The Faint Young Sun Paradox: Is There Even Life on Earth?

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Thanks to Jim Kasting (Penn State), Richard Linzen (MIT), Ed Guinan (Villanova), Steve Saar (CfA), and John Priscu (MSU)

The Faint Young Sun Paradox

The Sun was about 30% less luminous when life developed on Earth, yet geological and biological evidence points to a young Earth not cooler than now, perhaps warmer

Average Atmospheric Temperature: First Order Approximation

$$L(1 - A) = 4\sigma T_e^4$$

$\mathrm{A} = \mathrm{Earth's\ Albedo}$

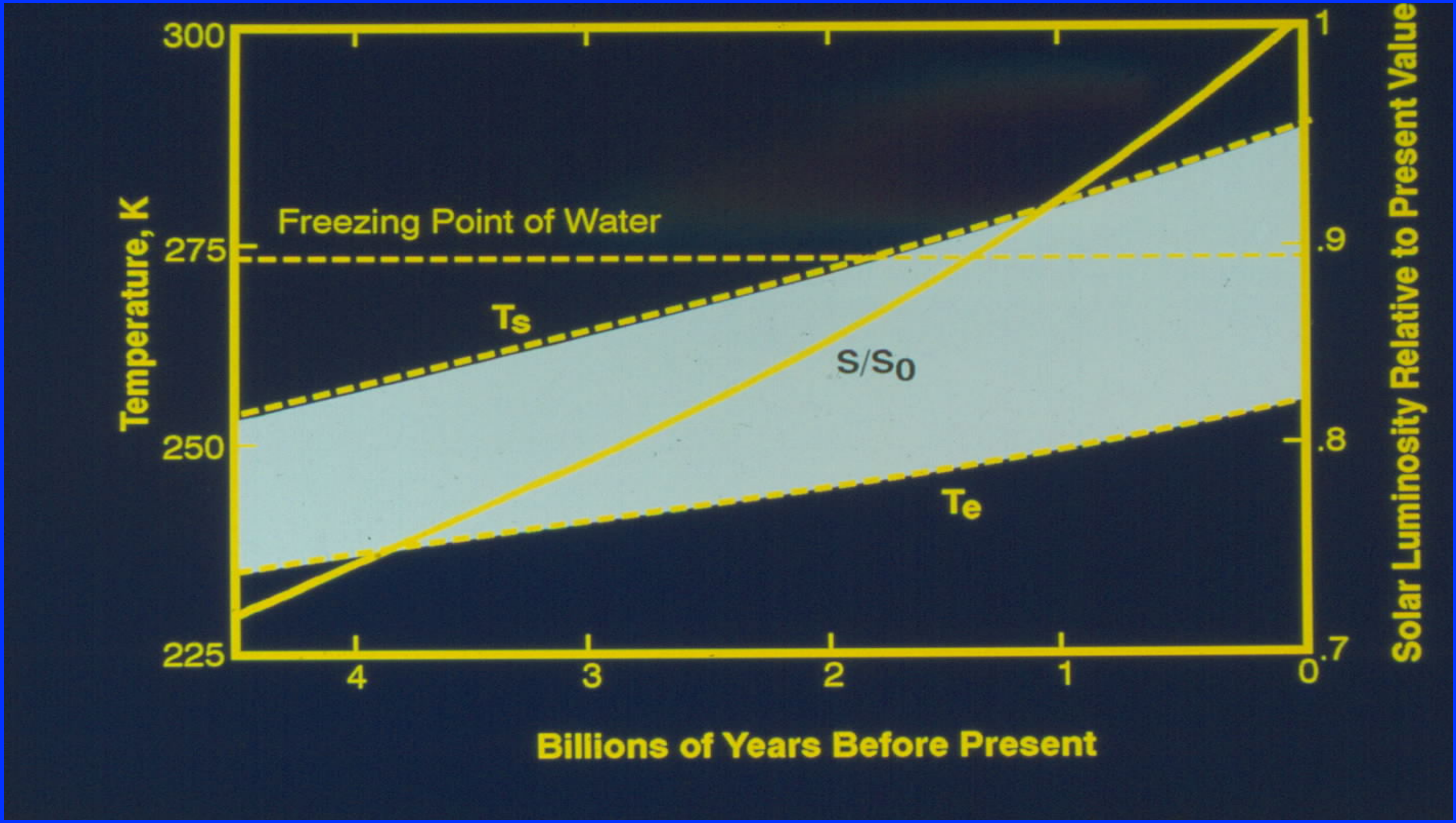
$\sigma = \mathrm{Stefan\ Boltzmann\ Constant}$

$\mathrm{T_e} = \mathrm{Radiative\ Equilibrium\ Temperature}$

$\mathrm{L} = \mathrm{Solar\ Irradiance\ at\ Top\ of\ Earth's\ Atmosphere}$

$$T_{atm} = T_e + \Delta T_{greenhouse}$$

A Faint Young Sun Leaves the Earth Frozen Solid



Kasting et al, Scientific American, 1988

Where to look for a solution?

- Early Earth Atmosphere: Right mix of greenhouse gases (Nathan Sheldon)
- Geology: Much more geothermal energy
- Biology: Life developed on a cold planet (John Priscu)
- Fundamental Physics: e.g., gravitational constant has varied
- Astrophysical Solutions: Young Sun was not faint

Biological Solution

- Early earth was cold and frozen over, yet life developed under unusual circumstances (John Priscu, MSU)

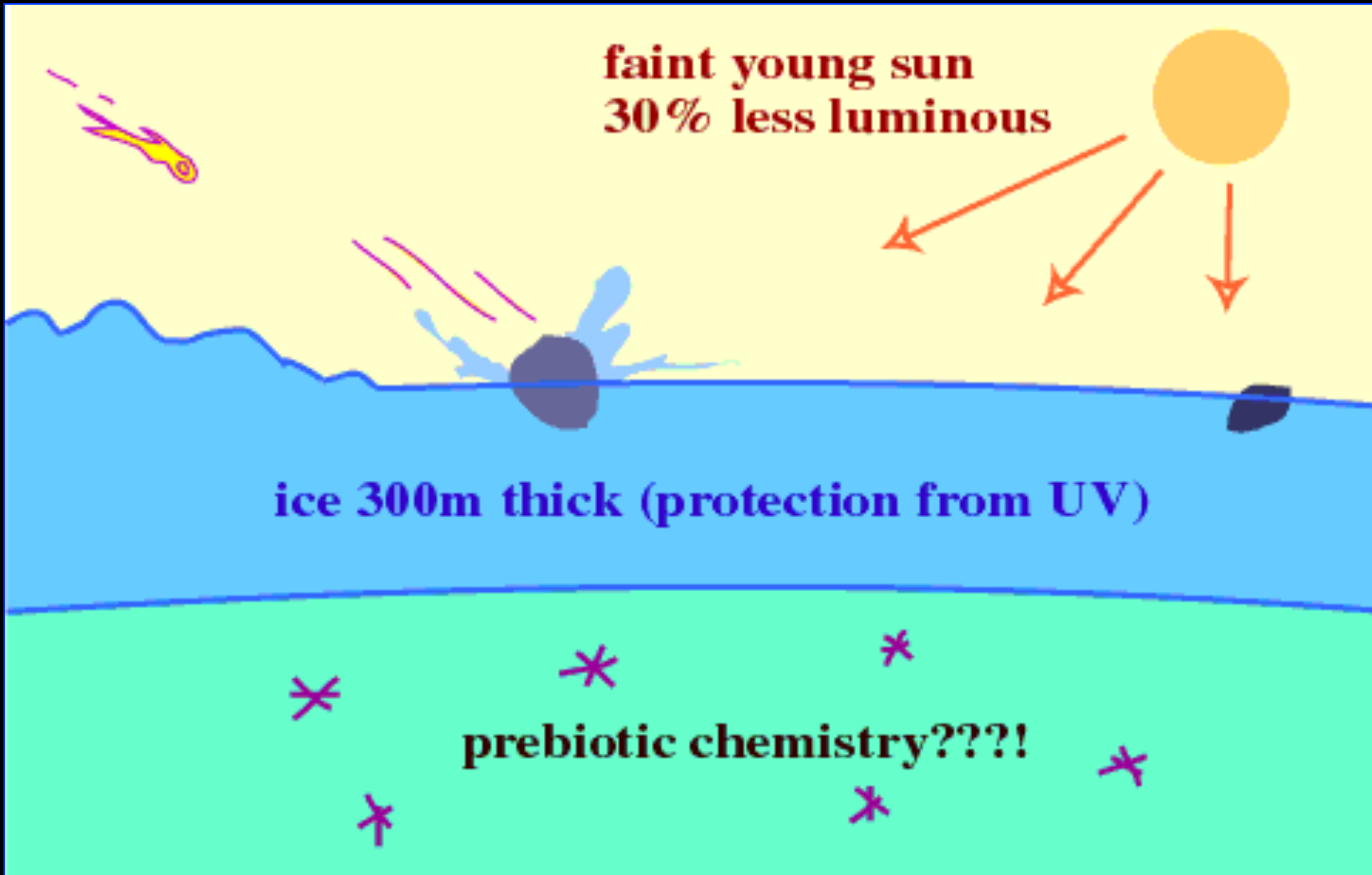
~4.5 Ga

LHB
3.8-4.0 Ga

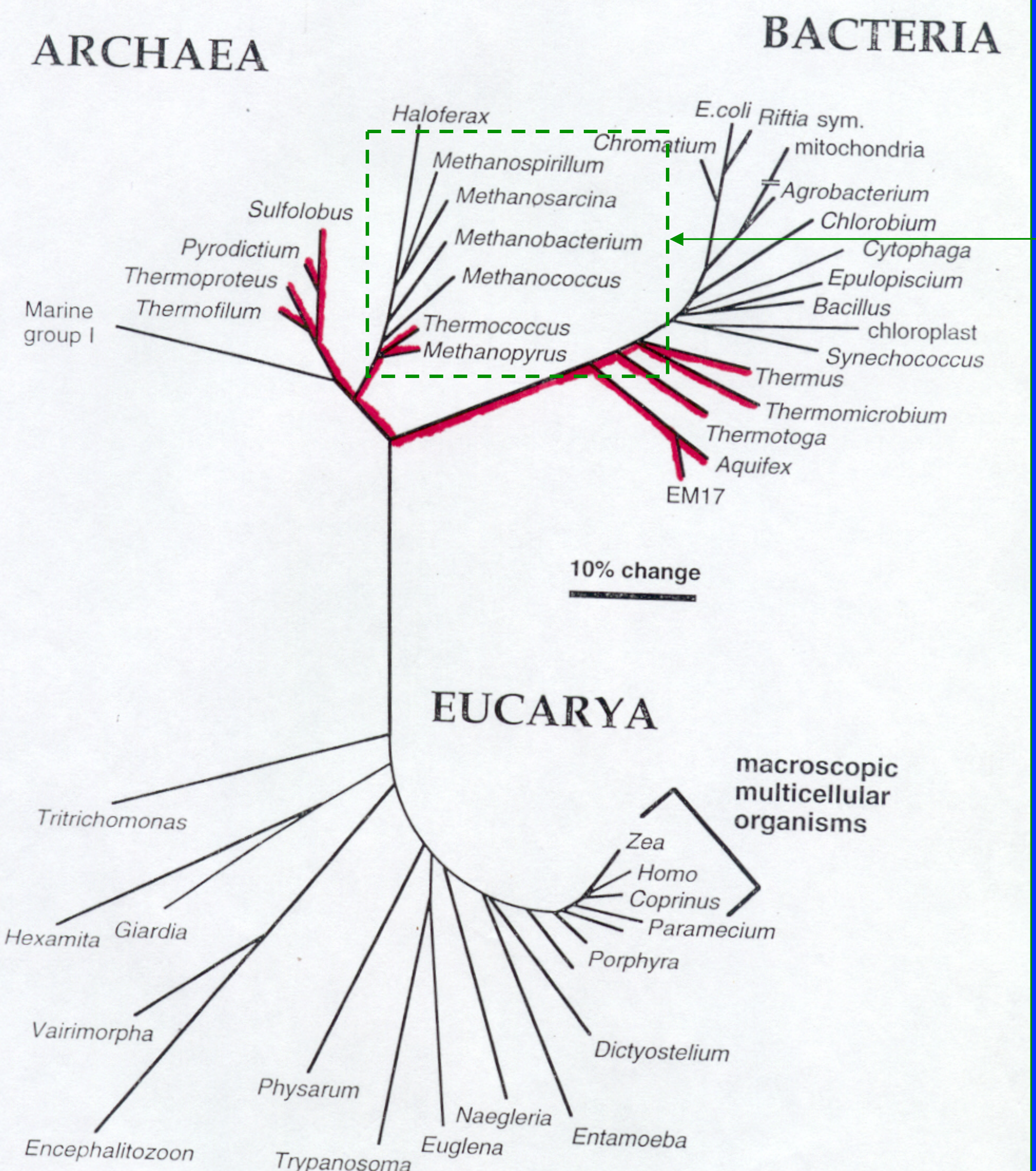
3.5 Ga

http://ircamera.as.arizona.edu/NatSci102/lectures/lifeform.htm
http://www.psi.edu/projects/moon/moon.html

Frozen Ocean on Early Earth?



Bada *et al.* 1994, PNAS, 91:1248-1250.
Image: http://www.chem.duke.edu/~jds/cruise_chem/Exobiology/sites.html



Methanogenic bacteria

"Universal" (rRNA) tree of life

Courtesy of Norm Pace

Early Earth Life Forms Still Exist

Lake Thetis Stromatolites (Ruth Ellison)

Stromatolites go back at least 3.5 Gyr

Precambrian stromatolite fossils from Glacier National Park

Problems with Cold Genesis

- Evidence for liquid water on continents
- Stromatolites live on surface

Climate Science Solution

- Thesis of Rodanelli (2009), adviser Richard Linzen (MIT)
- Stratospheric clouds in nitrogen/methane atmosphere can produce sufficient greenhouse shielding to obtain high temperatures (albedo effect minor)
- Does not work once atmosphere becomes oxygen rich/methane poor (~ - 2.5 Gyr)

Albedo Effects?

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

$$S \sim M_\odot^{\,6}$$

Liquid Water on Young Mars: Confirmed by NASA Rovers

NASA Press release, May 2009: “NASA Rover Sees Variable Environmental History at Martian Crater” …..“The data show water repeatedly came and left billions of years ago”. (Also presentation by Bob Craddock)

Squyres et al. (Nature, May 2009): “…alteration may have required several hundreds of millions of years of water exposure”.

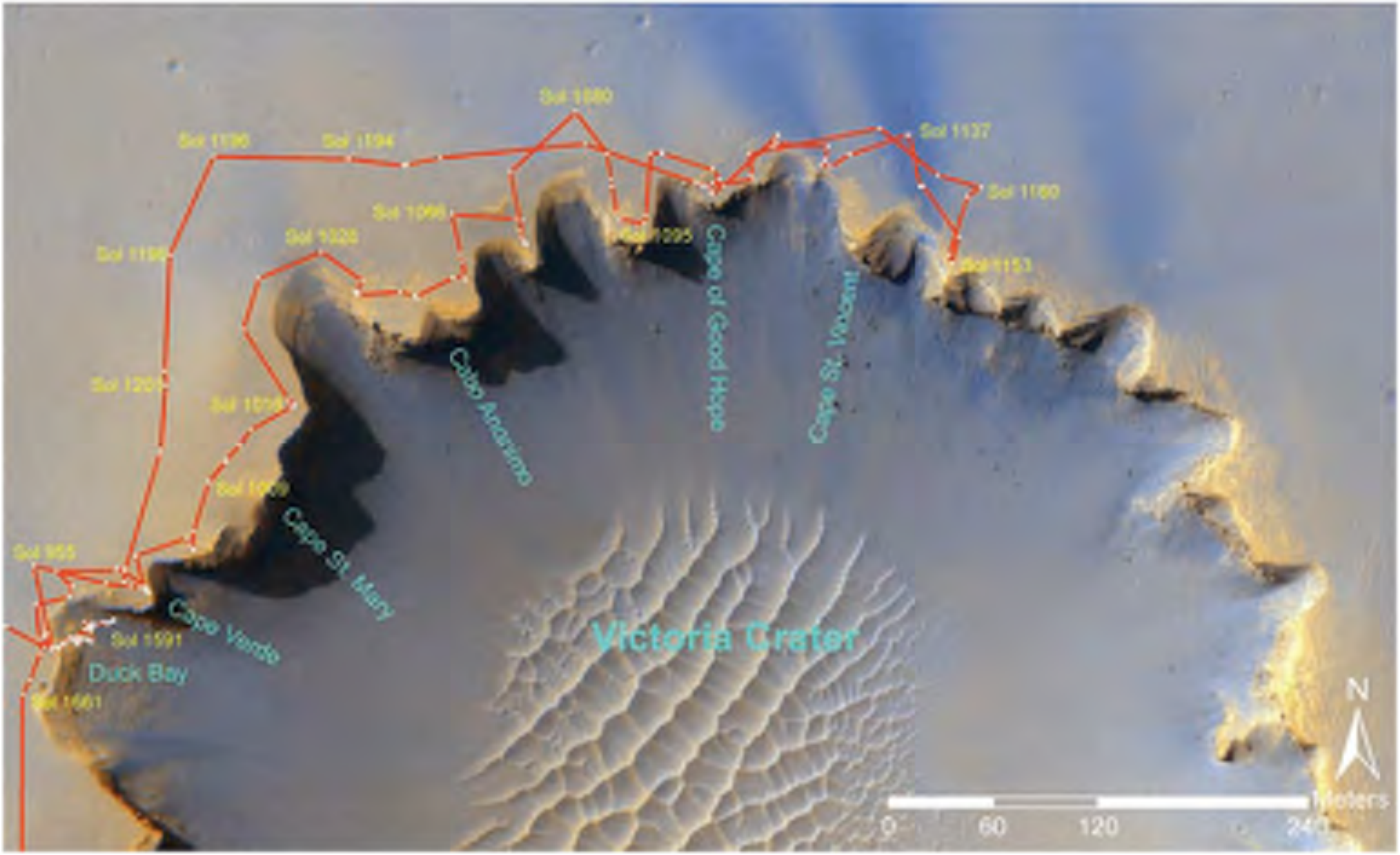


Fig. 1. Opportunity's traverse at Victoria crater. Image acquired by the Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment camera.

Occam's Razor Applied

If both the Earth and Mars throughout their history have had liquid surface water then it is reasonable to look for a common cause, i.e. a considerably brighter Sun than stellar evolution simulations predict.

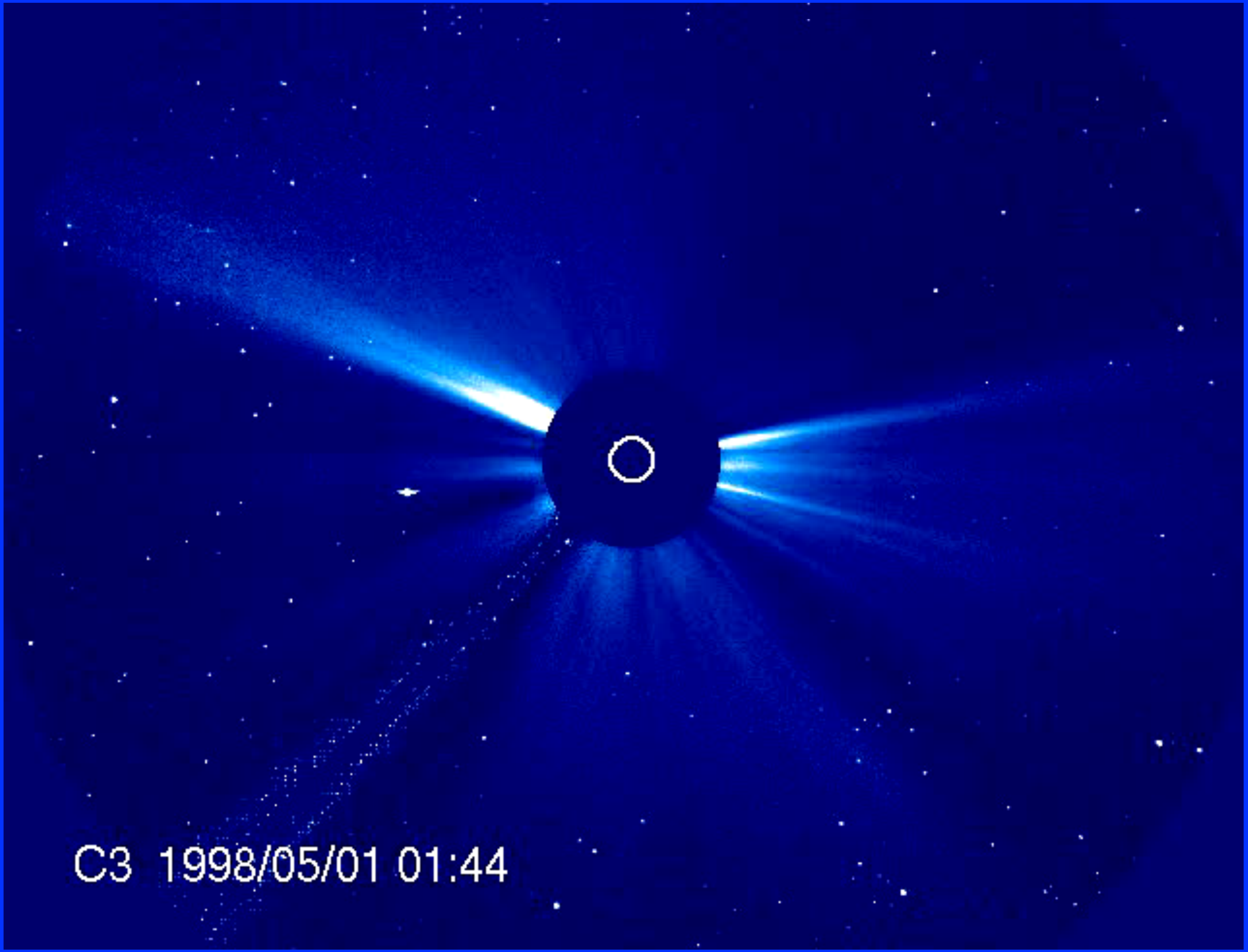
Mass Loss of a Younger Sun

- Solar flux to the planets goes as

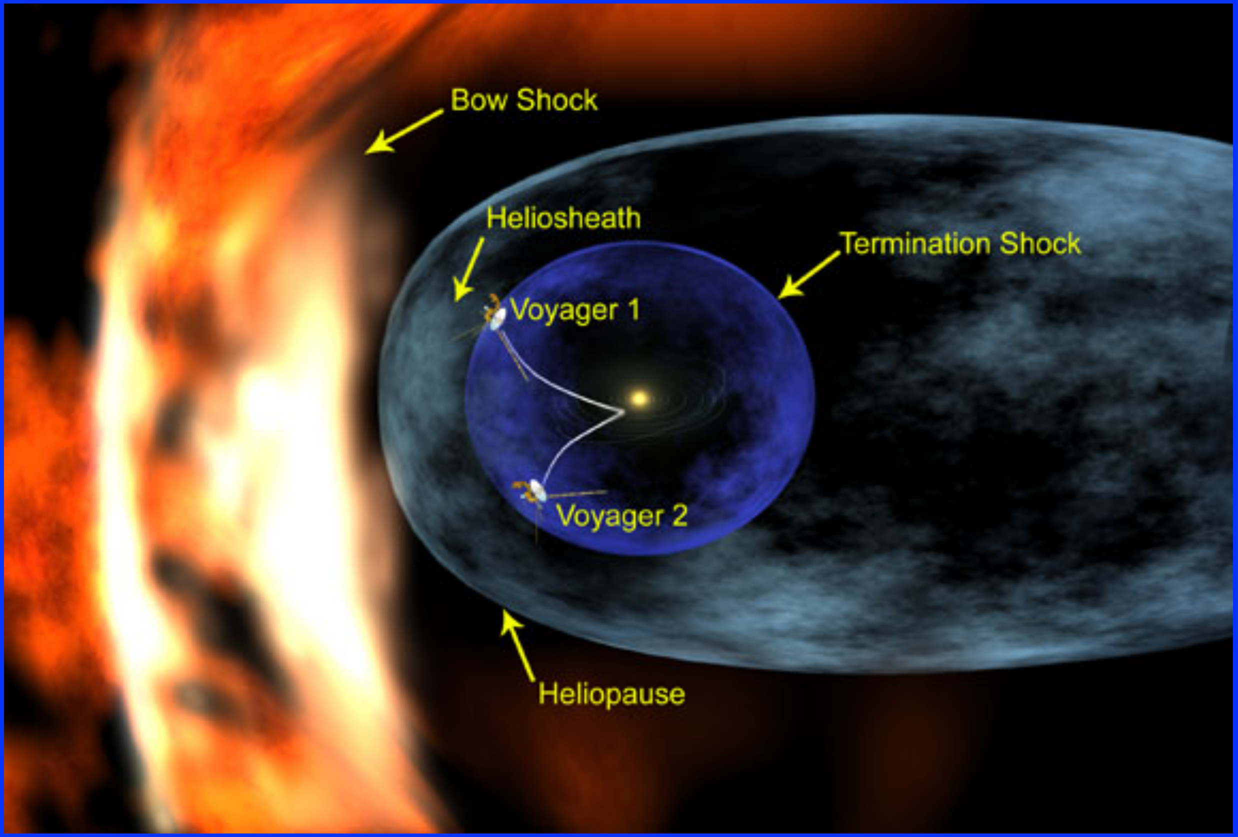
$$S \sim M_{\odot}^{6}$$

- So an early Sun that was ~5% more massive would yield 30% more irradiance, needed to have warm planetary atmospheres
- Hence, required solar mass loss is ~1% per billion years, i.e. $\dot{M}_{sun} = 10^{-11} M_{sun} / yr$
- Current (observed) mass loss $\dot{M}_{sun} = 3x10^{-14} M_{sun} / yr$
- Factor 300 off!

What is Solar Wind Anyway?



Observations of Mass Loss of Sun-like Stars



Mass loss of solar type stars is very hard to detect because it is so small. How is it done?

Some Observational Results

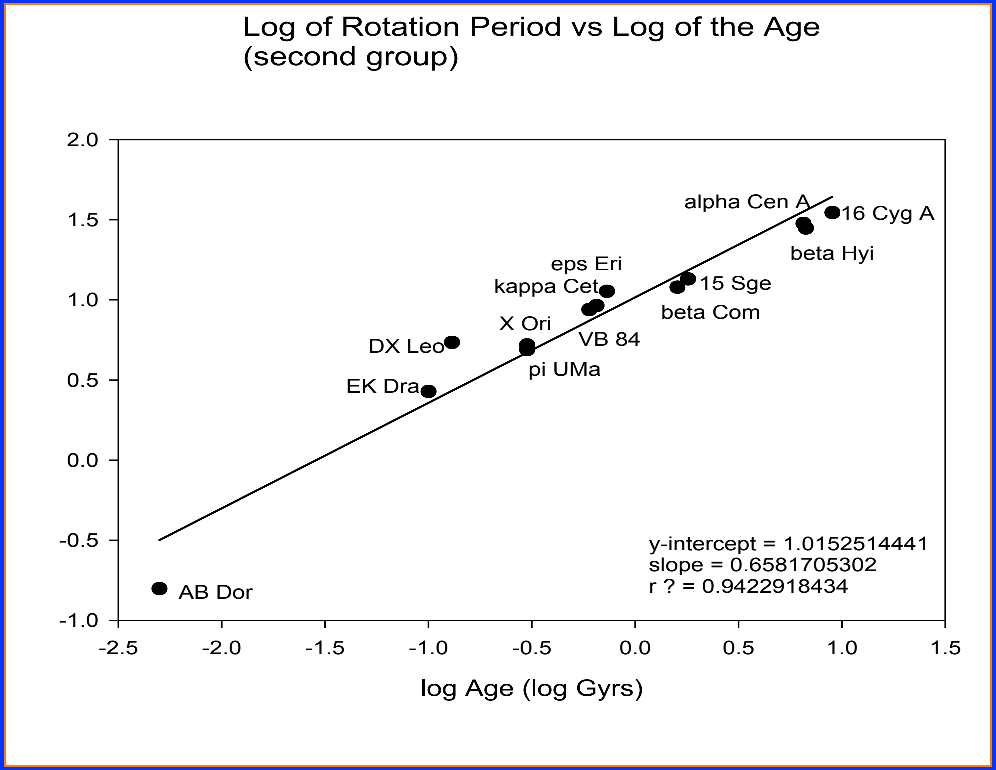
70 Ophiuchi, mass ~ 0.92 $M_{sun,}$ age ~ 0.8 billion years, mass loss ~ $3x10^{-12}$ M_{sun}/yr

E-Eridani, mass ~ 0.85 $M_{sun,}$ age ~ 0.5-1.0 billion years, mass loss ~ 10^{-12} M_{sun}/yr

Conclusion: Younger solar type starts have up to 100 times larger mass loss, but no solar-type star has been observed yet that has a mass loss of ~10^{-11} M_{sun}/yr. Wood et al. (2005) claim that $3x10^{-12}$ M_{sun}/yr is a physical upper limit

Spin-down Analysis

Much more is known about the spin-down of solar-type stars over their evolution. The spin-down is related to mass-loss



From Nandy and Martens 2007

$$P_{rot} \sim \tau^{-2/3}$$

$$\tau_{spin-down} \sim 2 \text{ billion years}$$

Spin-down versus Mass-loss

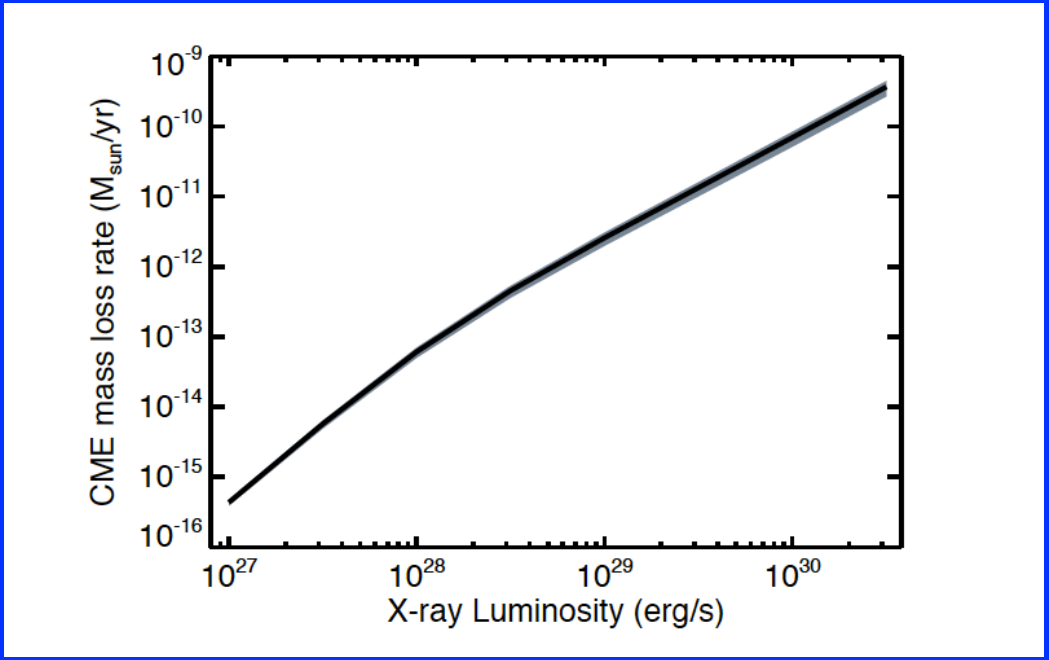
Definition: Alfven radius = radius where rotation velocity equals Alfven speed. Typical results are 3-10 stellar radii (depending on age).

Assumption: Inside Alfven radius rigid co-rotation, outside mass-loss is let go → momentum loss → magnetic braking

Rotating Arm Sprinkler, $ 32.95 on Amazon.com

Mass-Loss and X-Ray Luminosity

Key Result: Mass-loss rate via CME's scales with X-ray luminosity to the power 3/2 (Jeremy Drake et al. 2012). Yields good results for current Sun and for very young Suns (~ $3x10^{-12}$ M_{sun}/yr). Mass-loss may not be sustainable by stellar dynamo in upper range.



Mass Loss versus Spin-down Time Scales

$$\dot{L} = \dot{M} \times r_A \times v_{rot} = \dot{M} \times r_A^2 \times \omega$$

$$L = M \times r_I \times v_{rot} = M \times r_I^2 \times \omega$$

Result: Spin-down time scale (L/L-dot) does not depend on rotation rate, but is linearly connected with mass loss rate (M/M-dot) :

$$\tau_{mass-loss} = \tau_{spin-down} \times (r_I / r_A)^2$$

Mass Loss Time Scale from Spin Down

$$\tau_{mass-loss} = \tau_{spin-down} \times (r_I / r_A)^2$$

$$\tau_{spin-down} = 2 \times 10^9 \, years$$

$$r_I = r_{star} \times (1/3 - 1/6)$$

$$r_A = r_{star} \times (3 - 10)$$

$$\tau_{mass-loss} = 2 \times 10^{11} - 2 \times 10^{12} \, years$$

Close to what is needed, consistent with direct observations

Conclusions: A Work in Progress

- The resolution of the “Faint Young Sun” paradox may lie in that the young Sun was not as faint as mass-conserving stellar evolution simulations indicate.

- Mass loss is a likely candidate because planetary insolation scales so efficiently with mass loss.

- Direct observations of stellar mass loss and spin-down indicate a mass-loss rate that is shy by a factor 2-4 of what is required for a warm young Earth, and that may be sustained for too short a period.

This is very much a work in progress!