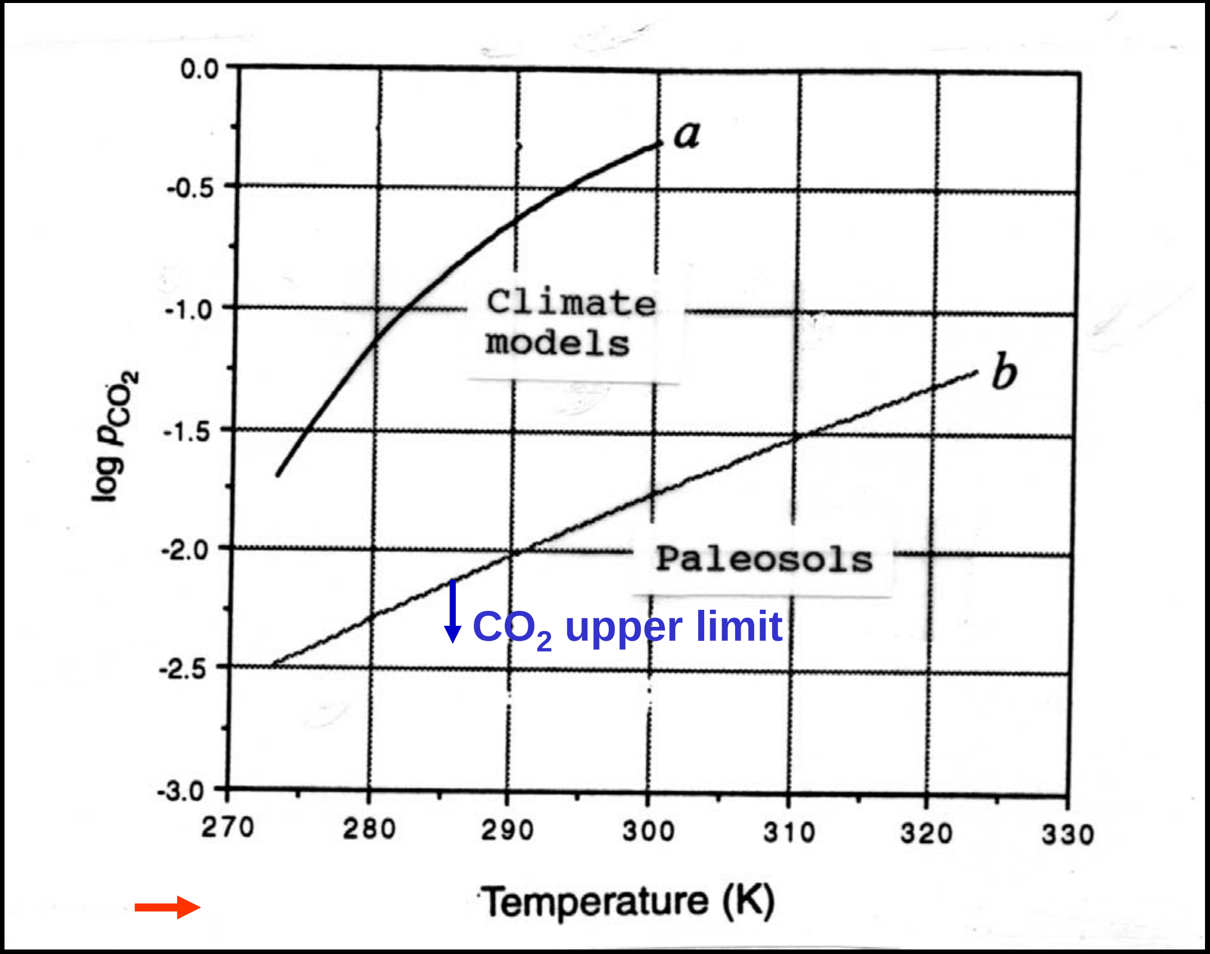
CO_2 vs. time *if* no other greenhouse gases (besides H_2O)



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)



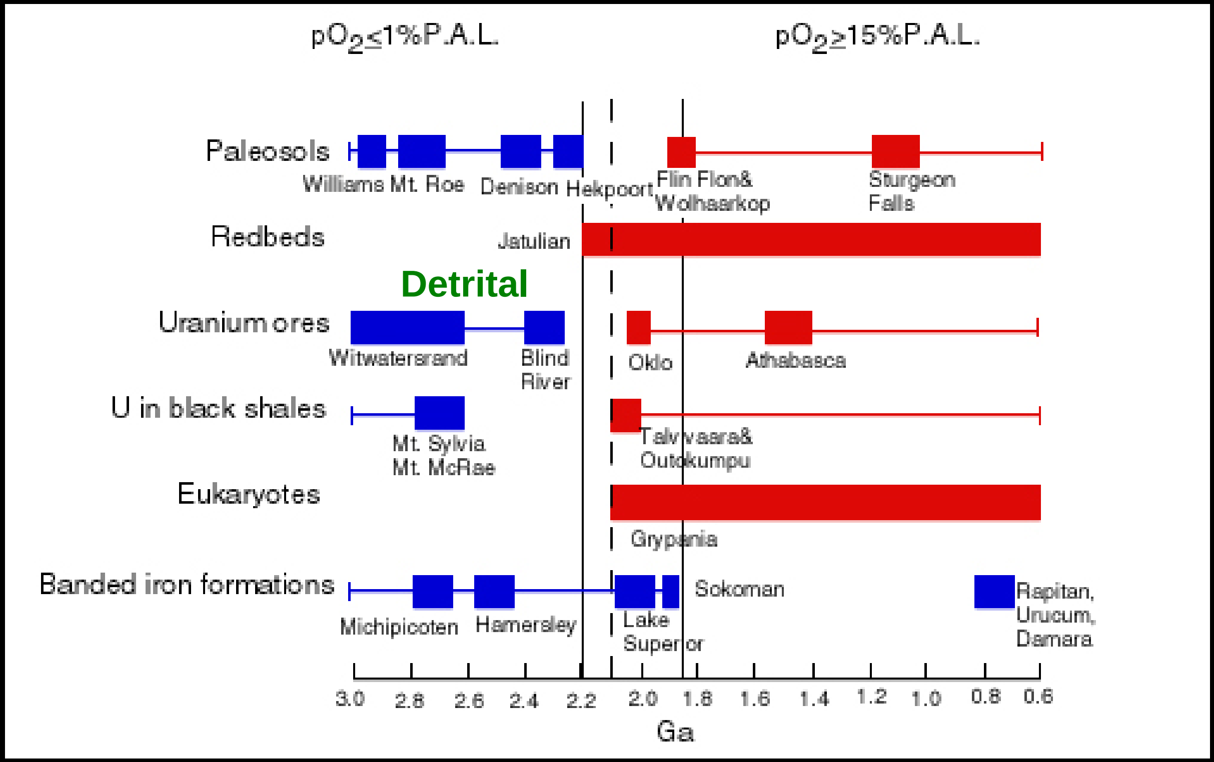
Today's CO_2 level (3×10^{-4} atm)

Rye et al., *Nature* (1995)

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

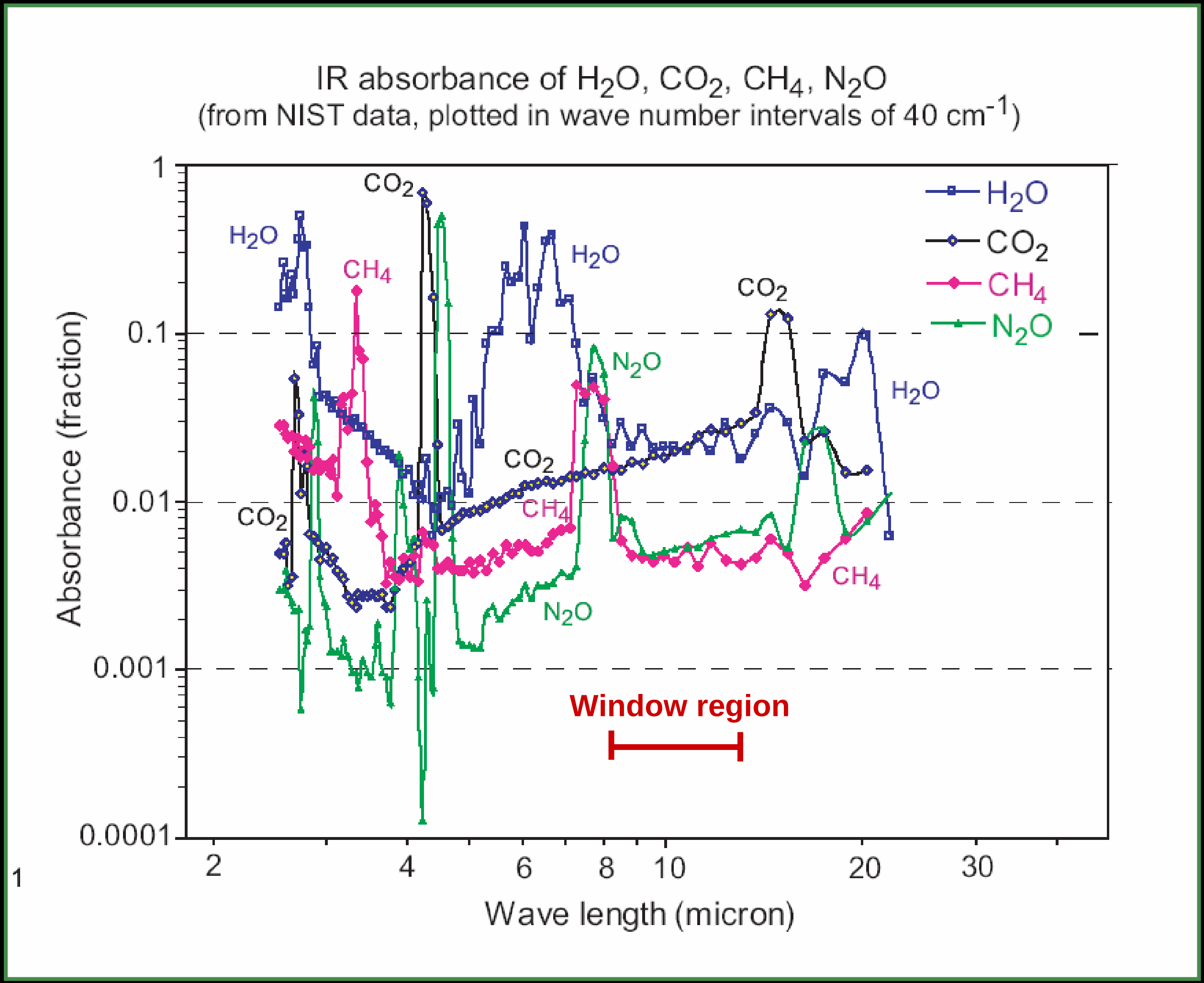
⇒ May need other green-house gases (CH_4?)

- CH_4 could have been higher because atmospheric O_2 was lower in the distant past



H.D. Holland (1994)

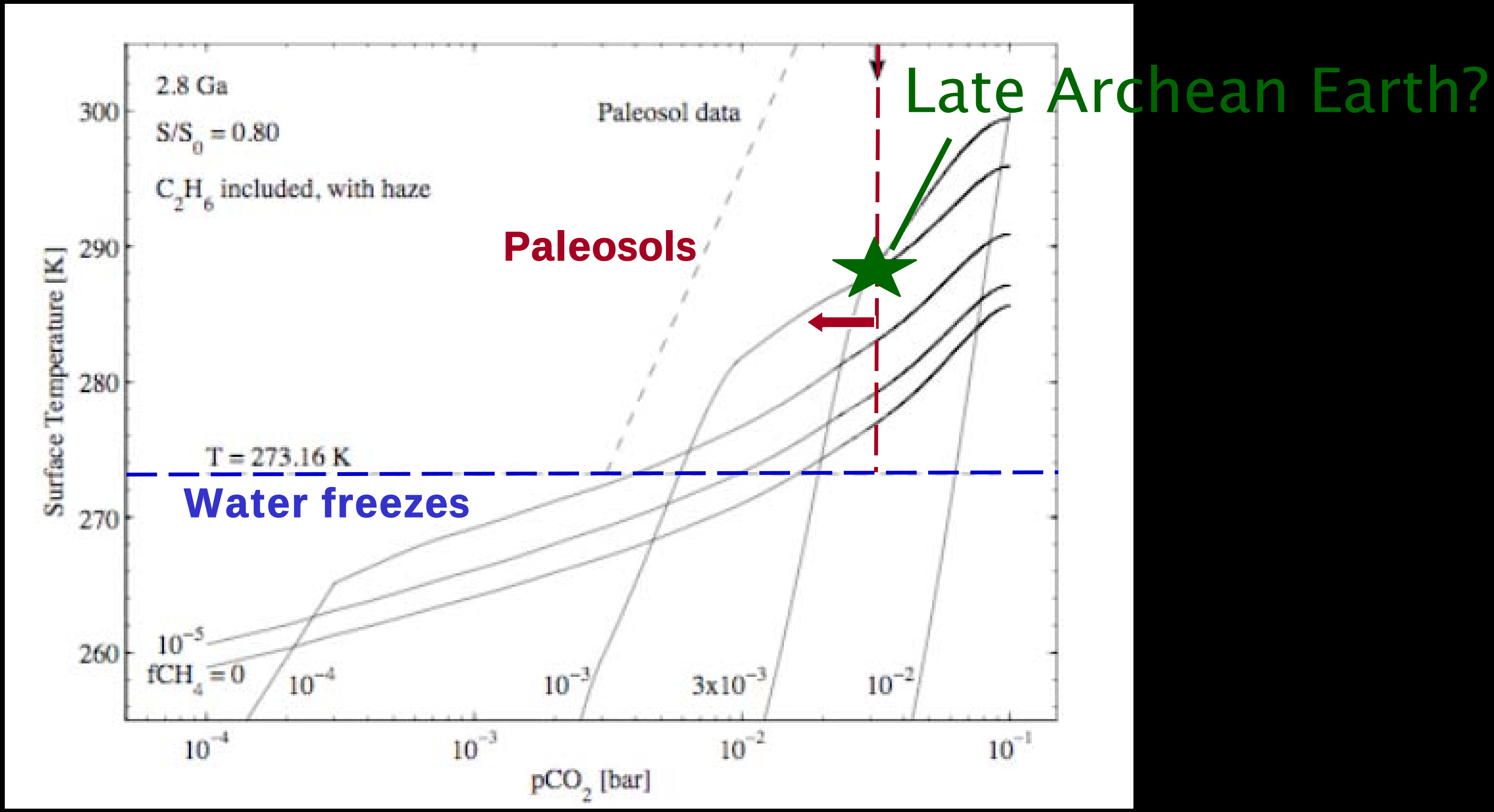
- Mass-independently fractionated S isotopes strongly support this conclusion



- 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.

$CH_4/CO_2/C_2H_6$ greenhouse with haze



- One can compensate for low solar luminosity by having higher concentrations of greenhouse gases, specifically, CO_2 and CH_4
- Warming by CH_4 is limited, however, by the formation of *organic haze,* which starts to form when the atmospheric CH_4/CO_2 ratio > 0.1

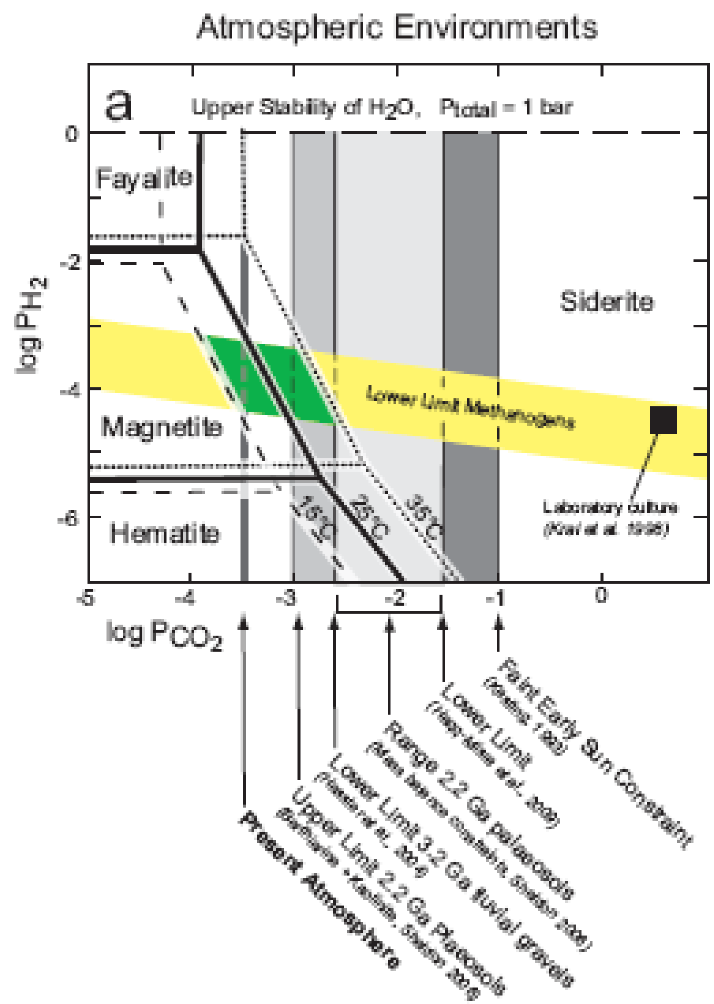
J. Haqq-Misra et al., *Astrobiology* (2008)

Nature, Apr. 1 (tomorrow!)

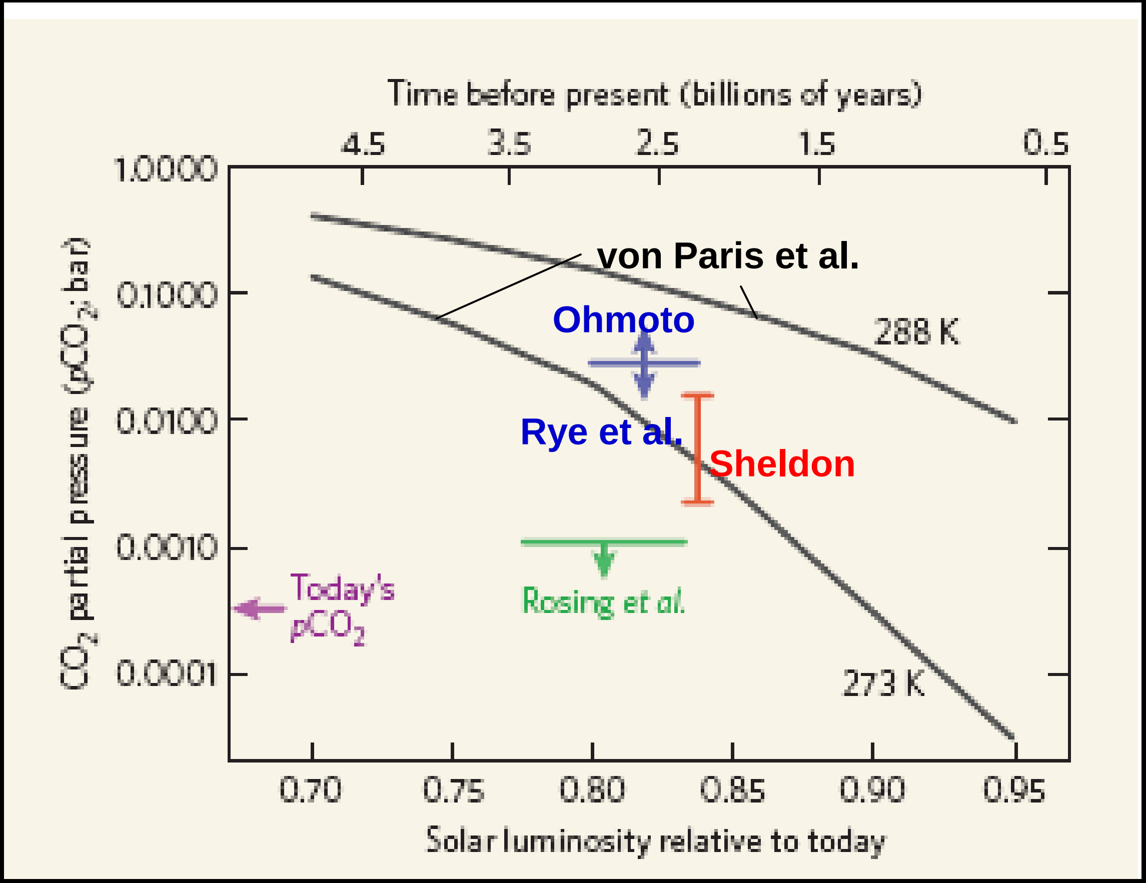
No climatic paradox under the faint early Sun

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

- 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



Rosing et al.: CO_2 from BIFs

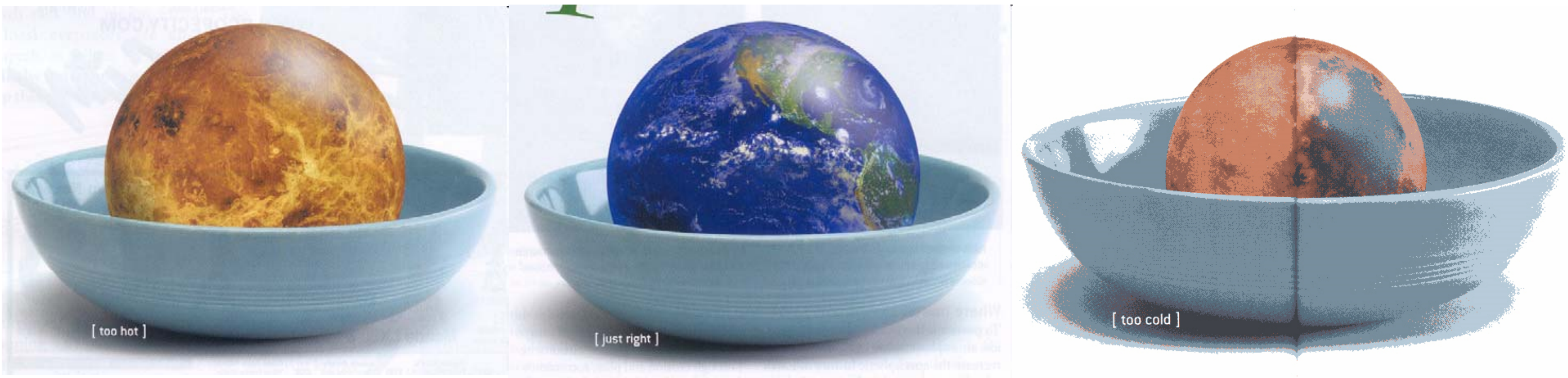


- If the new CO_2 constraints are correct, then other warming mechanisms are clearly needed
- Rosing et al. suggest a reduced *cloud albedo* caused by the absence of biogenic sulfur gases, but this doesn't work if the climate was really warm

J. F. Kasting, Nature, Apr. 1

- Finally (and briefly), why is Earth unique in our Solar System?

The Goldilocks paradox



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

  Lynn Margulis

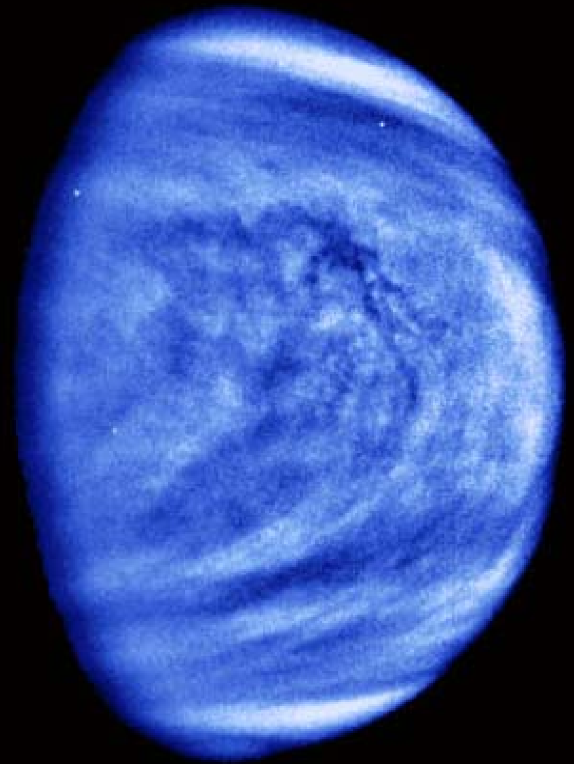
- The obvious answer concerns their relative distances from the Sun
- However, it turns out that this is only part of the story…

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*

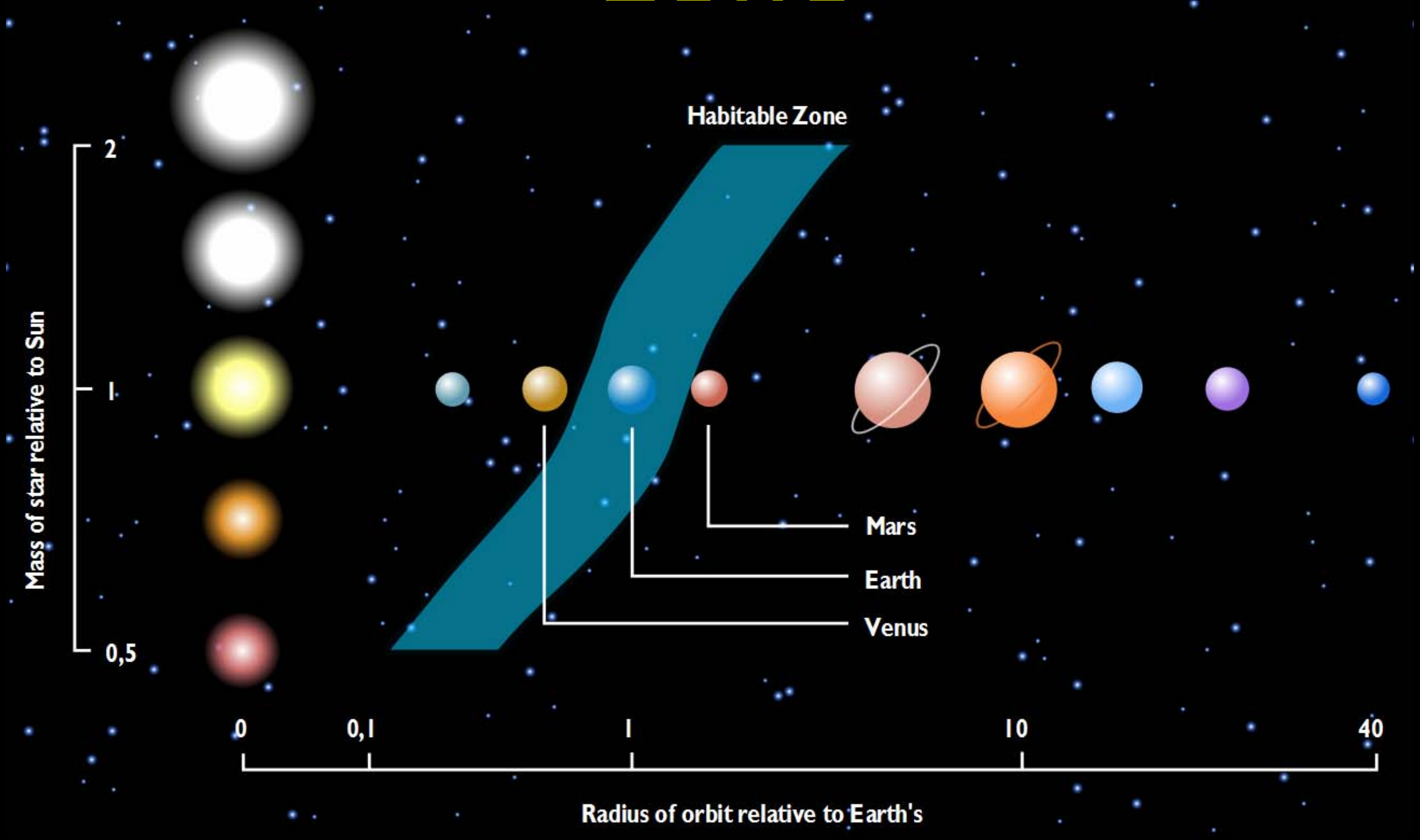
Why isn't Venus habitable?

- Venus apparently had a lot of water early in its history, but it lost it because of a *runaway greenhouse*
  - Very high D/H ratio (~150 times Earth's value)
- 93-bar, CO_2-rich atmosphere
- Surface temperature: 730 K
- Practically no water



UV image (false color) from the Galileo spacecraft. Courtesy of NASA.

The (liquid water) habitable zone



- If we put all this together, we can estimate the boundaries of the *habitable zone,* where liquid water can exist on a planet's surface
- The habitable zone is relative *wide* because of the negative feedback provided by the carbonate-silicate cycle

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

Conclusions

- The Archean Earth was *warm,* despite reduced solar luminosity. The answer most likely involves warming by some combination of greenhouse gases, including CO_2, CH_4, *and maybe something else*?
- Venus is too close to the Sun, and Mars is too small, to be habitable
- The *habitable zone* is reasonably wide, so the prospects for finding other Earth-like planets are good