Conditions on Early Earth and the Search for Other Earth-like Planets

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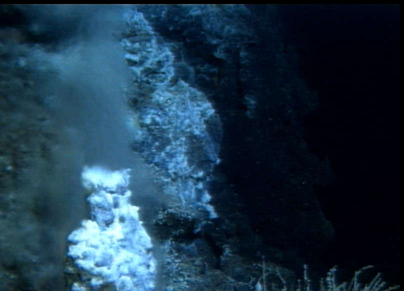
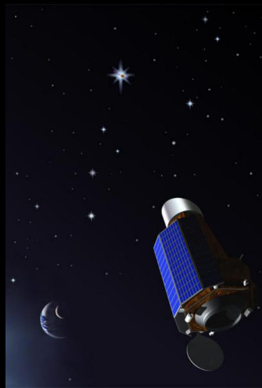




Talk outline

- Part 1: Conditions on the early Earth
- Part 2: The search for Earth-like planets and life outside the Solar System (only covered if questions arise…)

When did life arise?

- This question is currently in controversy
- Until the 1940’s, geologists thought that life only began around 540 m.y. ago at the dawn of the Phanerozoic Eon
- But we now know that the record of life extends well back into the Precambrian Eon

Artist’s depiction of life in the Cambrian oceans

http://www.fas.org/irp/imint/docs/rst/Sect20/A12.html

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

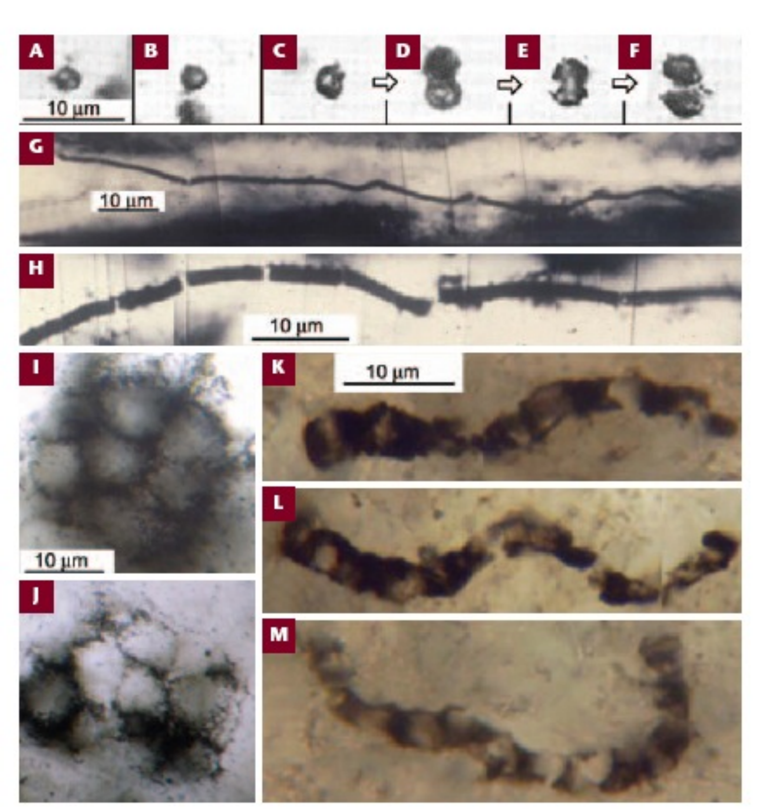
} Warm

← Rise of atmospheric O_2 (Ice age)

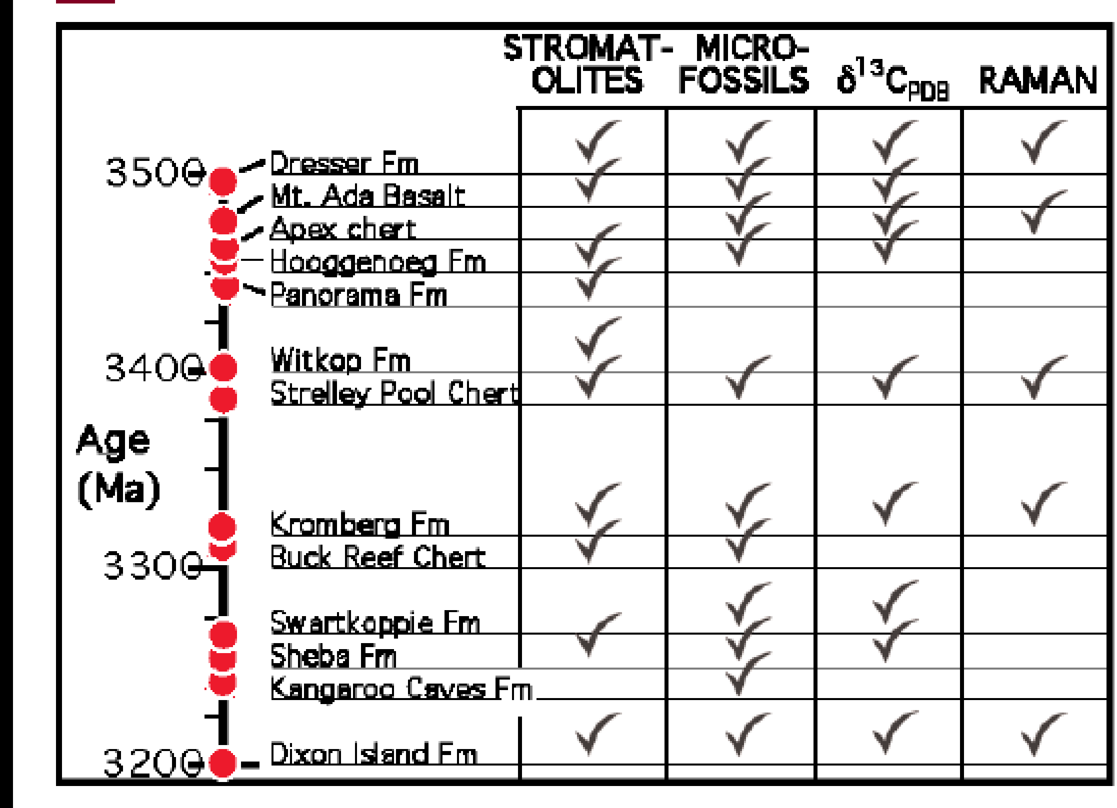
← Ice age

} Warm (?)

} Origin of life



Archean microfossils



Summary of evidence

- Taken as a whole, the evidence supports the idea that life had evolved by 3.5 Ga, and possibly earlier
- What were the environmental conditions at this time?

J. W. Schopf, *Elements* (2006)

1. What was the *atmospheric composition* during the Hadean/early Archean?

Early atmospheric composition

- Old idea : Early atmosphere was dominated by *methane* and *ammonia*
- This was based, in part, on Harold Urey's observations of Jupiter and Saturn
  - He thought that Earth should have resembled these planets before its hydrogen had time to escape
- Earlier thinkers: Oparin and Haldane

Miller-Urey experiment

- This hypothesis was supported by the famous Miller-Urey experiment
- Organic compounds were formed in the atmosphere by electrically and/or photochemically driven reactions
- Requires a strongly reduced atmosphere (CH_4, NH_3, H_2O)

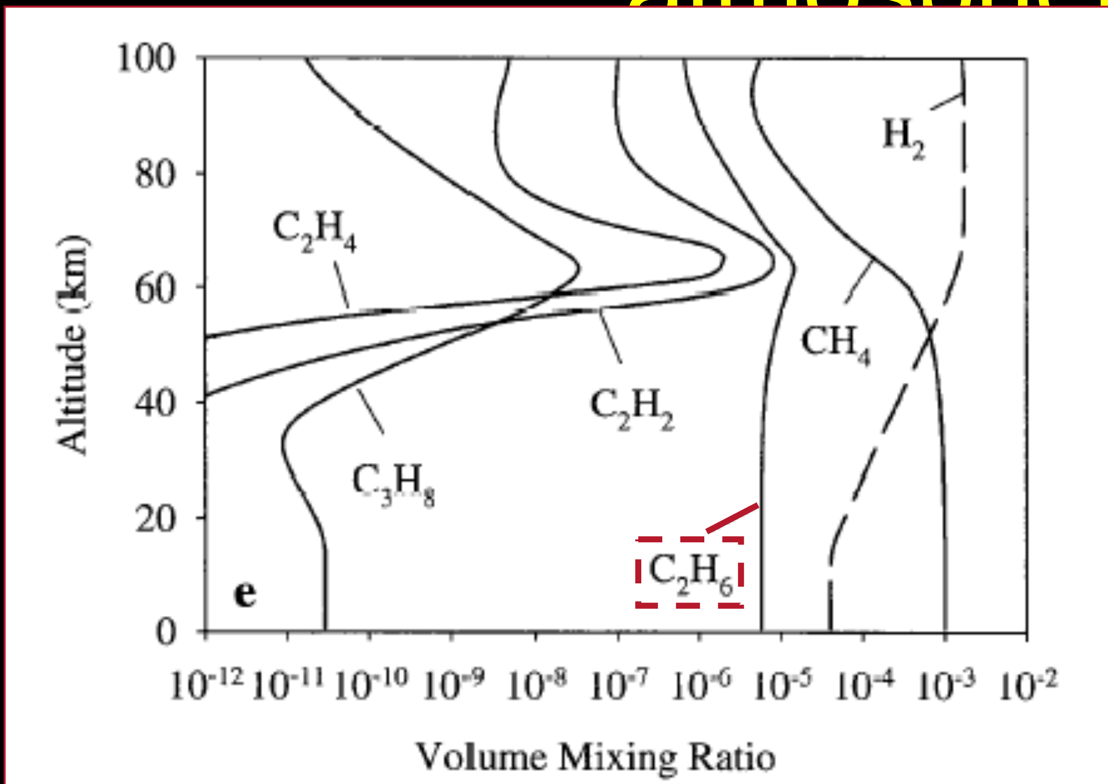
Spark discharge apparatus
(Image from Wikipedia)

Why you can't have a dominantly methane-ammonia atmosphere

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

Why you can't have a dominantly methane-ammonia atmosphere



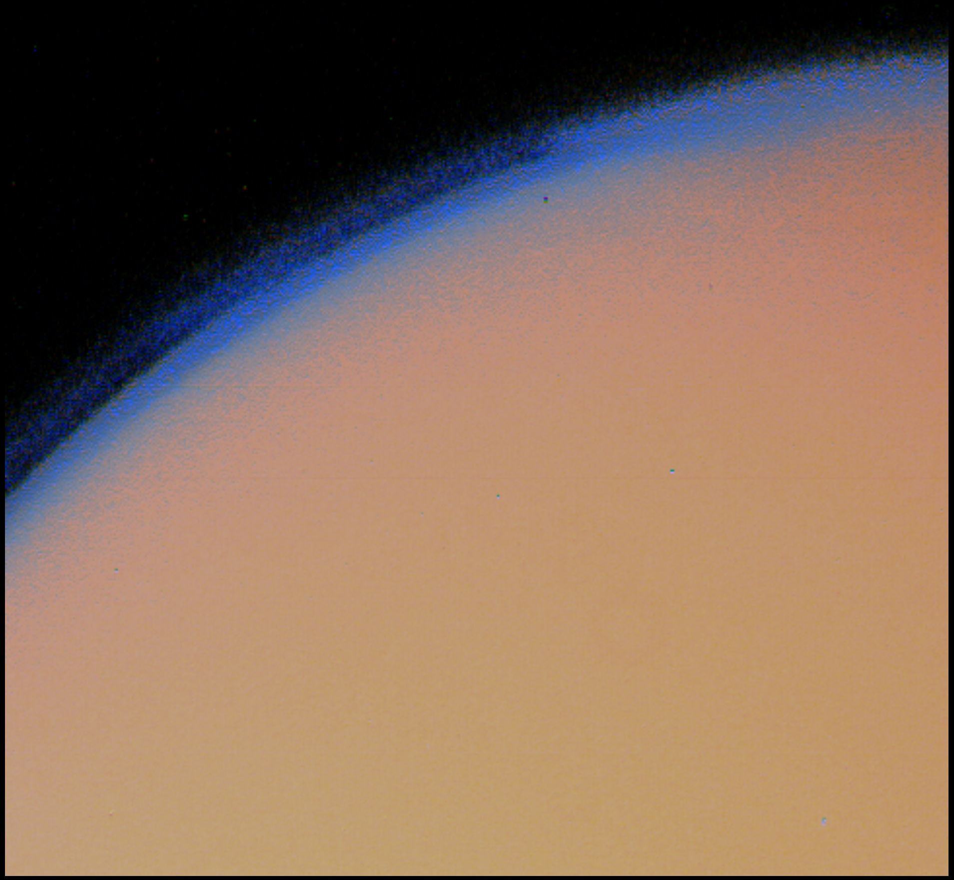
Ethane formation:

1) $CH_4 + h\nu \rightarrow CH_3 + H$
or
2) $CH_4 + OH \rightarrow CH_3 + H_2O$

Then
3) $CH_3 + CH_3 + M \rightarrow C_2H_6 + M$

- CH_4 also photolyzes, although at a slower rate than does NH_3
- This leads to the formation of longer-chain hydrocarbons by a process termed *polymerization…*

Titan's organic haze layer



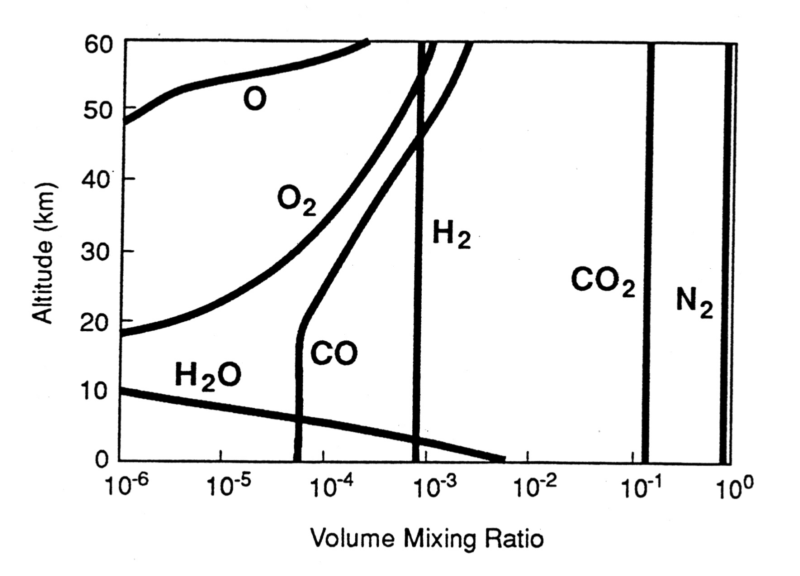
(Picture from Voyager 2)

- The net result is formation of organic haze, like the haze that exists on Saturn's moon, Titan
- It can produce an *anti-greenhouse effect* if it gets too thick

Weakly reduced atmosphere

Furthermore

- Modern volcanic gases are relatively oxidized
  - Mostly CO_2 and H_2O, little CH_4 or NH_3
- For all these reasons, the early atmosphere is thought to have been only *weakly reduced*
- Such an atmosphere is not very conducive to Miller-Urey type synthesis

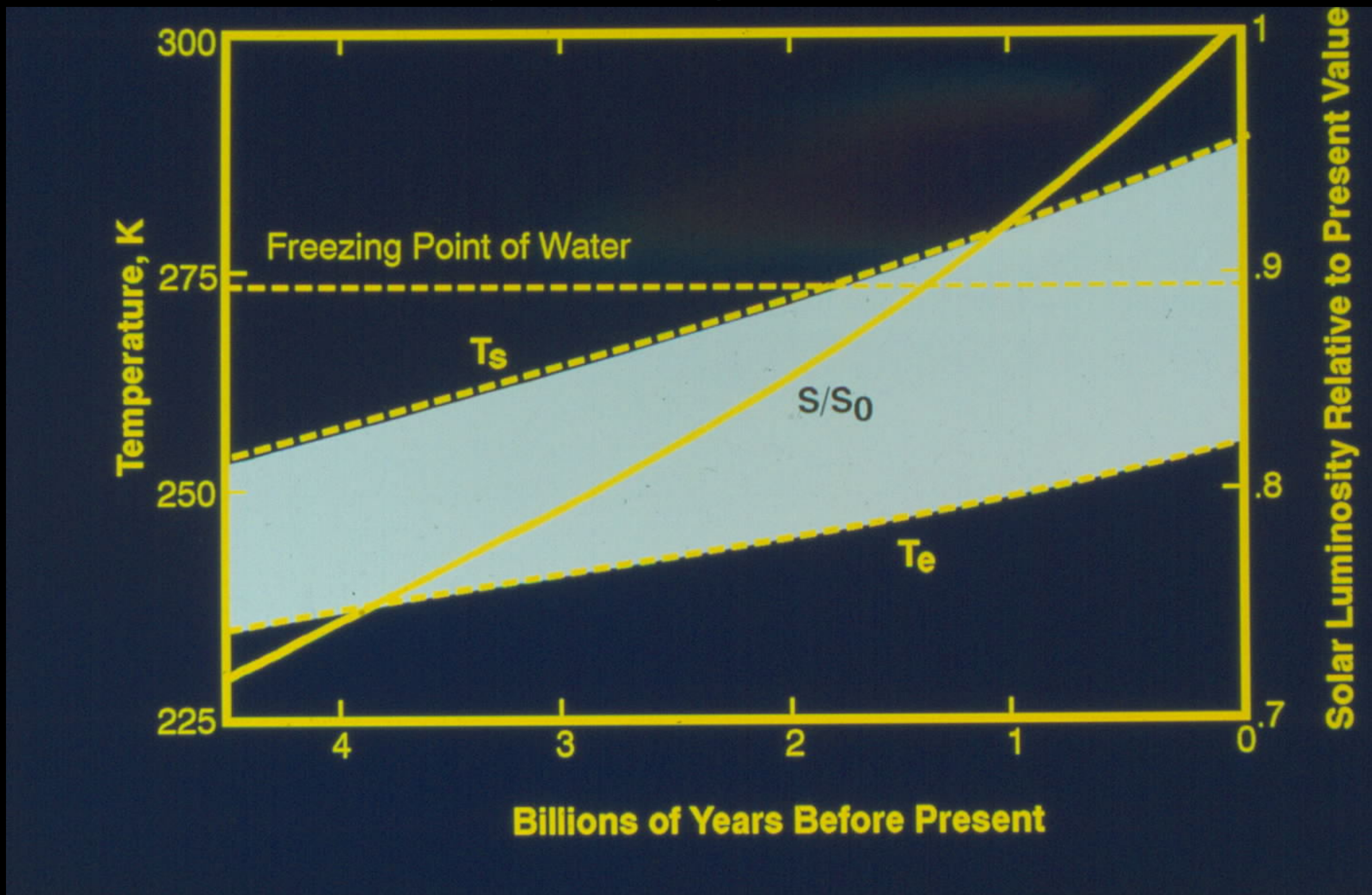


J. F. Kasting, *Science* (1993)

2. What was the *climate* like during the Hadean/early Archean?

   – The young Sun was significantly (25-30%) *fainter* than today

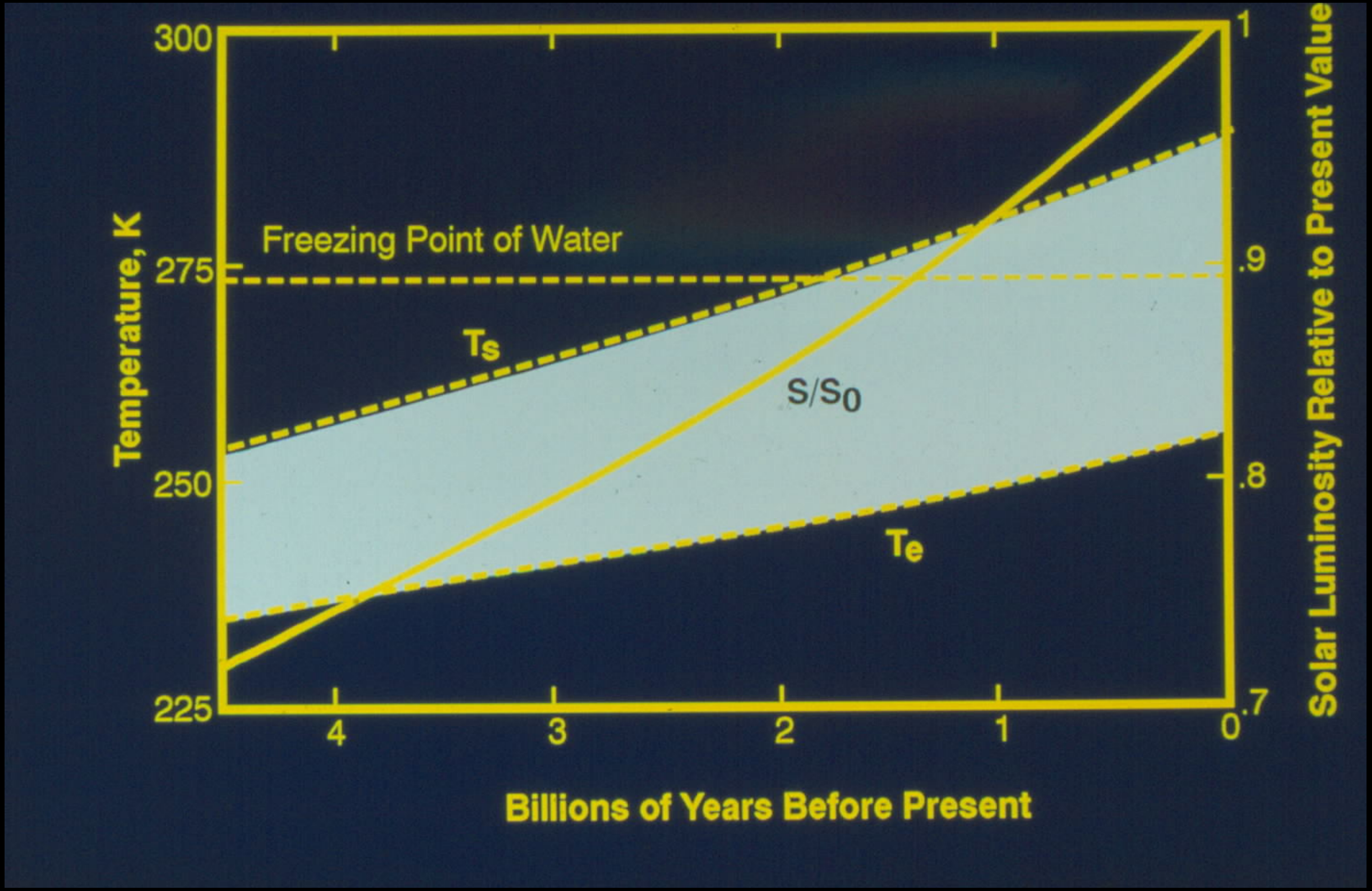
The faint young Sun problem



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

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

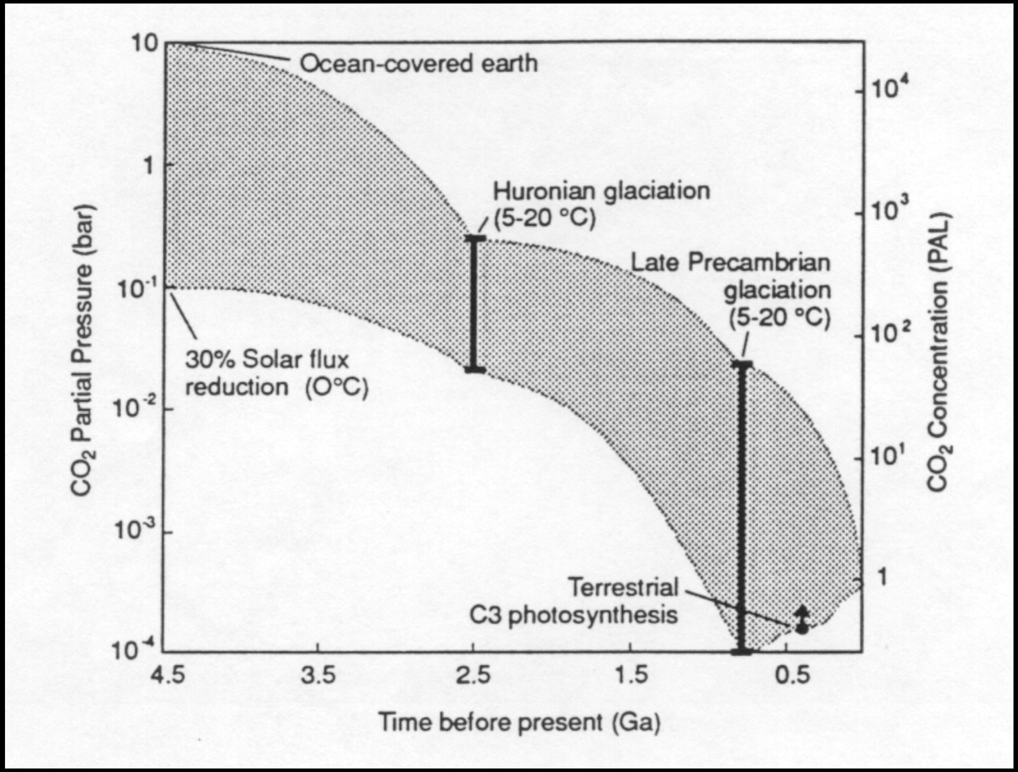
The faint young Sun problem



- The best solution to this problem is higher concentrations of greenhouse gases in the distant past

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

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

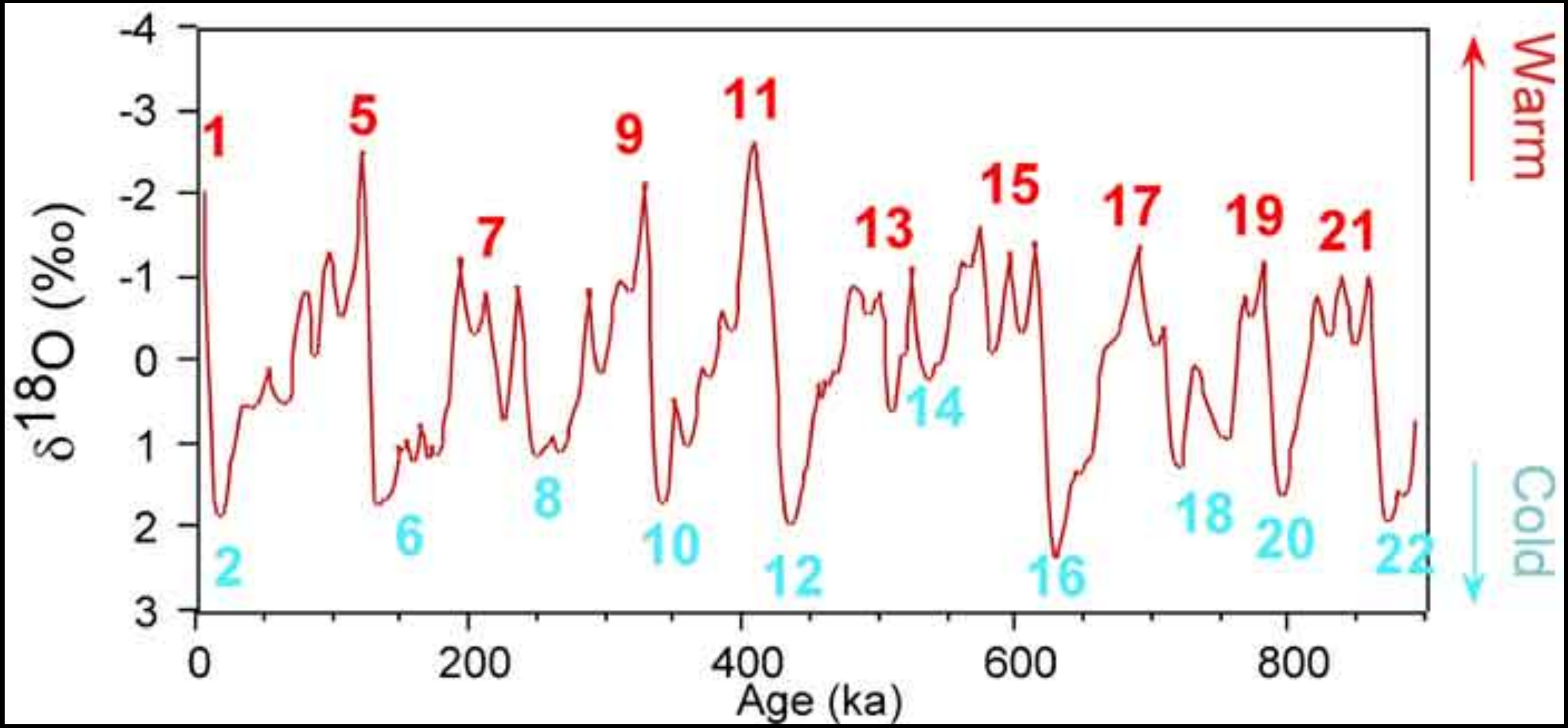


J. F. Kasting, *Science* (1993)

- In the simplest story, atmospheric CO_2 levels should have declined monotonically with time as solar luminosity increased
- Various geochemists have challenged this hypothesis, but I now think that those challenges are all baseless

- Despite the theoretical expectation for cool temperatures based on low solar flux, oxygen isotopes predict extremely *high* surface temperatures

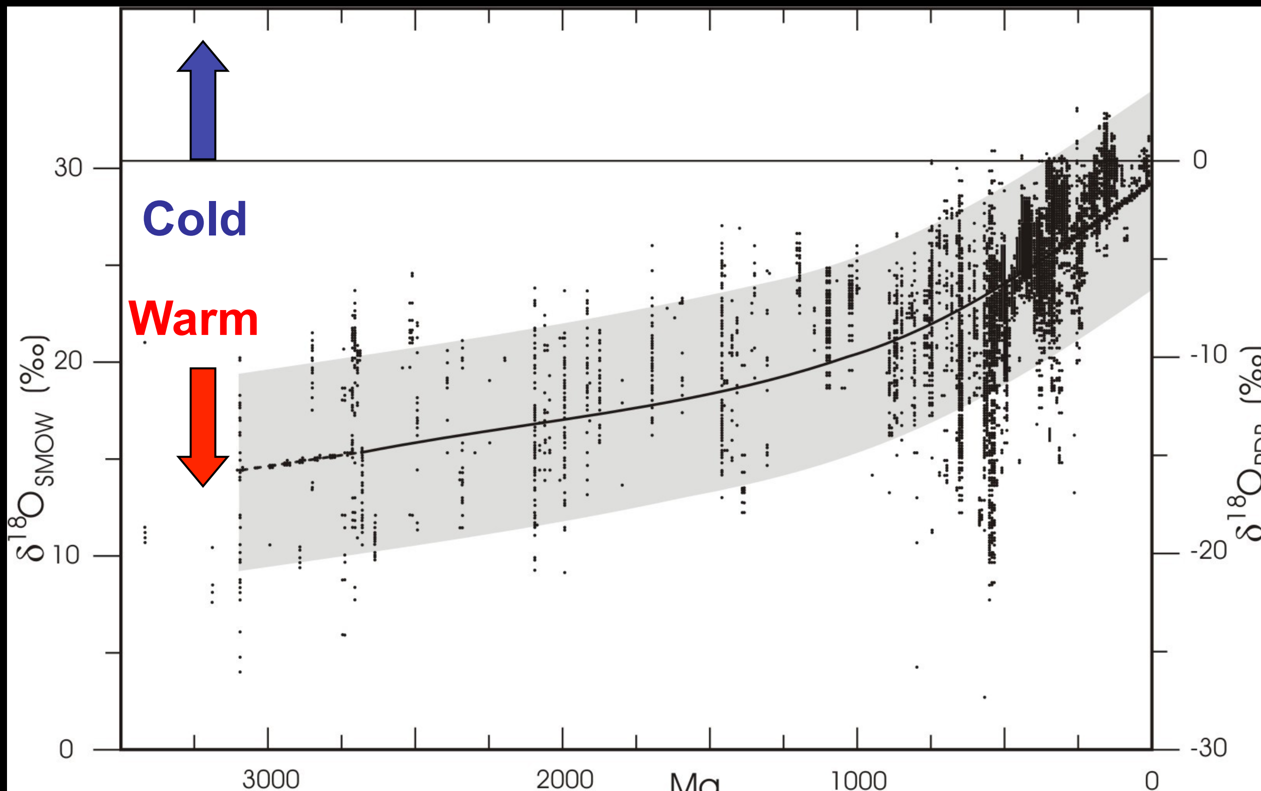
O isotopes—the last 900 k.y.



after Bassinot et al. 1994

- Oxygen isotopes are used routinely to infer paleotemperatures on the glacial-interglacial time scale

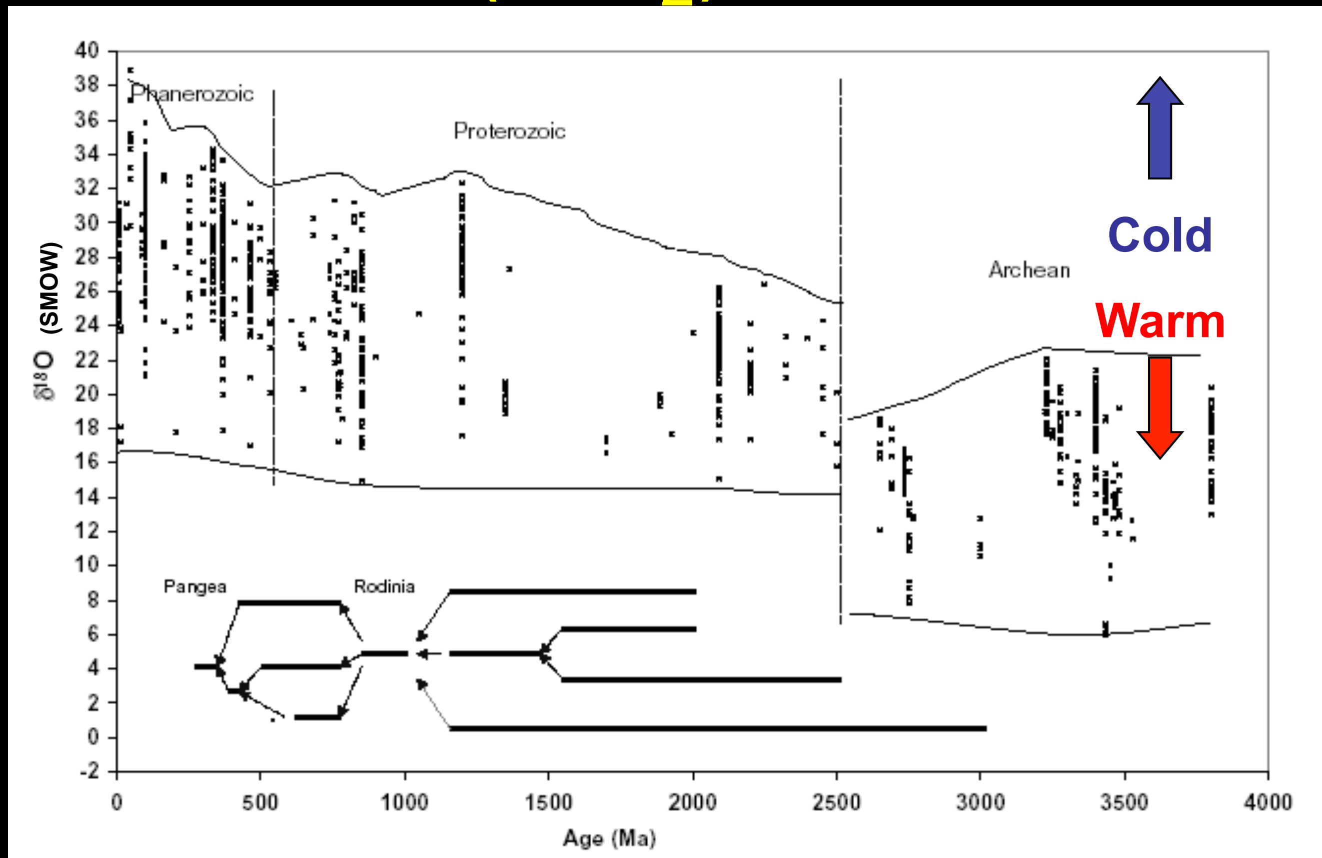
Marine carbonate $\delta^{18}O$ vs. time
(detailed, time axis reversed)



- When one looks at long time scales, however, one finds a very large negative shift in $\delta^{18}O$, suggesting high surface temperatures

Shields & Veizer, G^3, 2002

δ^{18}O of modern and ancient cherts (SiO_2)



- Cherts, which are better preserved, tend to show the same trend, *i.e.*, they get isotopically lighter (in O) as they get older

P. Knauth, *Paleo*^{3} 219, 53 (2005)

Chert data:

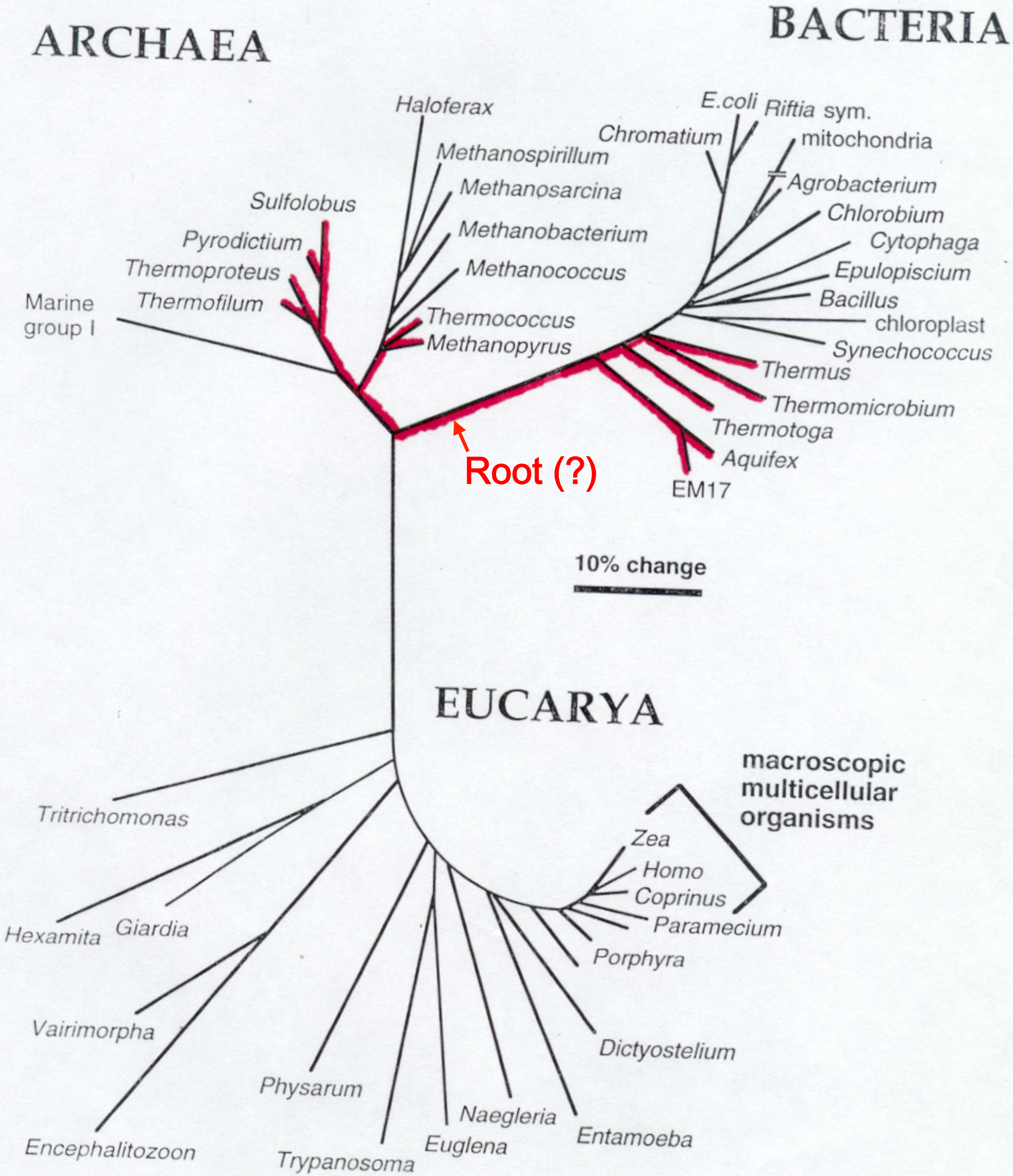
- Mean surface temperature was 70±15^{o}C at 3.3 Ga
  - Ref.: Knauth and Lowe, GSA Bull., 2003

Carbonate data:

- Surface temperatures remain significantly elevated until as recently as the early Devonian (~400 Ma)

- Biological data *seem* to support the idea of a high-temperature origin of life, and possibly a hot early Earth

- We see this in ribosomal RNA and in proteins



"Universal" (rRNA) tree of life

Red shading indicates hyperthermophiles (T_{growth}>80^{o}C)

Courtesy of Norm Pace

- I don’t believe that the Archean Earth was hot, however, because there were *glaciations* at ~2.4 Ga and 2.9 Ga

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Possible explanations for the oxygen isotope data

- All ancient carbonates and cherts have been altered by *diagenesis*
  - The $\delta^{18}O$ values represent the temperature in the sediments, not in the ocean
- Seawater $\delta^{18}O$ has varied with time
- The high temperatures derived from the cherts are a result of widespread hydrothermal activity on the seafloor (van den Boorne et al., Geology, 2007)

Possible explanations for thermophilic common ancestors

1. Phylogenetic data may be *biased* (?)
2. Surface temperatures on the early Earth were uniformly hot
3. Life originated at high temperatures, perhaps in a midocean ridge hydrothermal vent
4. Life originated at low temperatures in some surface environment, then colonized the midocean ridge vents
   – Surface life was then wiped out by a big impact, and life recolonized the Earth from the vents

Hydrothermal vent model for life's origin

- Organic synthesis took place in hydrothermal vents at midocean spreading ridges
- Liquid-solid interfaces available
- Strong free energy gradients
- "Pyrite-pulled" reactions (Wächtershauser)

(Photo taken from *Alvin*)
T ≈ 350^{0}C
pH = 4-5

Conclusions

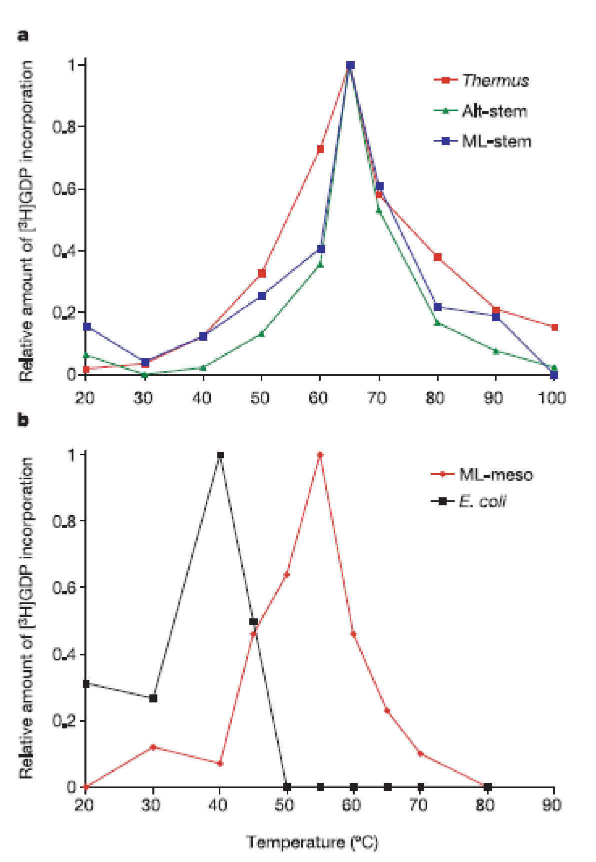
- Earth's early atmosphere was probably weakly reduced
  – Mostly N_2 and CO_2 with a little H_2 and CO
- The climate was probably relatively cool by the time that life originated
- Life may have originated in an off-axis hydrothermal vent environment
  – Such environments may have been widespread on the ancient seafloor
- A promising way to investigate the origin of life is to search for habitable worlds around other stars and see if life has originated elsewhere

Further biological evidence for warm early temperatures

Inferring the palaeoenvironment of ancient bacteria on the basis of resurrected proteins

Eric A. Gaucher[1], J. Michael Thomson[2*], Michelle F. Burgan[3] & Steven A. Benner[1,2,3]

Nature, 2003



- Ancestral *elongation factor proteins* (EF-Tu) of all organisms (panel a) and even of mesophiles (panel b) indicate a *thermophilic* common ancestor for extant life (40-80^{o}C)

Palaeotemperature trend for Precambrian life inferred from resurrected proteins

Eric A. Gaucher[1], Sridhar Govindarajan[2] & Omjoy K. Ganesh[3]

Nature, Feb., 2008

- More recent work by this group proposes a detailed time scale for surface temperature evolution, based on two different molecular clock techniques
- Ancestral genes were synthesized and cloned into *E. coli* to allow them to be expressed as proteins
- Protein *melting points* were then measured in the lab

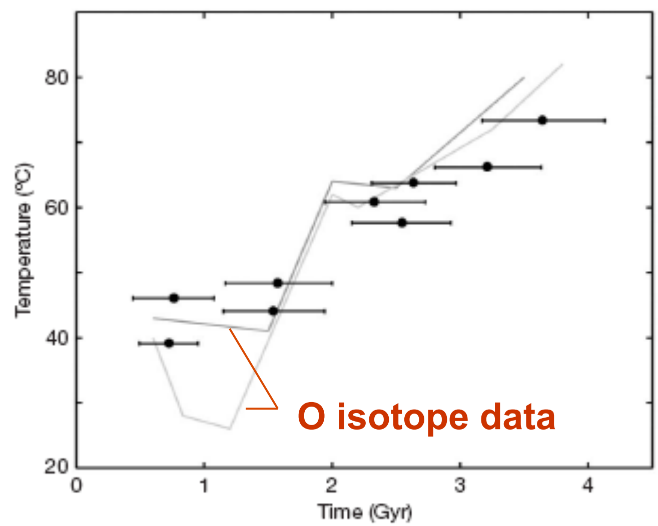
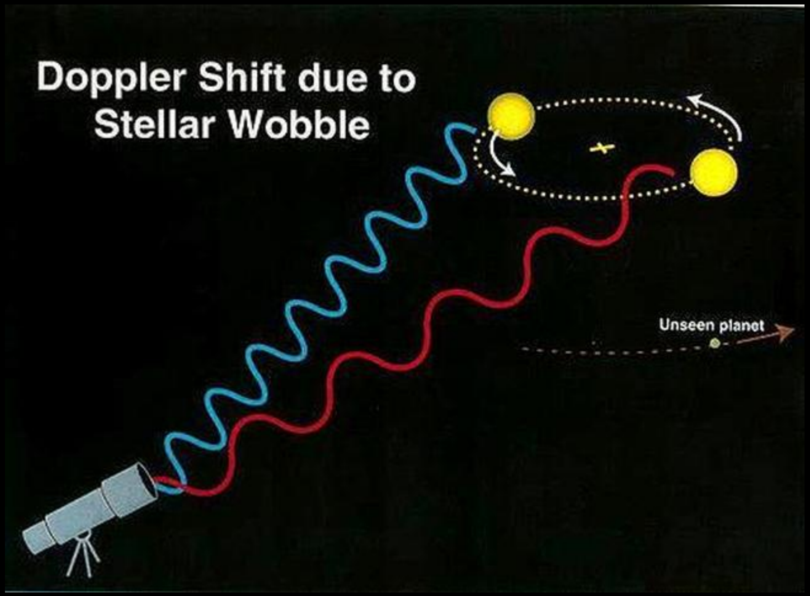


Figure 3 | Plot of ancestral EF melting temperatures against geological time. Molecular clock estimates are shown with their confidence intervals (horizontal bars) from ref. 16, using a 2.3-Ga minimum constraint for the Great Oxidation Event. Solid lines are temperature curves of the ancient ocean inferred from maximum $\delta^{18}O$ (light grey[3,4], dark grey[5]). Although not shown, an analogous trend is seen with $\delta^{30}Si$ isotopes[5].

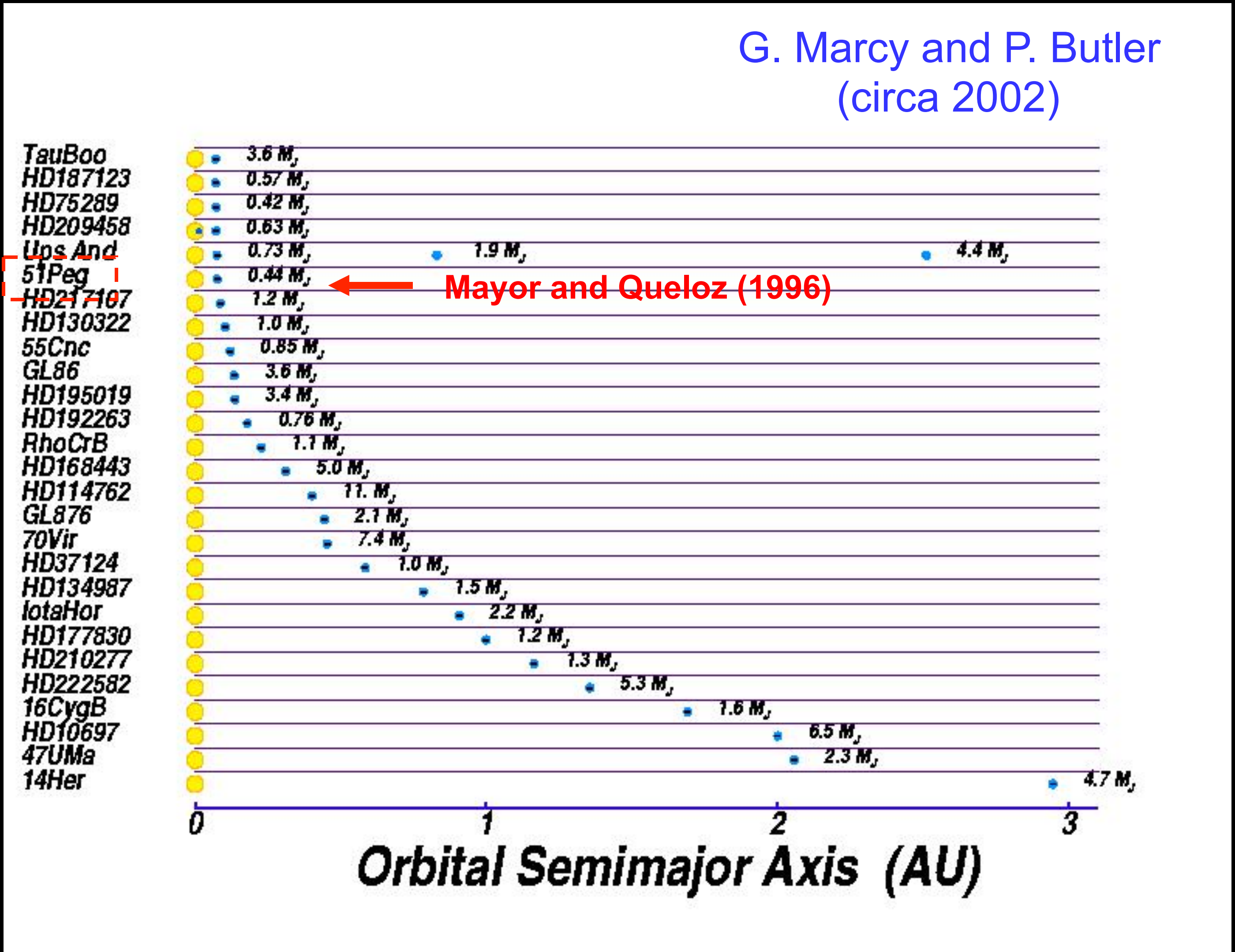
- Part 2: The search for Earth-like planets and life outside the Solar System

Radial velocity (Doppler) method

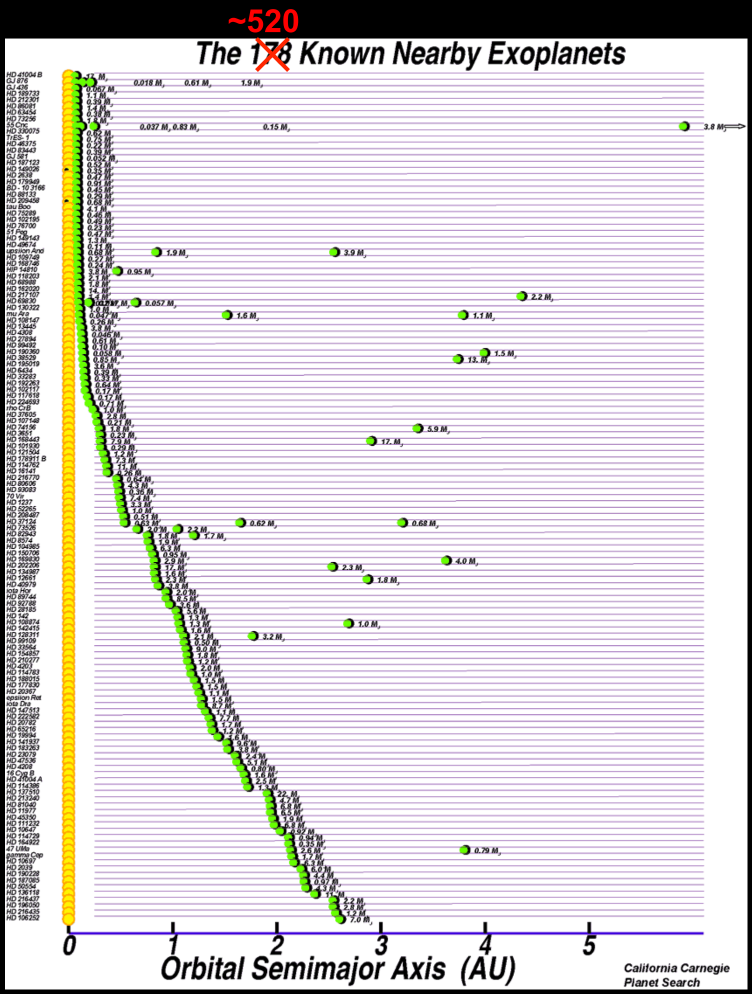
- Many extrasolar planets (over 500) have been detected already, most by using the *radial velocity,* or Doppler, method
- None of these RV planets are as small as Earth, however
  - Detecting Earth-mass planets around solar-type stars may or may not be possible with this technique (ongoing debate)



"Hot Jupiters"



Known extrasolar planets



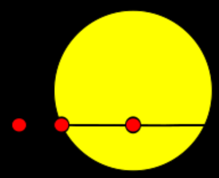
http://exoplanets.org/massradiiframe.html

- 548 extrasolar planets identified as of May 11, 2011
  - 500 by radial velocity
  - 128 transiting planets
  - 12 microlensing
  - 24 direct imaging
  - 12 pulsar planets
  - 60(?) multiple planet systems
- Few, if any, of these planets are very interesting, however, from an astrobiological standpoint
  - Gliese 581g (the "Goldilocks planet") is probably not real

Info from *Extrasolar Planets Encyclopedia* (Jean Schneider, CNRS)

Transit method

- The light from the star dims if a planet passes in front of it
- Jupiter's diameter is 1/10th that of the Sun, so a Jupiter transit would diminish the sunlight by 1%
- Earth's diameter is 1% that of the Sun, so an Earth transit decreases sunlight by 1 part in 10^4
- The plane of the planetary system must be favorably oriented
  - Transit probability is $\approx R_*/a$



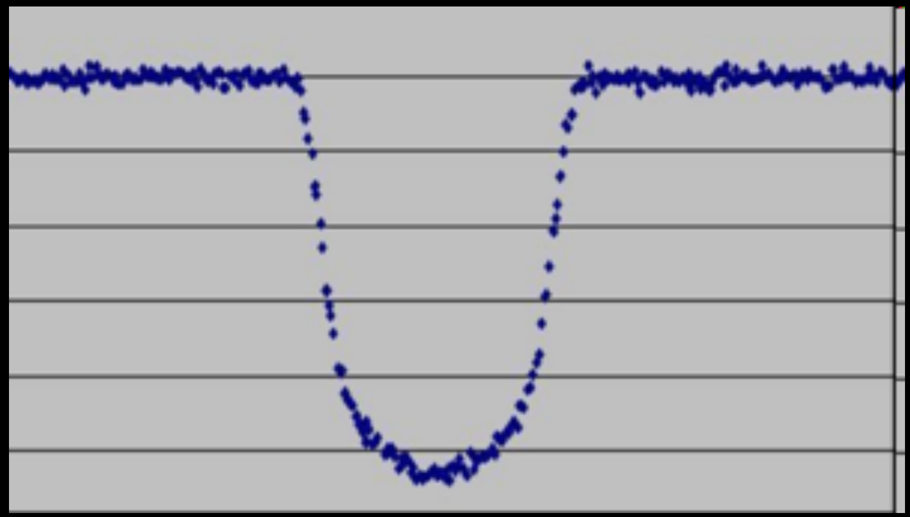
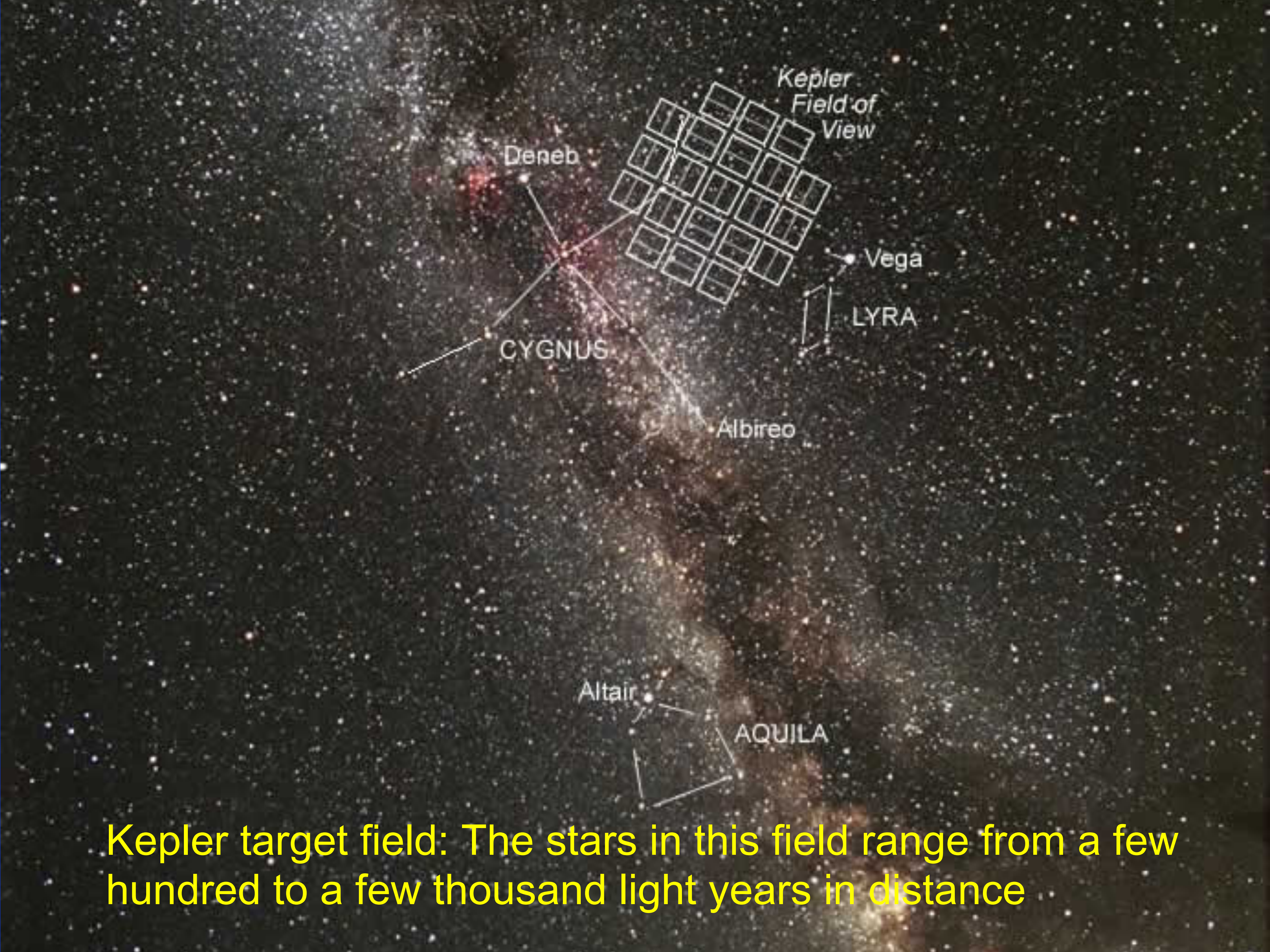


Image from Wikipedia

Kepler Mission

- This space-based telescope will point at a patch of the Milky Way and monitor the brightness of ~160,000 stars, looking for transits of Earth-sized (and other) planets
- 10^{-5} precision *photometry*
- 0.95-m aperture → capable of detecting Earths
- Launched: March 5, 2009

http://www.nmm.ac.uk/uploads/jpg/kepler.jpg



Kepler target field: The stars in this field range from a few hundred to a few thousand light years in distance

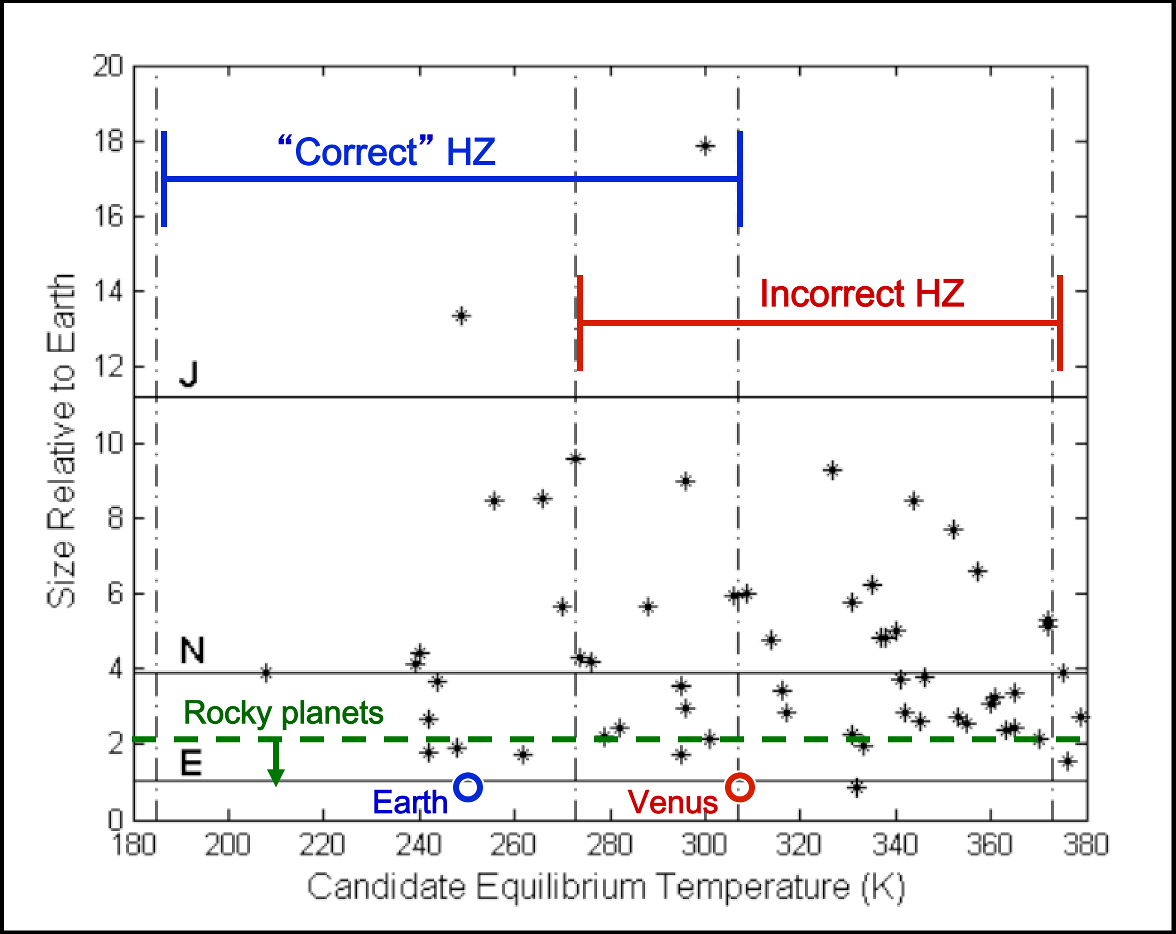
February 2011 data release

Table 5. Number of Candidates versus Size.

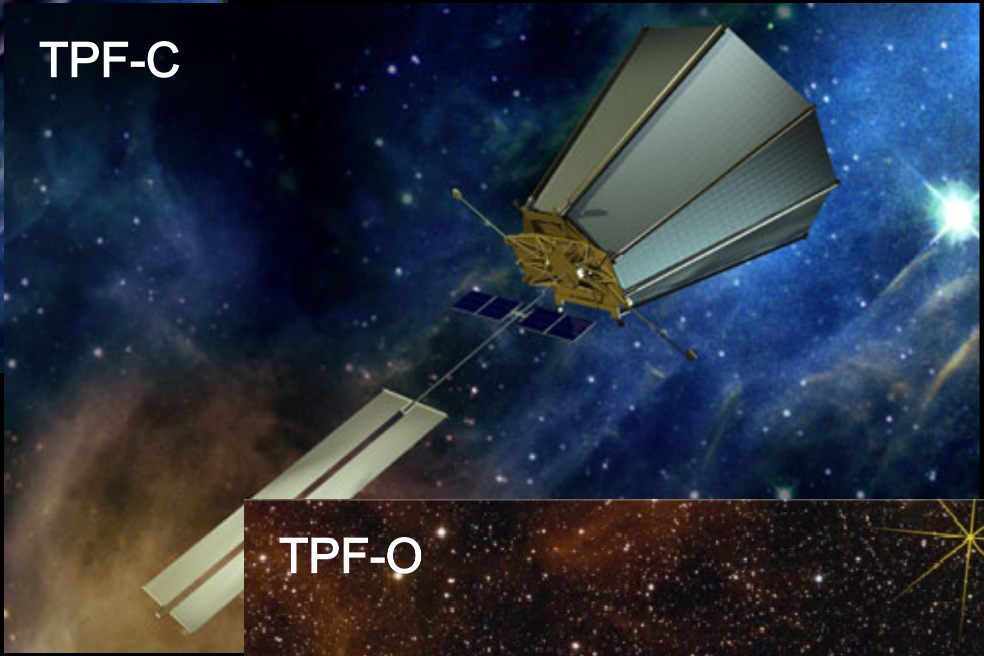
Candidate Label	Candidate Size (R_*)	Number of Candidates plus known planets
Earth-size	$R_p \leq 1.25$	68
super-Earth-size	$1.25 < R_p \leq 2.0$	288
Neptune-size	$2.0 < R_p \leq 6.0$	662
Jupiter-size	$6.0 < R_p \leq 15$	165
very-Large-size	$15.0 < R_p \leq 22.4$	19
Not considered	$R_p > 22.4$	15

- 1235 "planet candidates" total orbiting 997 stars
- 54 planets within the habitable zone (as defined by the Kepler team), 4 or 5 of which are probably rocky

Kepler habitable zone planets



Borucki et al., Ap. J., v2, submitted Mar., 2011 (Fig. 4)



- What we' d really like to do is to build a big TPF (Terrestrial Planet Finder) telescope and search directly for Earth-like planets
- We can also look for spectroscopic biomarkers (O_2, O_3, CH_4) and try to infer the presence or absence of life on such planets
- Need a lot of money ($5B or more) to do this!