41st Saas-Fee Course
From Planets to Life
3-9 April 2011

The Faint Young Sun Problem

Long-term climate/
Solar luminosity changes/
Constraints on atmospheric CO_2/
The methane greenhouse

J. F. Kasting

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				

Ice age (Late Cenozoic)

← Dinosaurs go extinct

Warm

← First dinosaurs

Ice age

← First vascular plants on land

← Ice age

← Age of fish

← First shelly fossils

s, based on the principles of

Geologic time

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

- From a theoretical standpoint, it is curious that the early Earth was *warm*, because the Sun is thought to have been *less bright* $\Rightarrow$

Why the Sun gets brighter with time

- H fuses to form He in the core
- Core becomes denser
- Core contracts and heats up
- Fusion reactions proceed faster
- More energy is produced $\Rightarrow$ more energy needs to be emitted

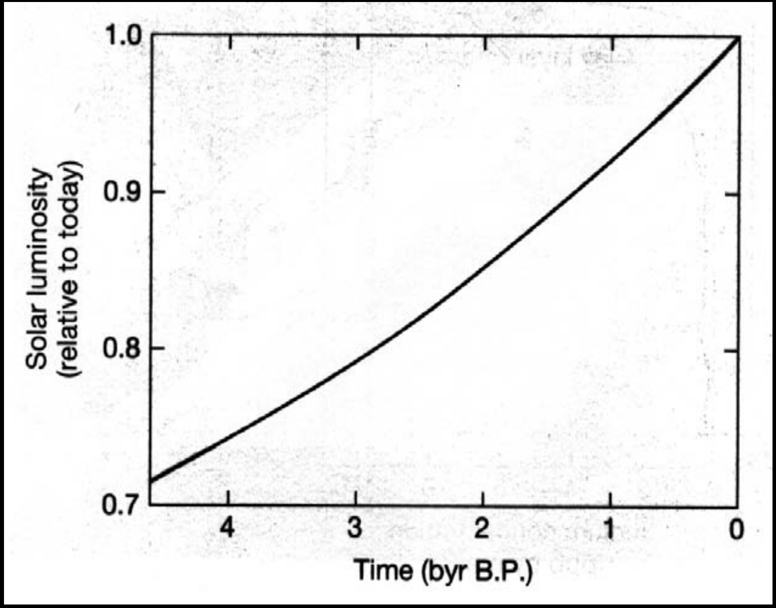
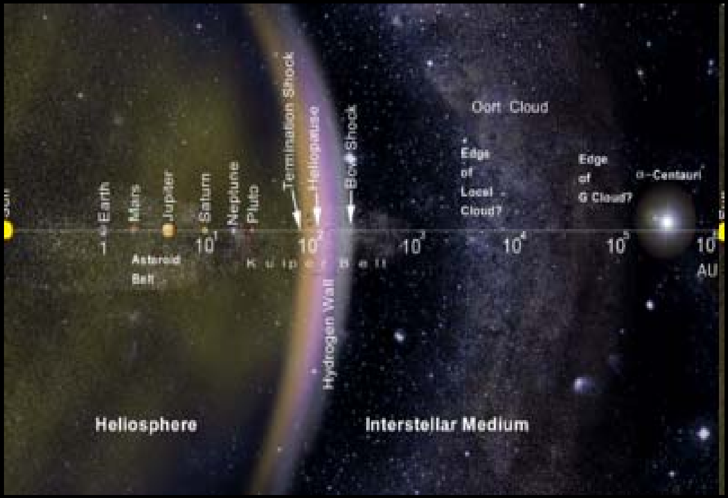


Figure redrawn from D.O. Gough, Solar Phys. (1981)

$$\frac{S}{S_0} = \frac{1}{1 + 0.4(t / 4.6\,\mathrm{Ga})}$$

Enhanced solar mass loss?

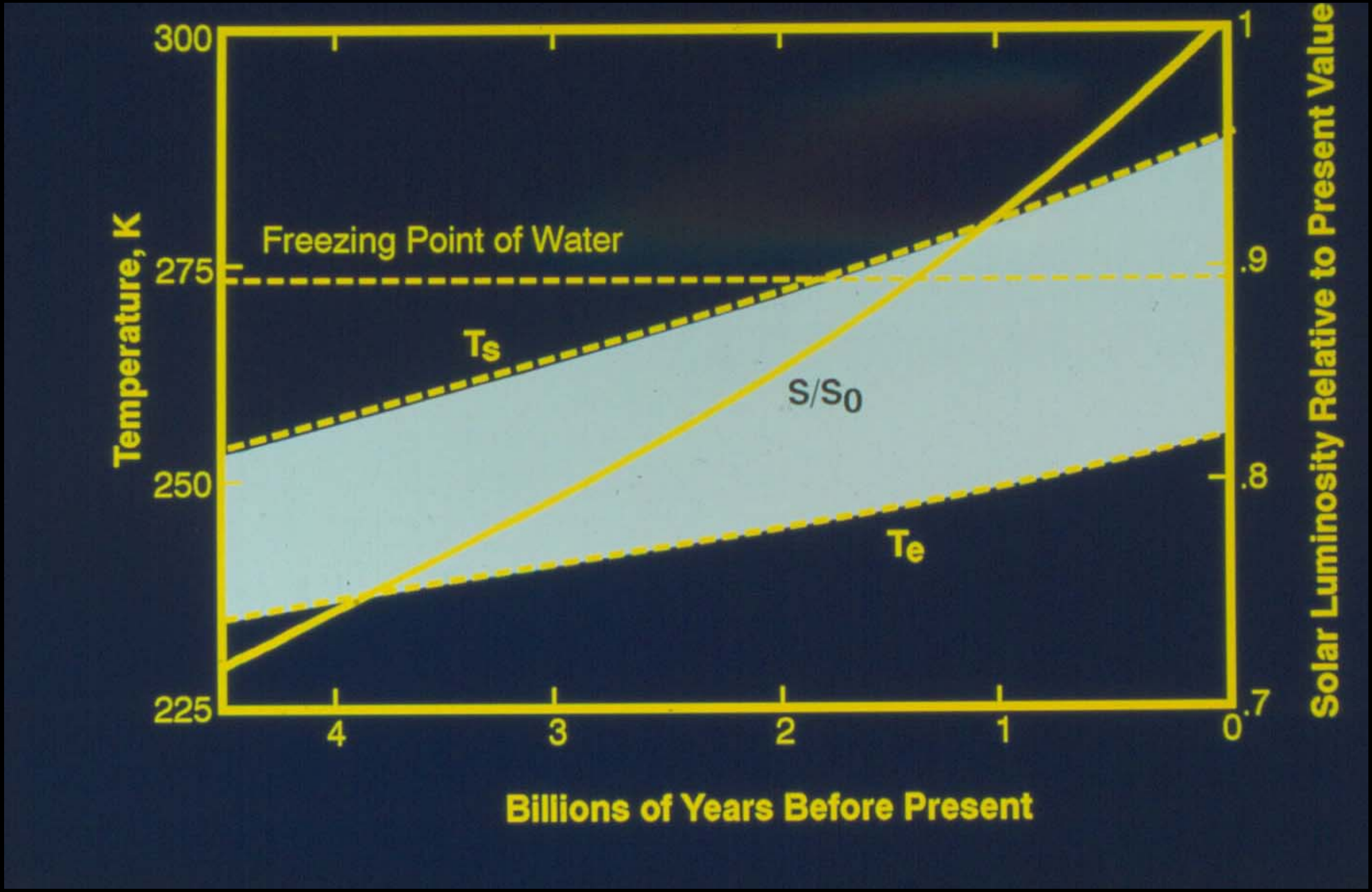
- Are we sure that the Sun was less bright back in the past?
- What if the young Sun was more massive than today?
  - Brian Wood and colleagues at Univ. of Colorado have derived empirical constraints from observations of nearby young stars (see backup slides)
  - Their conclusion is that any massive solar mass loss must have occurred very early, within the first 100-200 m.y.; hence, it does not affect the Earth during the time period of interest to geologists or astrobiologists



- One cannot measure (fully ionized) stellar winds directly, but one can look at neutral hydrogen that builds up the the stellar *astrosphere*

- So, I will assume that the young Sun was really faint, as predicted by the standard model
- This has big implications for planetary climates, as first pointed out by Sagan and Mullen (1972)…

The faint young Sun problem

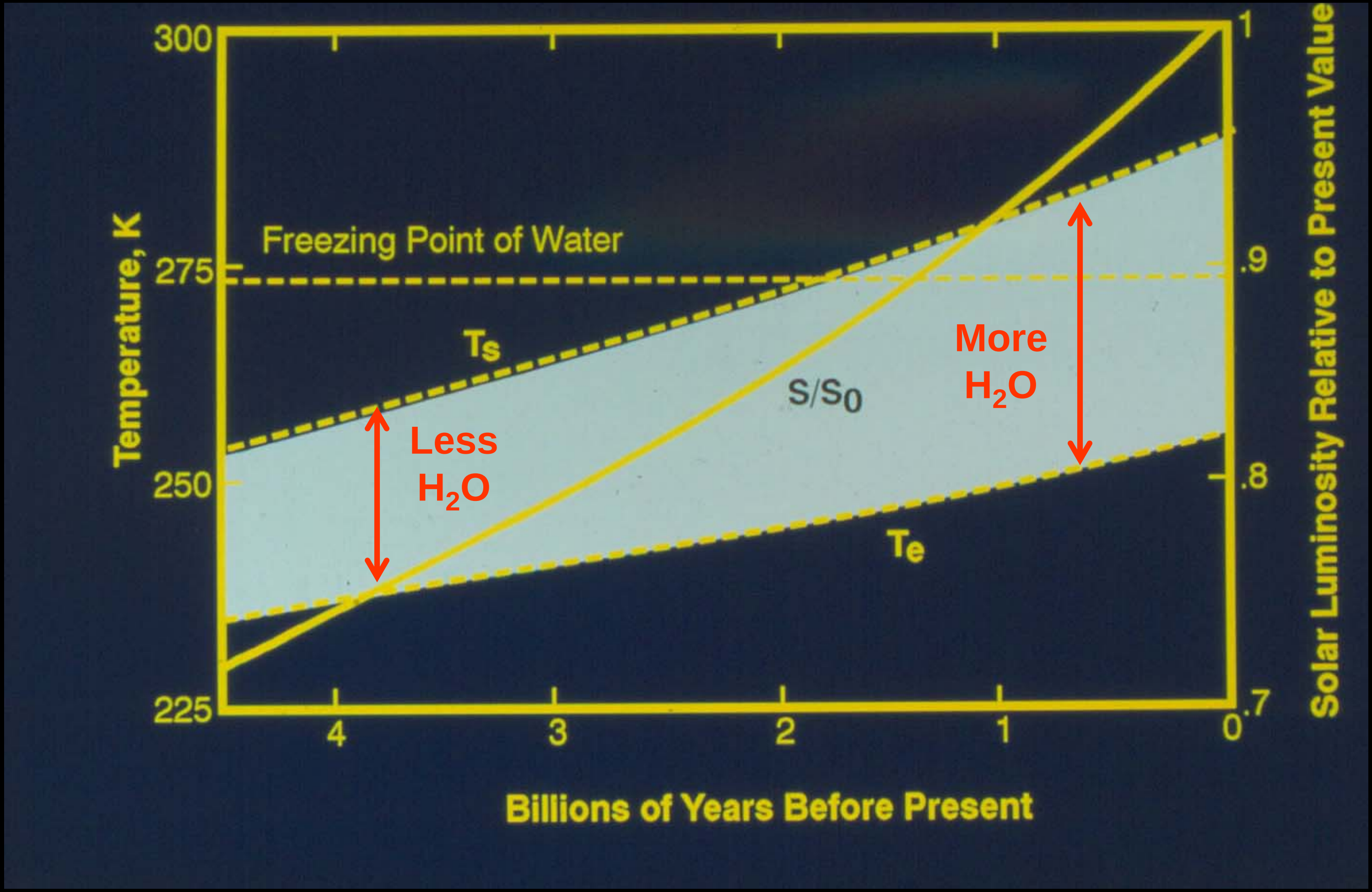


T_e = effective radiating temperature = $[S(1-A)/4\sigma]^{1/4}$

T_S = average surface temperature

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

The faint young Sun problem

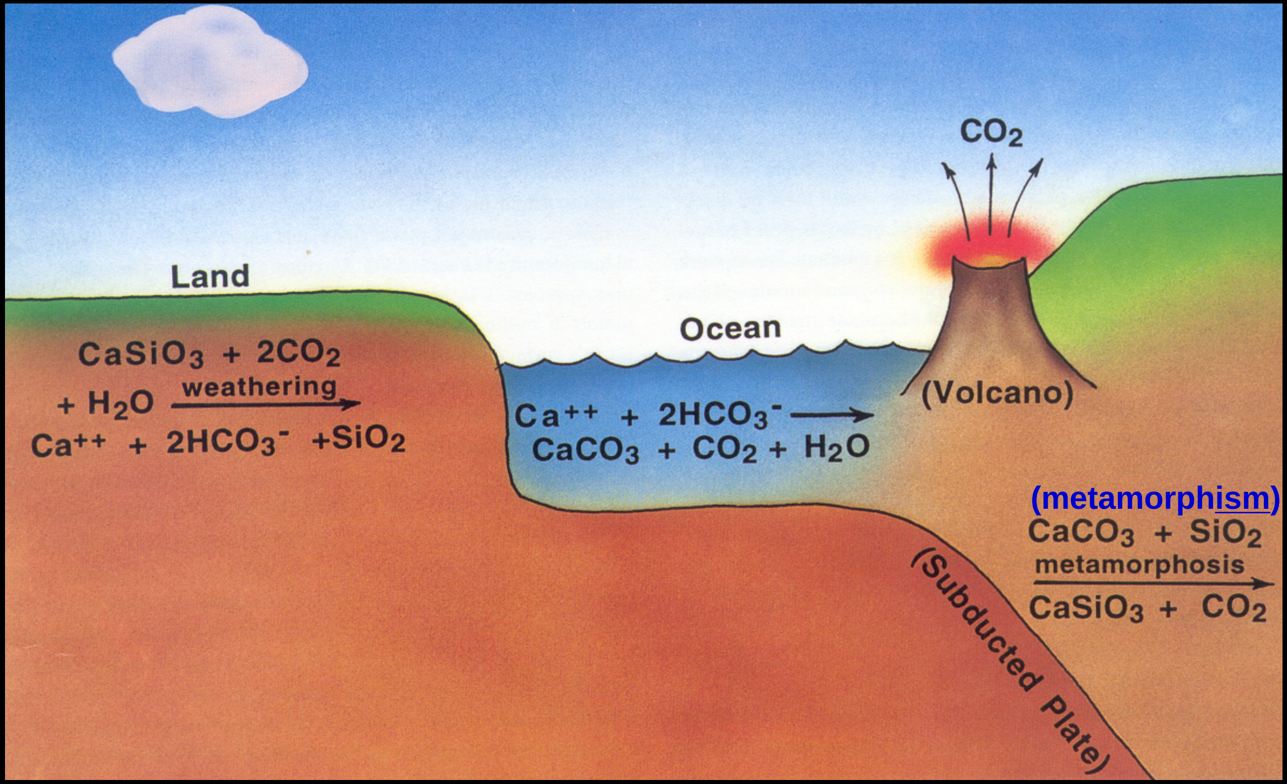


- The best solution to this problem is higher concentrations of greenhouse gases in the distant past (but not H_2O, which only makes the problem worse)

Greenhouse gases

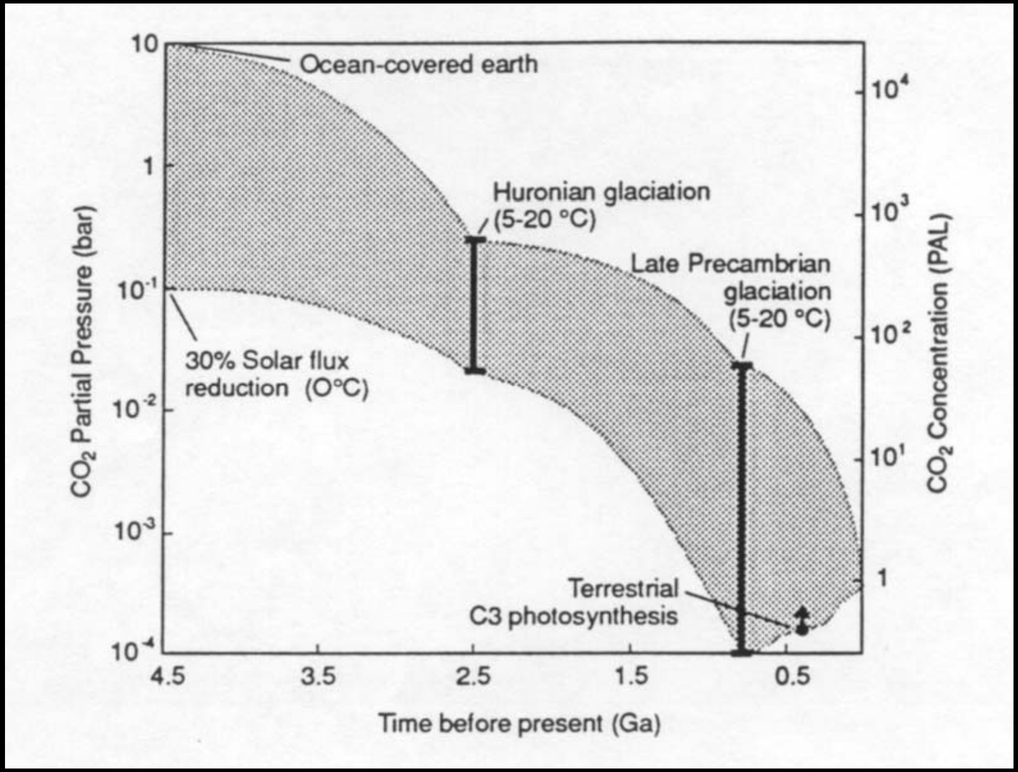
- Greenhouse gases are gases that let most of the incoming visible solar radiation in, but absorb and re-radiate much of the outgoing infrared radiation
- Important greenhouse gases on Earth are CO_2, H_2O, and CH_4
  - H_2O, though, is always near its condensation temperature; hence, it acts as a *feedback* 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, higher CH_4, or both. Let's consider CO_2 first $\Rightarrow$

The carbonate-silicate cycle



- Silicate weathering slows down as the Earth cools
  $\Rightarrow$ atmospheric CO_2 should build up
- This is probably at least part of the solution to the faint young Sun problem

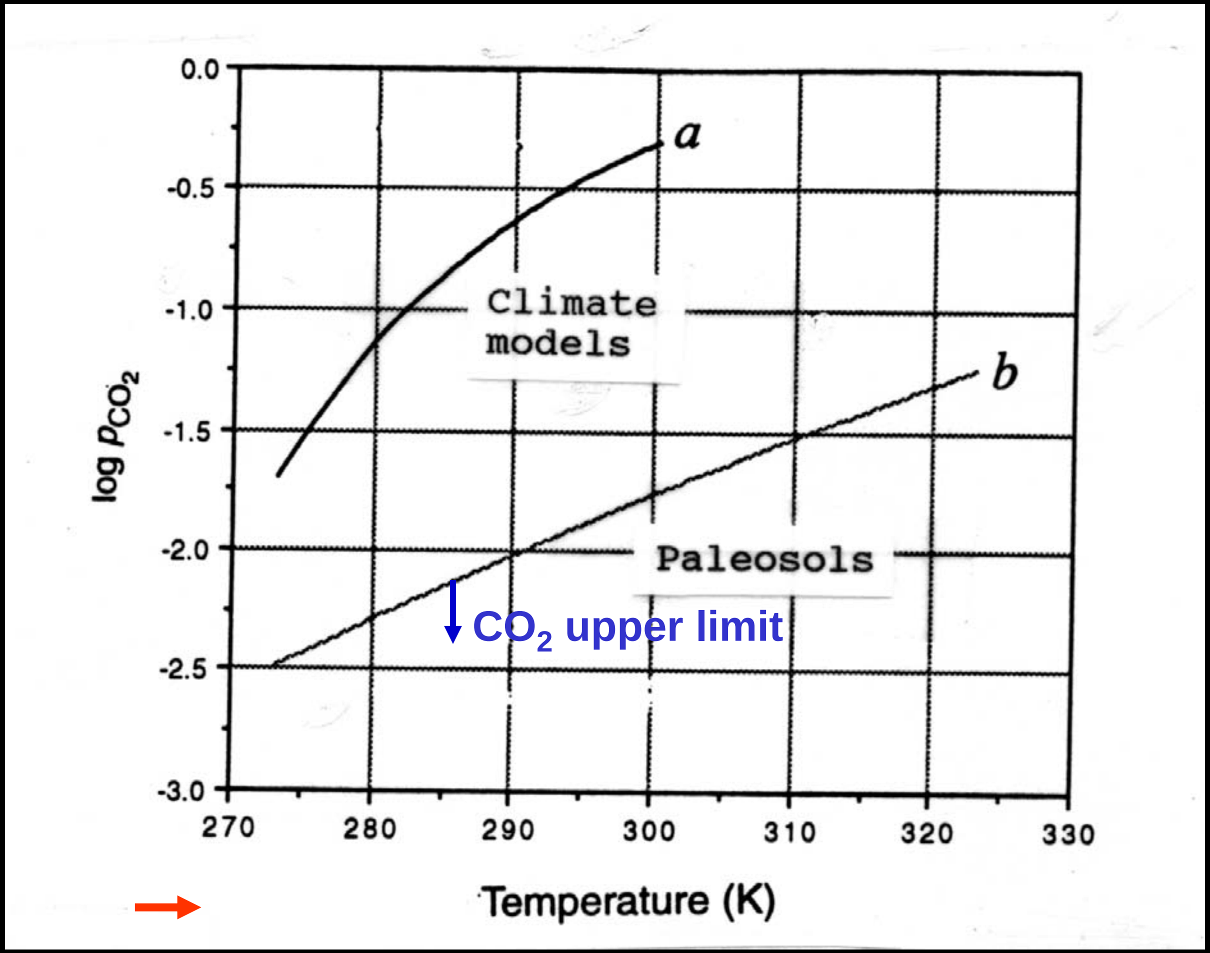
CO_2 vs. time *if* no other greenhouse gases (besides H_2O)



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

- In the simplest story, atmospheric CO_2 levels should have declined monotonically with time as solar luminosity increased

pCO_2 from paleosols (2.8 Ga)

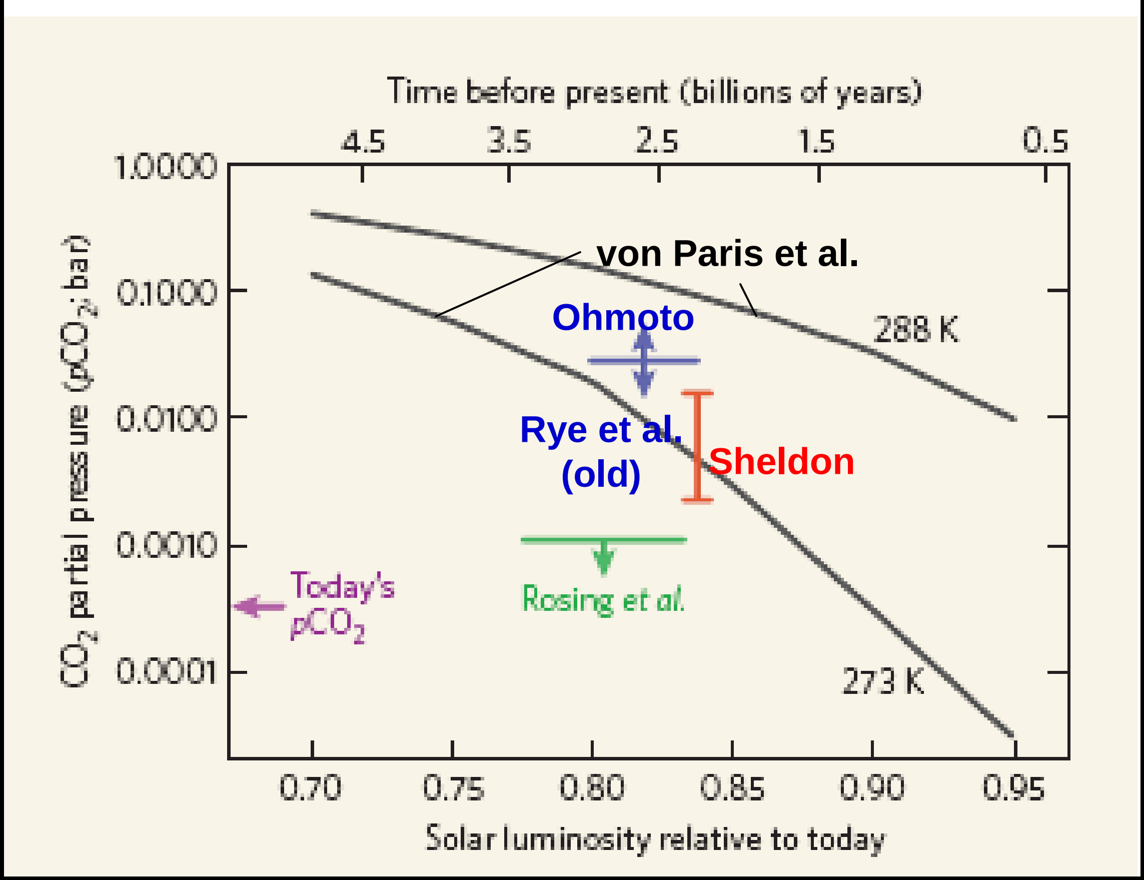


Today's CO_2 level (3×10^{-4} atm)

Rye et al., *Nature* (1995)

- But, various geochemists have attempted to place limits on past CO_2 levels
- According to these authors, the absence of siderite ($FeCO_3$) places an upper bound on pCO_2

Rosing et al.: CO_2 from BIFs



J. F. Kasting
Nature (2010)

- More recently, Rosing et al. (Nature, 2010) have tried to place even more stringent constraints on past CO_2 using banded iron-formations (BIFs)
- I actually don't believe *any* of these constraints
- Nevertheless, there are reasons to think that other greenhouse gases were present

Sagan and Mullen, Science (1972)

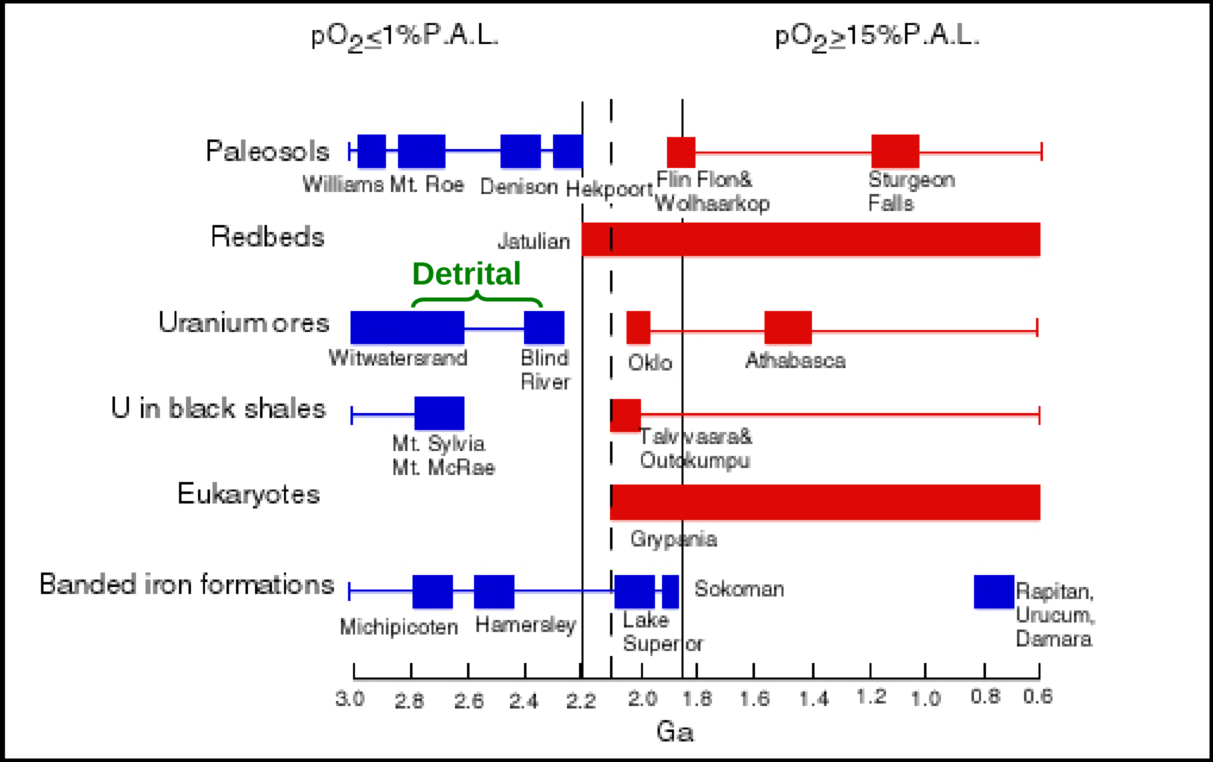
Reports

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) and methane (CH_4) as Archean greenhouse gases
- As a result of Preston Cloud's work in the late 1960's, they were aware that atmospheric O_2 was low on the early Earth $\Rightarrow$

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



H.D. Holland (1994)

- Mass-independently fractionated sulfur isotopes strongly support this conclusion
  -- I’ll return to this topic in the next lecture

- But Sagan and Mullen hadn't thought about the photochemistry of ammonia $\Rightarrow$

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)	$N_2H_3 + N_2H_3 \rightarrow N_2H_4 + N_2H_2$
	$\rightarrow N_2H_4 + N_2 + H_2$

-- N_2 and H_2 do not readily recombine to form NH_3

-- N_2 ($N \equiv N$) is stable, and the H_2 escapes to space

-- This said, CH_4 remains a viable candidate…

Other reasons for liking CH_4 in addition to CO_2

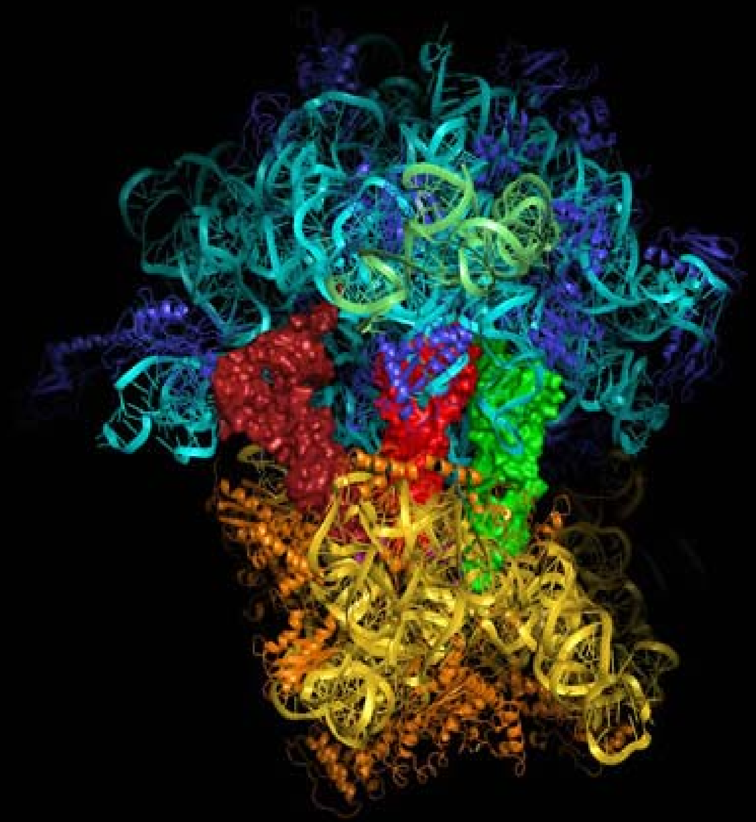
- Substrates for methanogenesis should have been widely available, e.g.:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$$

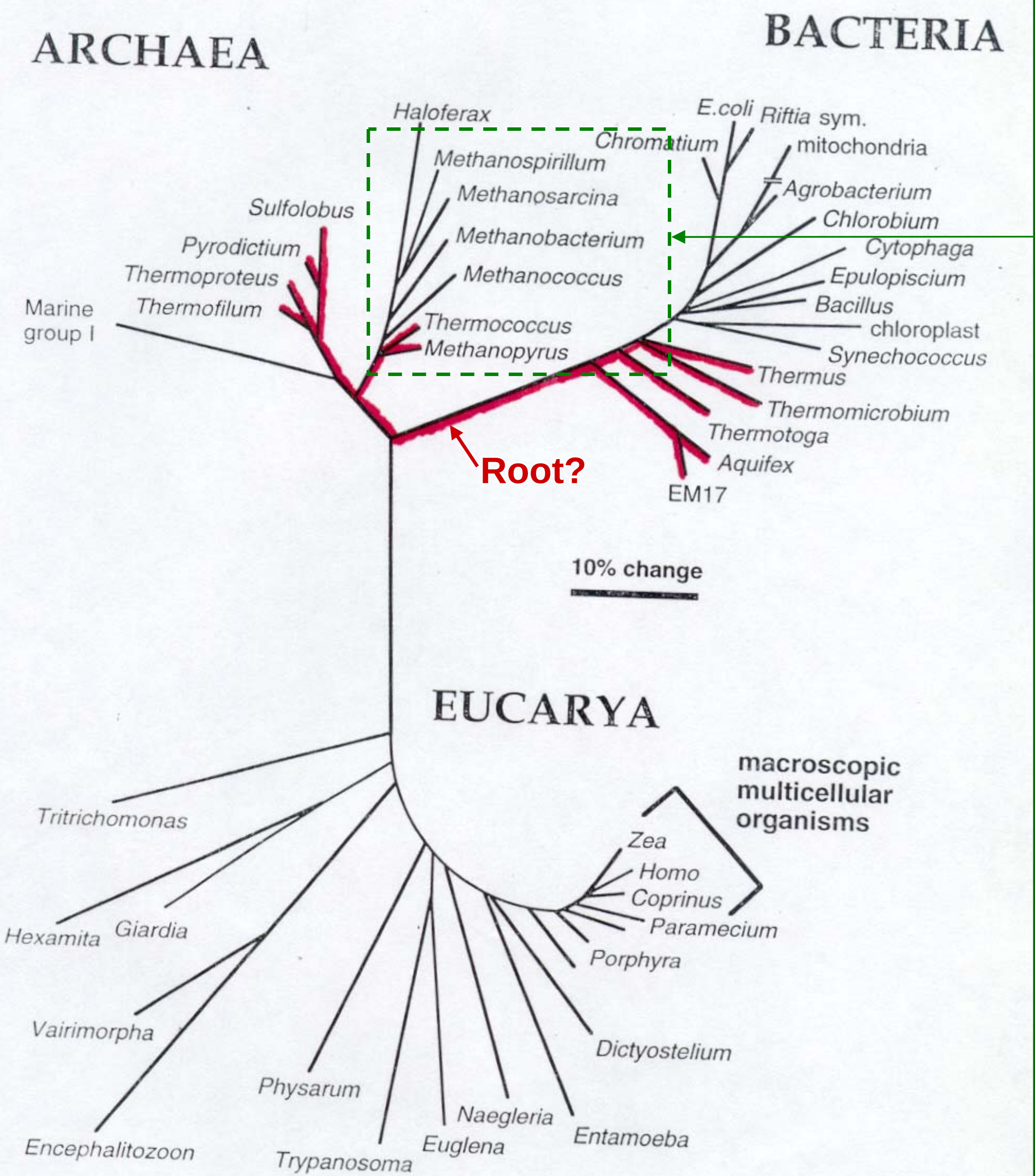
- Methanogens (organisms that produce methane) are evolutionarily ancient
  – We can tell this by looking at their DNA
  – In particular, we look for that part of the DNA that codes for the RNA in their *ribosomes* $\Rightarrow$

Ribosomal RNA

- Ribosomes are organelles (inclusions) within cells in which proteins are made
- Surprisingly (or not), ribosomes contain their own RNA (ribonucleic acid)
  - The RNA is also the catalyst for protein synthesis, indicating that life may have passed through an "RNA World" stage
- The RNA in ribosomes evolves very slowly, so looking at differences in the RNA of different organisms allows biologists to look far back into evolution



http://www.scilogs.eu/en/blog/lindaunobel/2010-06-29/mountains-beyond-mountains



Methanogenic bacteria

“Universal” (rRNA) tree of life

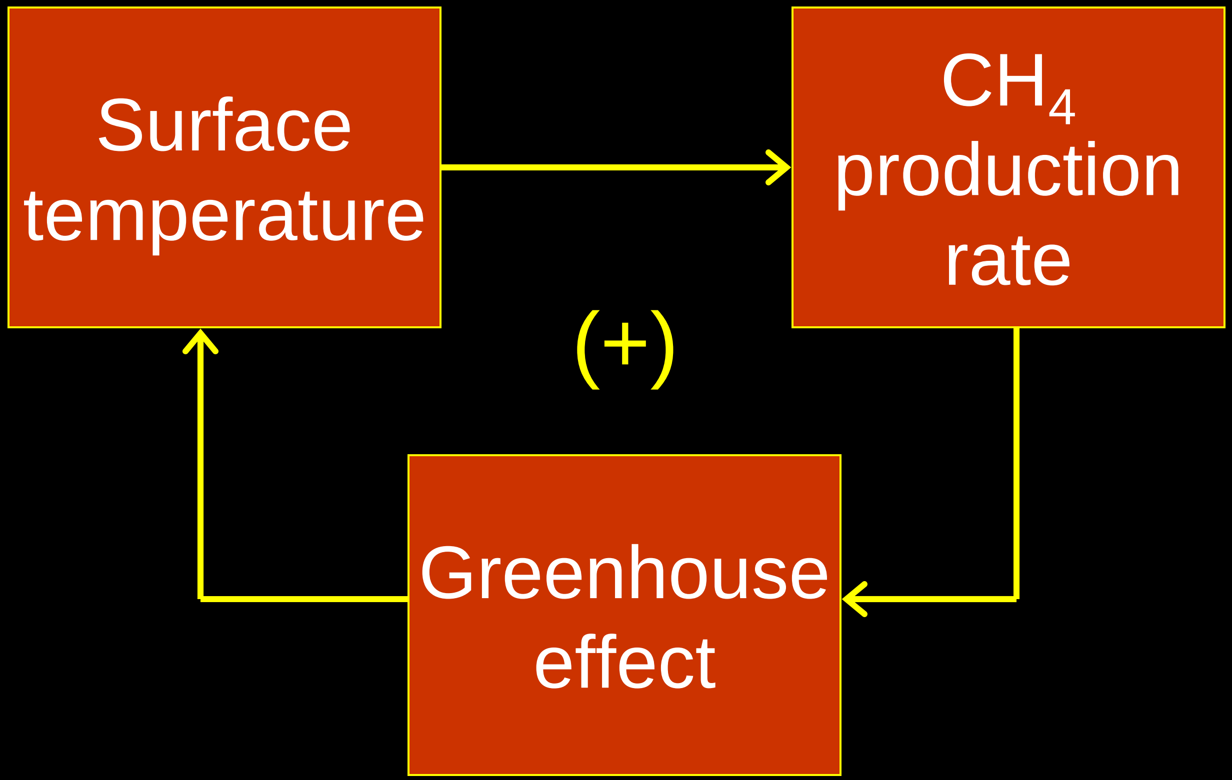
Courtesy of Norm Pace

- Back to climate…

Feedbacks in the methane cycle

- Furthermore, there are strong *feedbacks* in the methane cycle that would have helped methane become abundant
- Doubling times for thermophilic methan-ogens are shorter than for mesophiles
- Thermophiles will therefore tend to outcompete mesophiles, producing more CH_4 and further warming the climate

CH_4-climate positive feedback loop

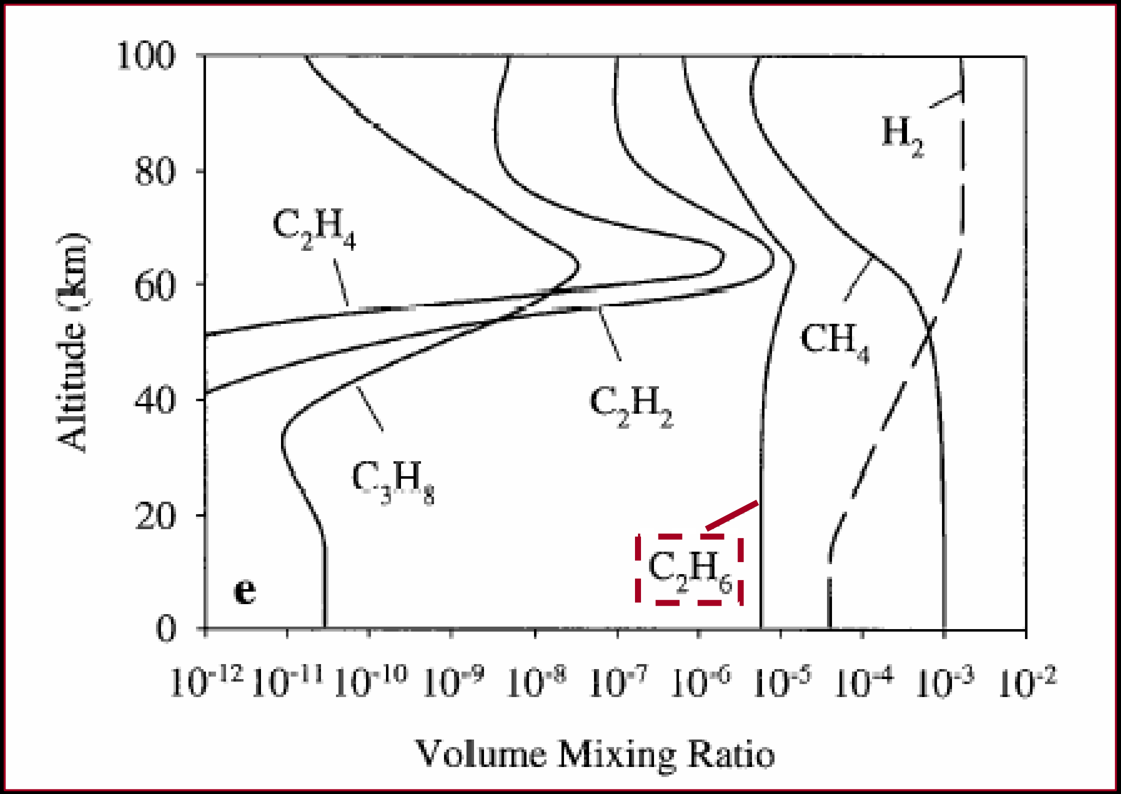


- Methanogens grow faster at high temperatures

Furthermore,

- If CH_4 becomes more abundant than about 1/10th of the CO_2 concentration, it begins to *polymerize* $\Rightarrow$

Organic haze photochemistry



This leads to the formation of *ethane* (C_2H_6), *ethylene* (C_2H_4), and *acetylene* (C_2H_2)

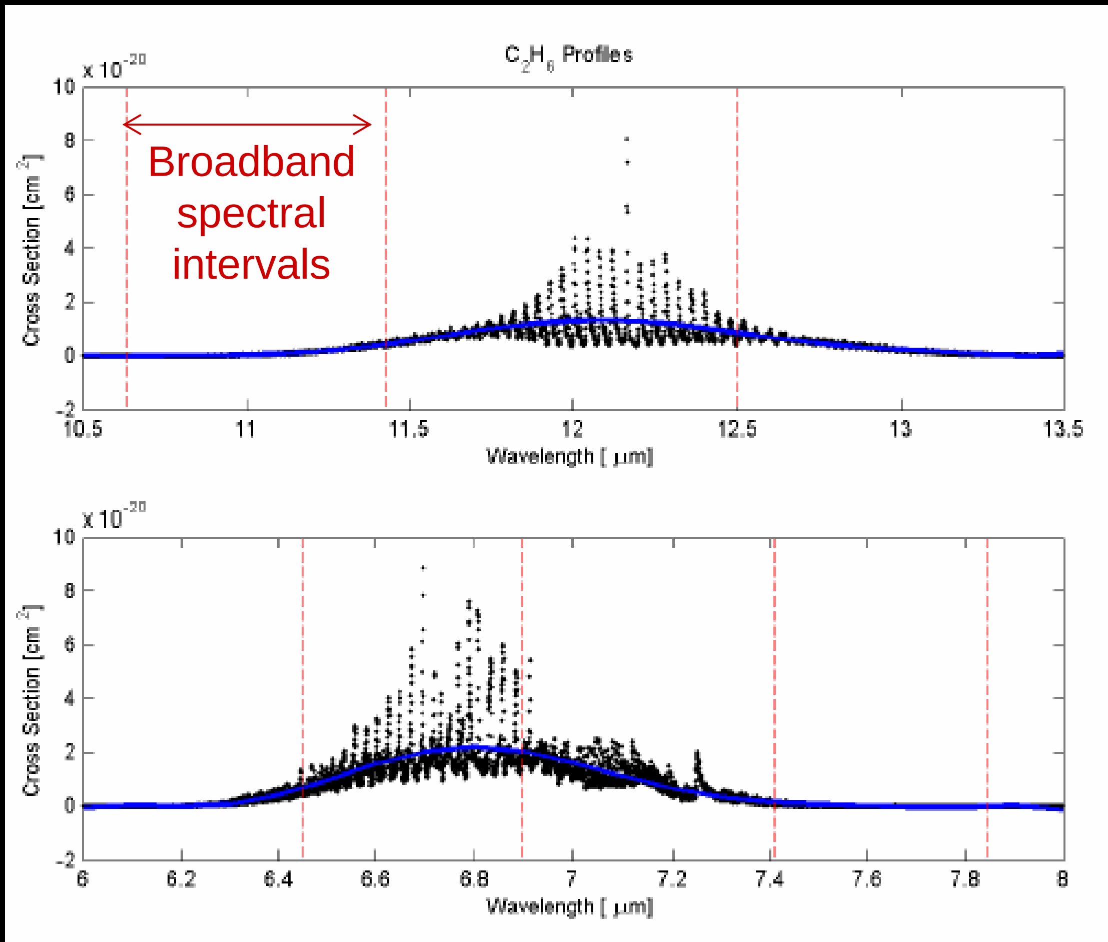
Ethane formation:

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

or

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

- "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



Important ethane band

- Ethane (C_2H_6) is a good greenhouse gas because it absorbs within the 8-12 μm "window" region
- It can provide several degrees of greenhouse warming

- If the CH_4:CO_2 ratio exceeds about 0.1, however, *organic haze* begins to form, as it does on Saturn's moon, Titan $\Rightarrow$

Titan's organic haze layer

- The haze is formed from UV photolysis of CH_4
- It creates an *anti-greenhouse effect* by absorbing sunlight up in the stratosphere and re-radiating the energy back to space
- This cools Titan's surface

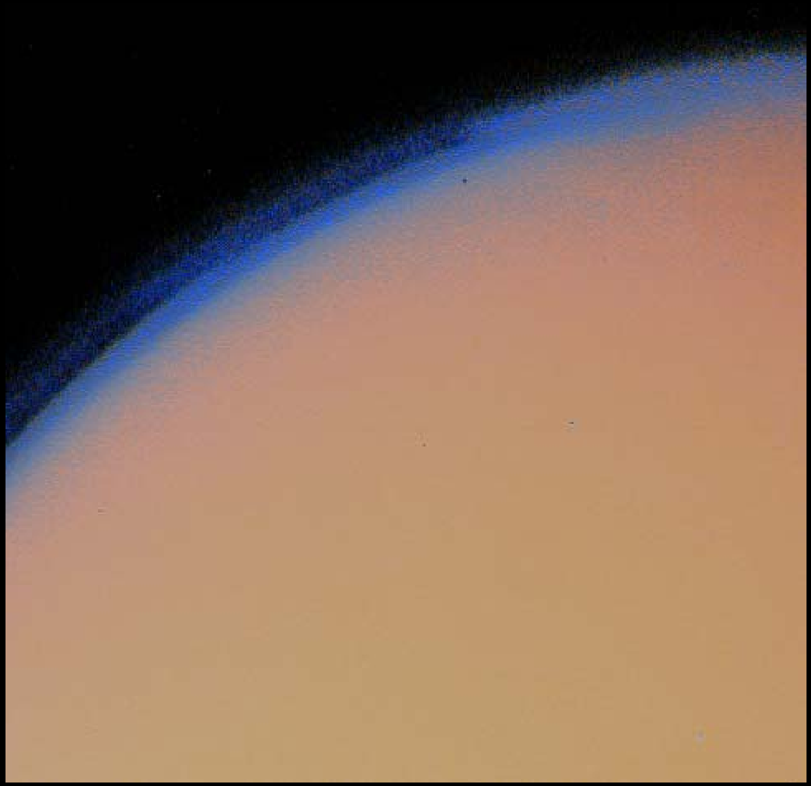
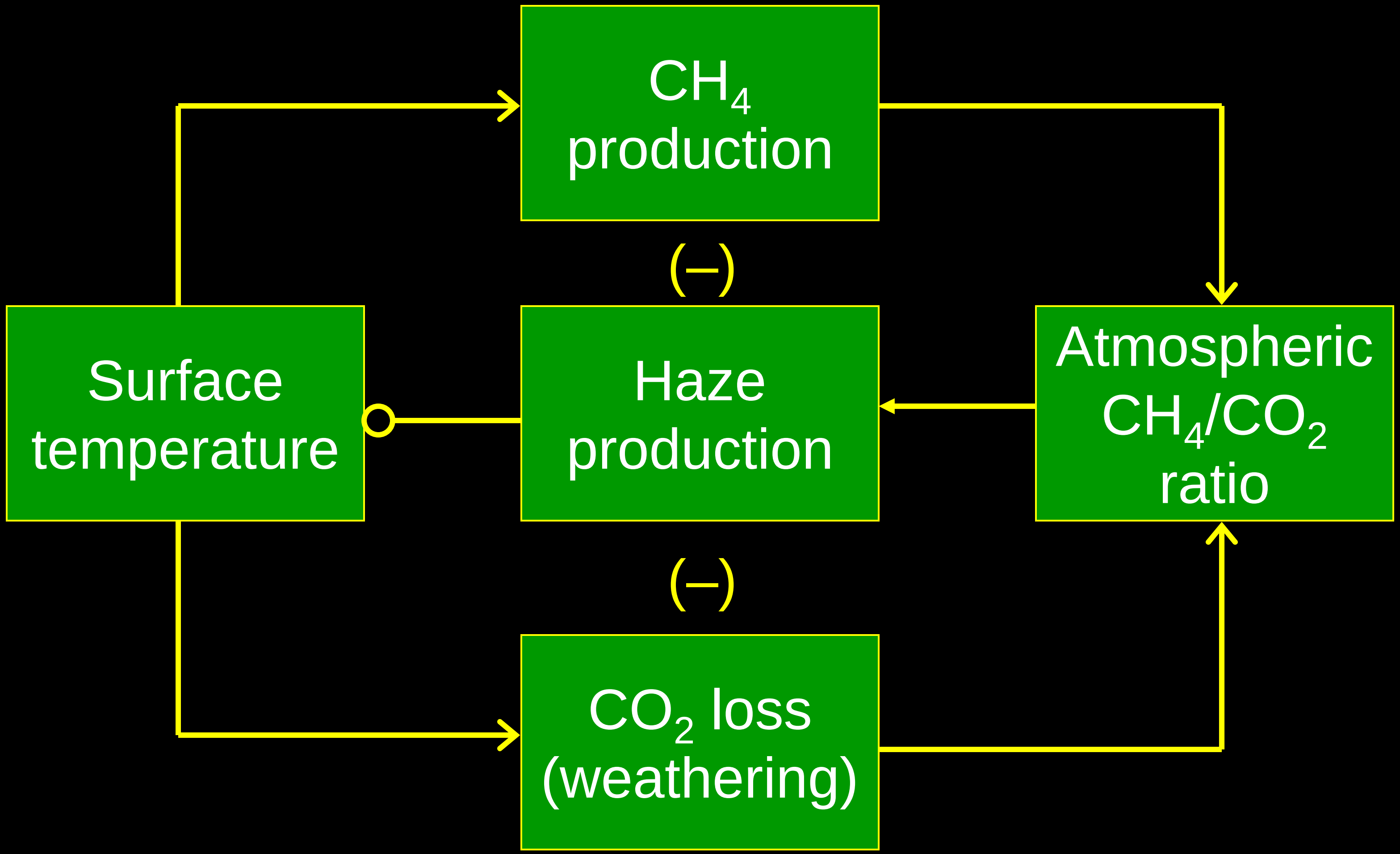
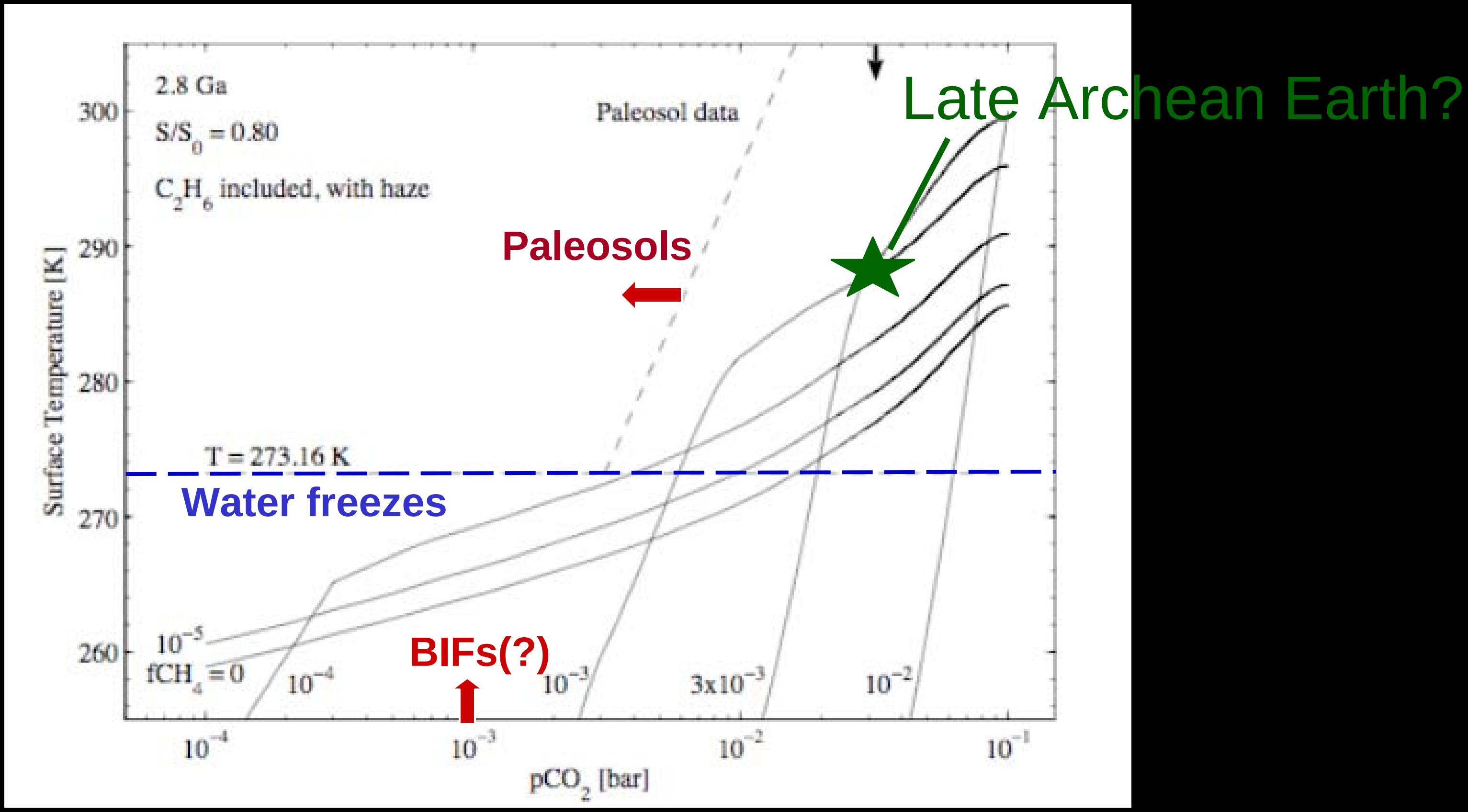


Image from Voyager 2

Possible Archean climate control loop



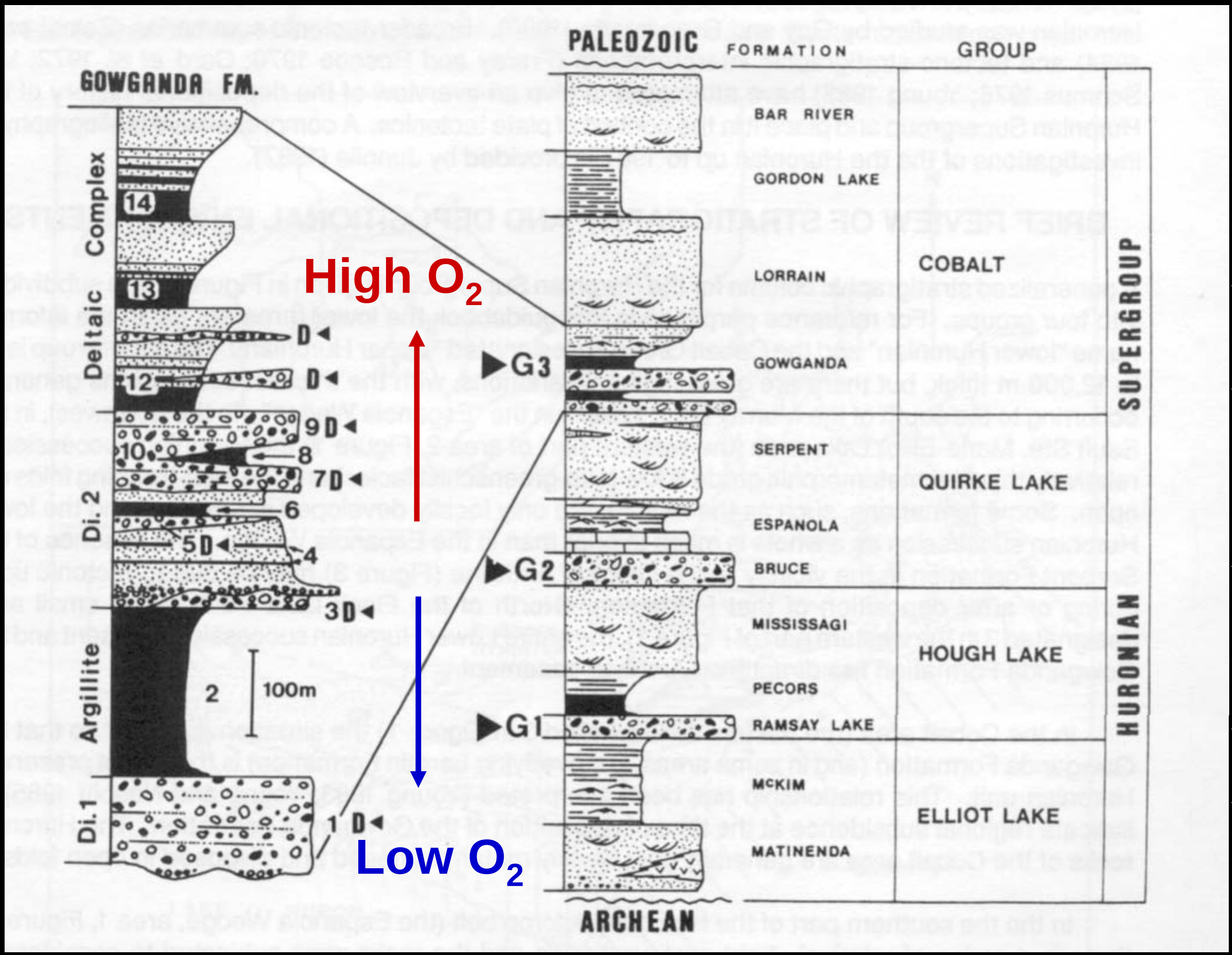
$CH_4/CO_2/C_2H_6$ greenhouse with haze



- When one puts all of this together, one can estimate surface temperature as a function of fCH_4 and pCO_2
- When atmospheric O_2 went up at 2.4 Ga, CH_4 would have gone down, possibly triggering the *Paleoproterozoic glaciations* ⇒

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

Huronian Supergroup (2.2-2.45 Ga)



Redbeds

Glaciations

Detrital uraninite and pyrite

S. Roscoe, 1969

Conclusions

- The Sun really was ~30% dimmer during its early history
  - Any deviation from this would have been too short-lived to be meaningful
- CO_2, CH_4, and C_2H_6 may all have contributed to the greenhouse effect back when atmospheric O_2 levels were low
- High atmospheric CH_4/CO_2 ratios can trigger the formation of organic haze. This has a cooling effect.
  - Stability arguments suggest that the Archean climate may have stabilized when a thin organic haze was present
- The Paleoproterozoic glaciation at ~2.4 Ga may have been triggered by the rise of O_2 and loss of the methane component of the atmospheric greenhouse

- Backup slides (stellar mass loss constraints)

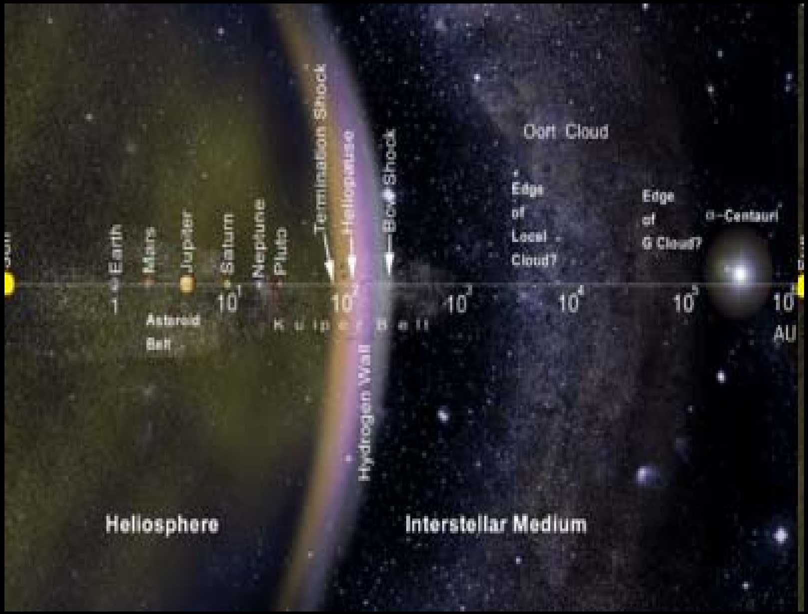
Was the young Sun really faint?

- Solar luminosity is a strong function of solar mass: $L_\odot \sim M_\odot^4$
- Planetary orbital distance varies inversely with solar mass: $a \sim M_\odot^{-1}$
- Solar flux varies inversely with orbital distance: $S \sim a^{-2}$
- Flux to the planets therefore goes as

$$S \sim M_\odot^6$$

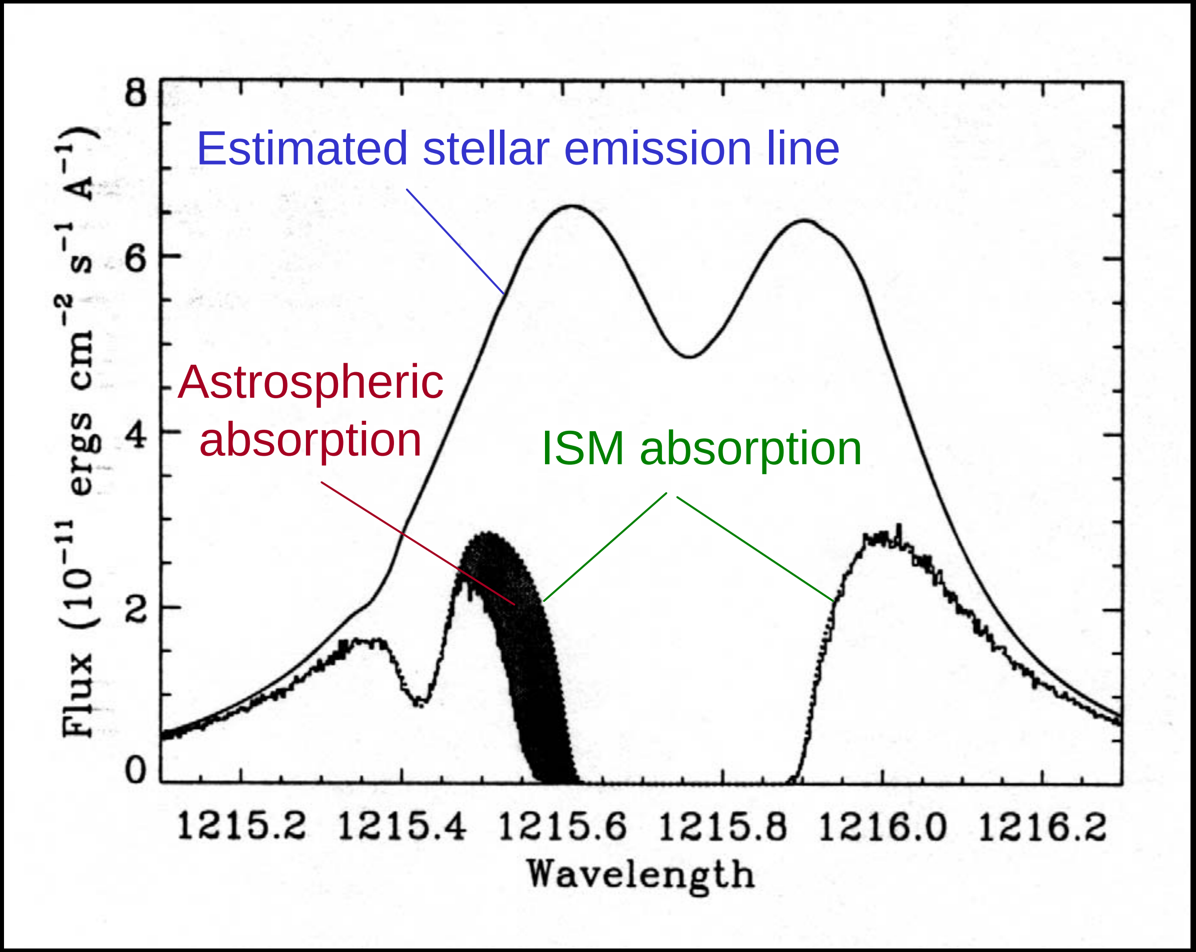
Estimating stellar mass loss

- The question of stellar mass loss has been addressed empirically by Brian Wood and colleagues at Univ. of Colorado
- They looked for evidence of bow shock interactions around nearby young solar analog stars
  - Stellar winds themselves are fully ionized and impossible to see, but neutral hydrogen builds up at the bow shock



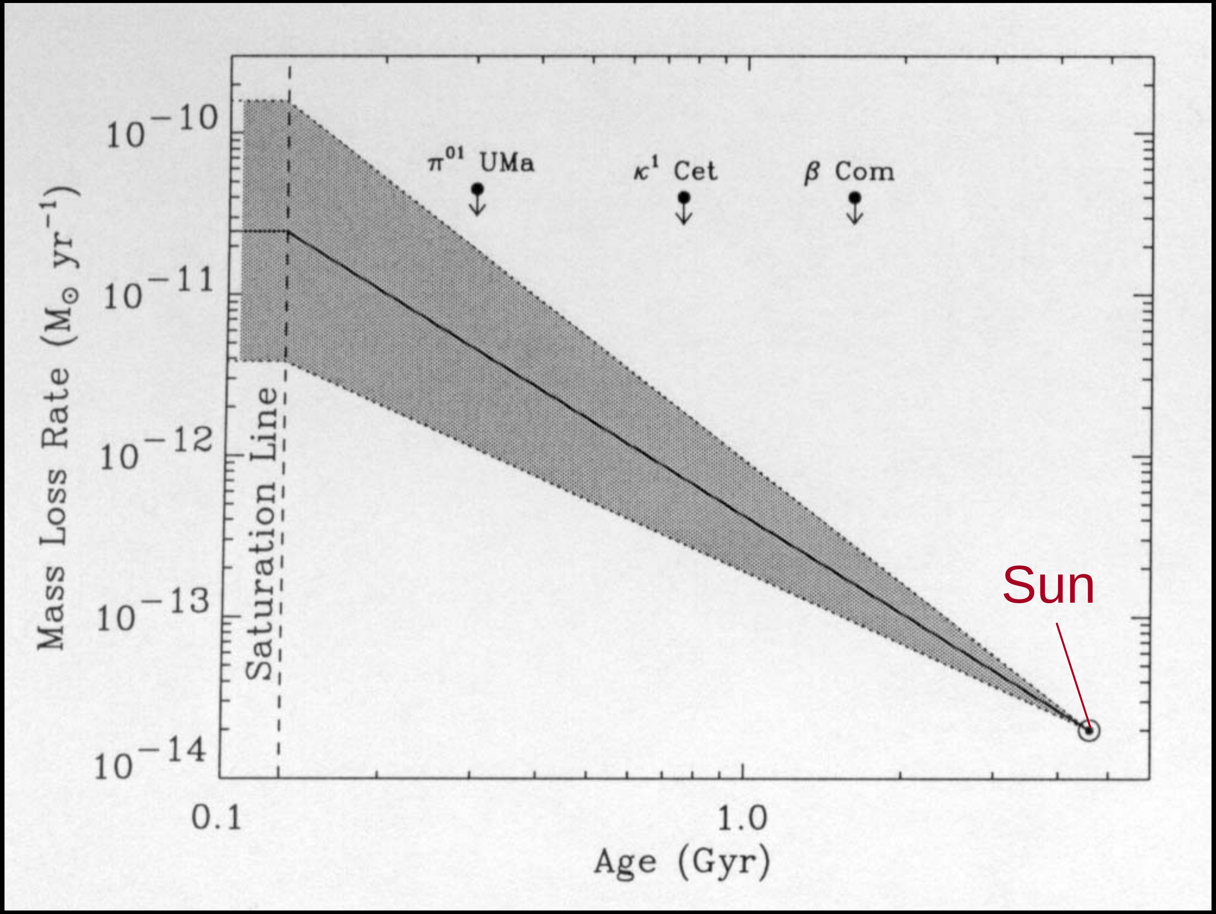
http://www.answers.com/topic/heliosphere

Ly α spectrum of ε Eridani (from HST)



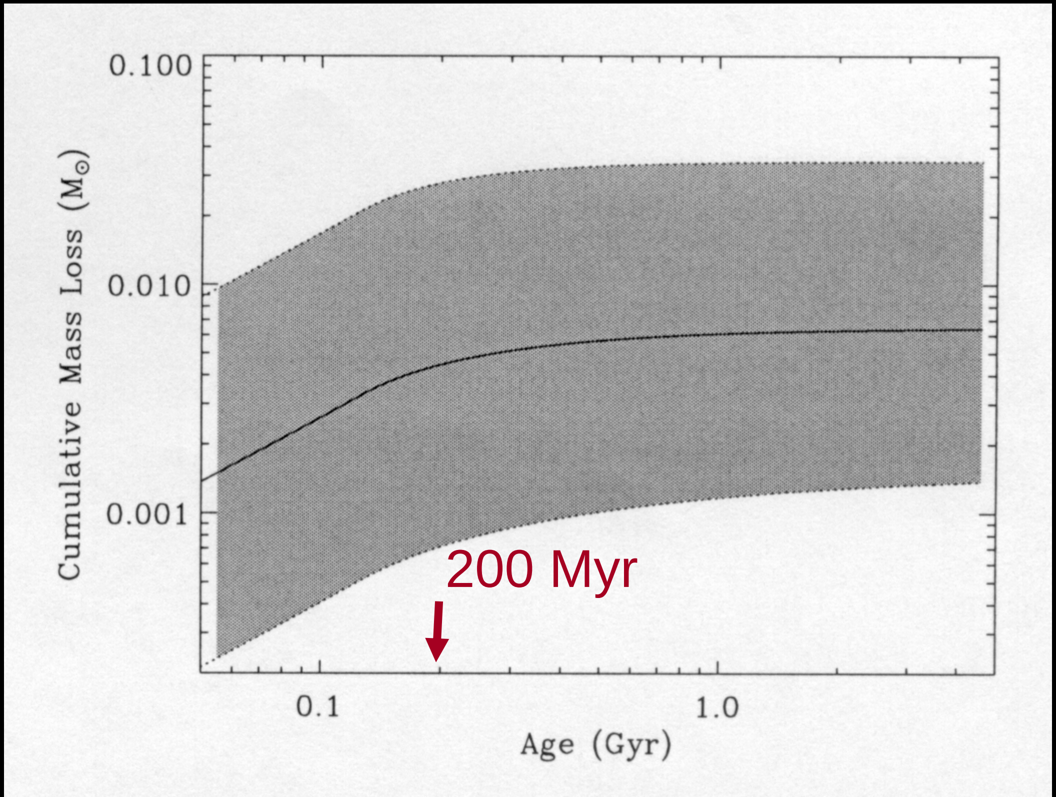
B. Wood et al., *Ap. J.* **574**, 412 (2002)

Estimated mass loss rate vs. stellar age



Wood et al. (2002)

Integrated mass loss vs. time



Wood et al. (2002)

% Changes

Mass loss	ΔS
0.6	3.6
1.0	6.0
2.0	13
3.0	19

⇒ The Sun was probably back on the standard solar evolution curve by ~4.4 Ga (*i.e.*, 4.4 Gyr ago)