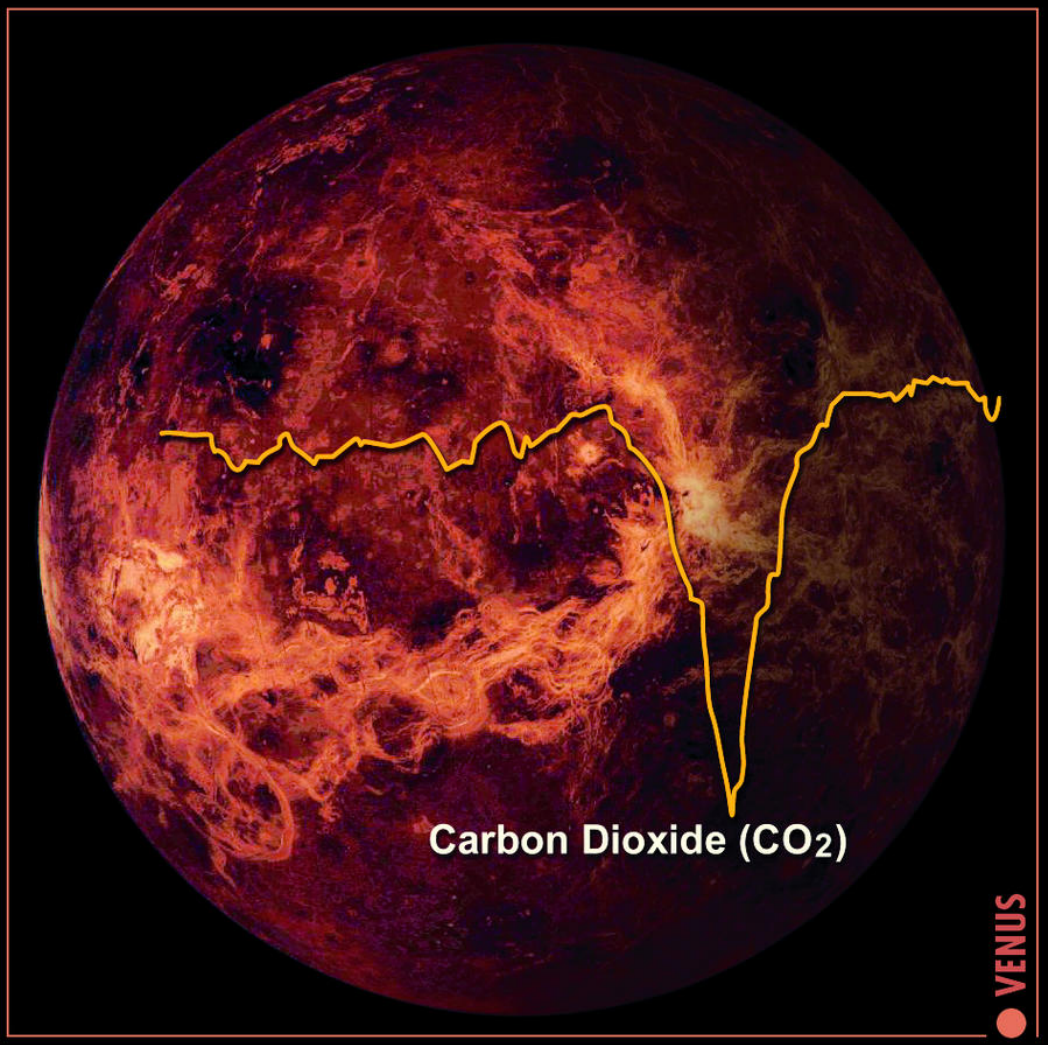
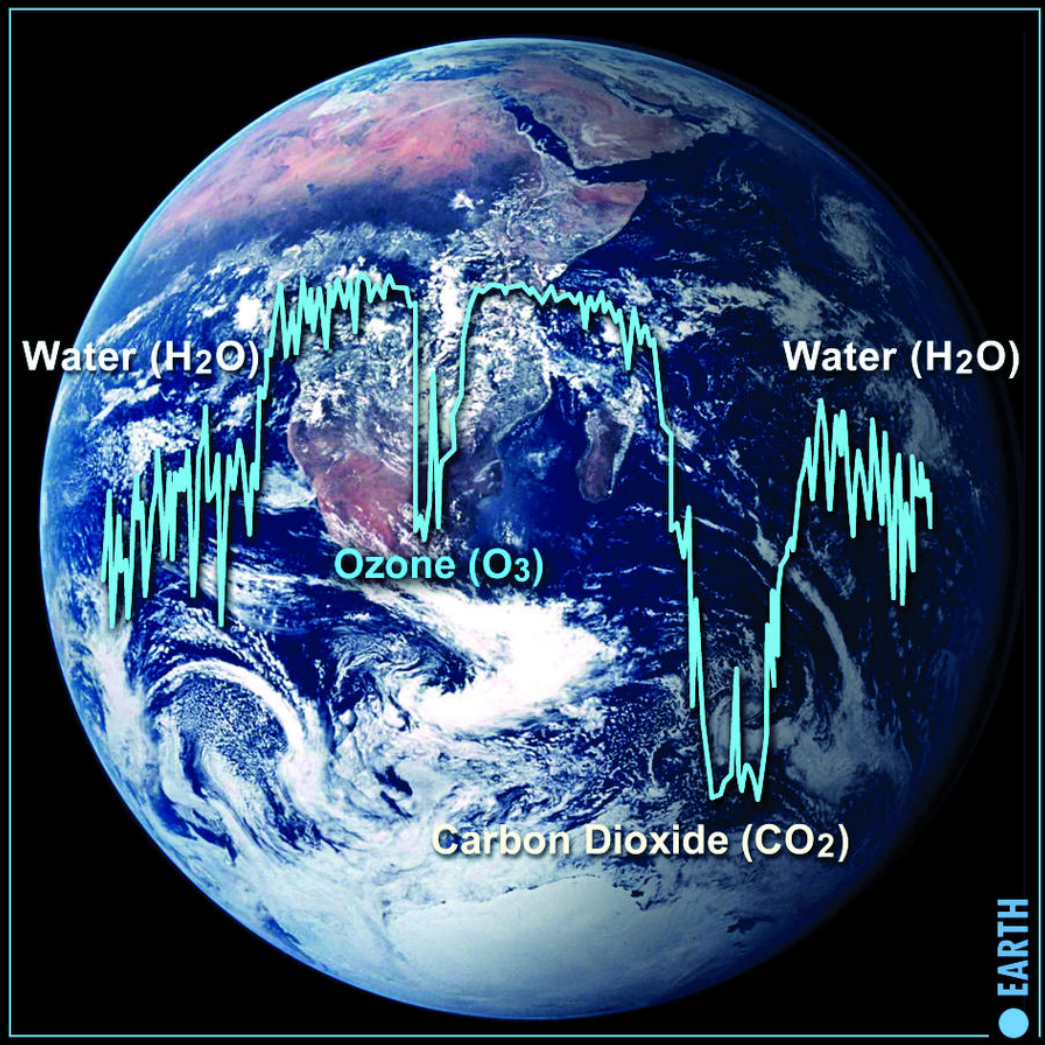
# Planetary Habitability




**Stephen Kane**

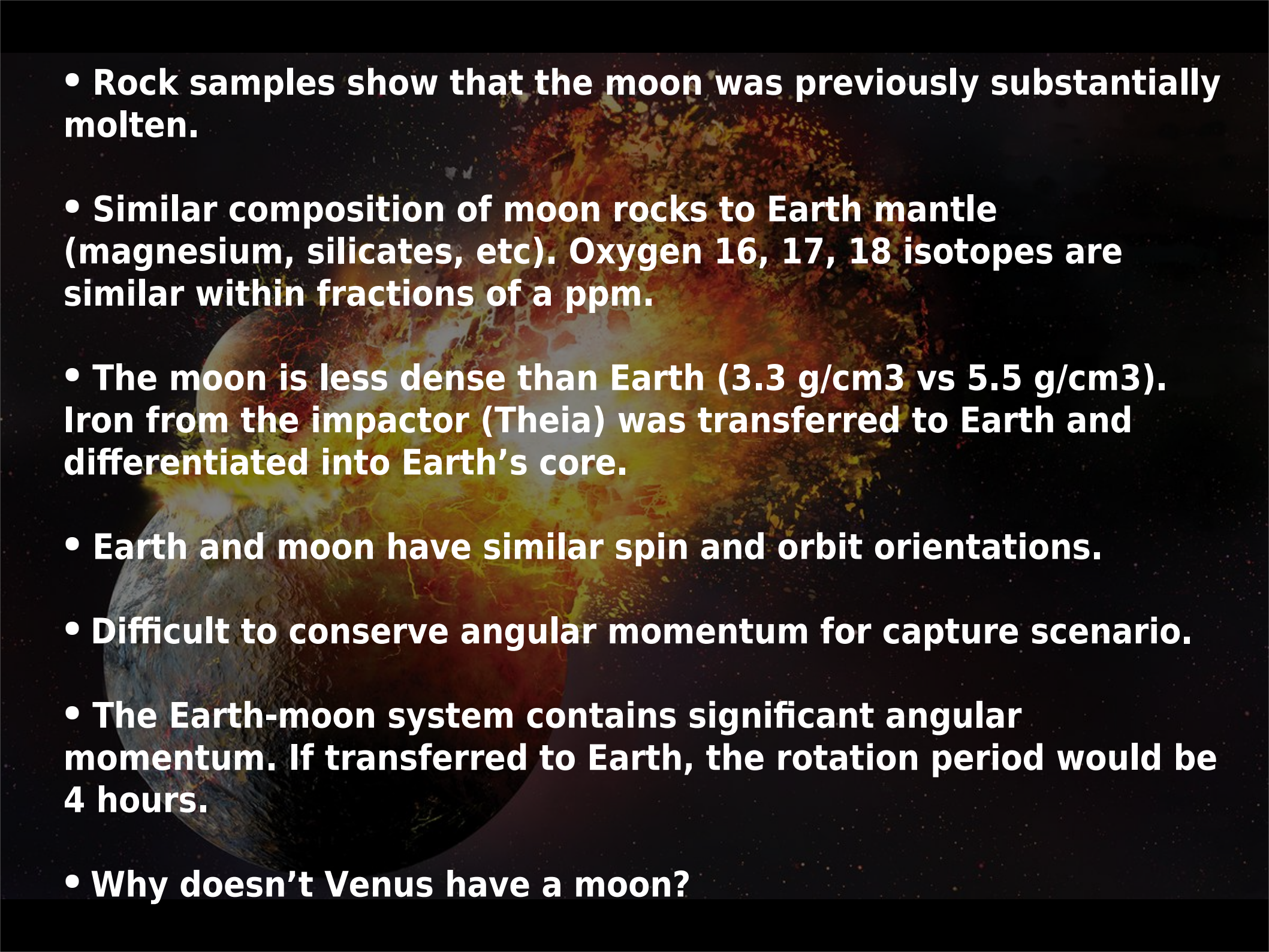
UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

# Topics

- Lecture 1 – Introduction
- Lecture 2 – Habitability Factors
- Lecture 3 - Stars
- Lecture 4 – Planetary Atmospheres
- Lecture 5 – Planetary Interiors
- Lecture 6 – Planetary Energy Balance
- Lecture 7 – Habitable Zone I
- Lecture 8 – Habitable Zone II
- Lecture 9 – Earth as a Living Planet
- Lecture 10 – Mars
- Lecture 11 – Icy Moons
- Lecture 12 – Venus
- Lecture 13 – Mercury & the Moon
- Lecture 14 – The Role of Giant Planets
- Lecture 15 – Stellar Influences
- Lecture 16 – Magnetic Fields
- Lecture 17 – Milankovitch Cycles
- Lecture 18 – Geological Cycles
- Lecture 19 – The Next Steps
- Lecture 20 – Summary/Discussion

# Earth's Habitability

- Effect of moon-forming impact.
- Habitability regions on the planet.
- Earth's radiative budget.
- The Faint Young Sun and Earth's thermostat.
- Earth's orbital variations.



- Rock samples show that the moon was previously substantially molten.

- Similar composition of moon rocks to Earth mantle (magnesium, silicates, etc). Oxygen 16, 17, 18 isotopes are similar within fractions of a ppm.

- The moon is less dense than Earth (3.3 g/cm3 vs 5.5 g/cm3). Iron from the impactor (Theia) was transferred to Earth and differentiated into Earth's core.

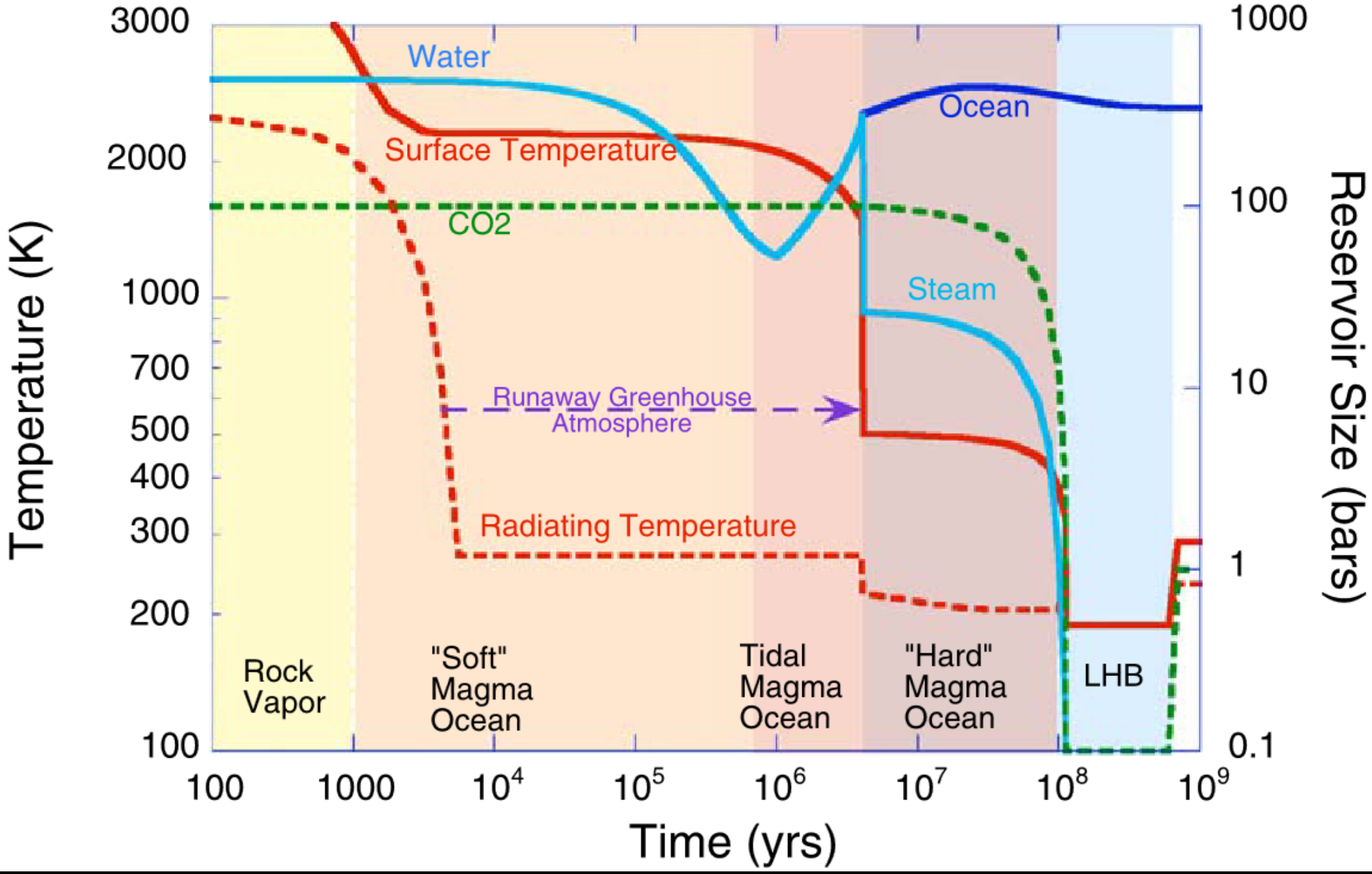
- Earth and moon have similar spin and orbit orientations.

- Difficult to conserve angular momentum for capture scenario.

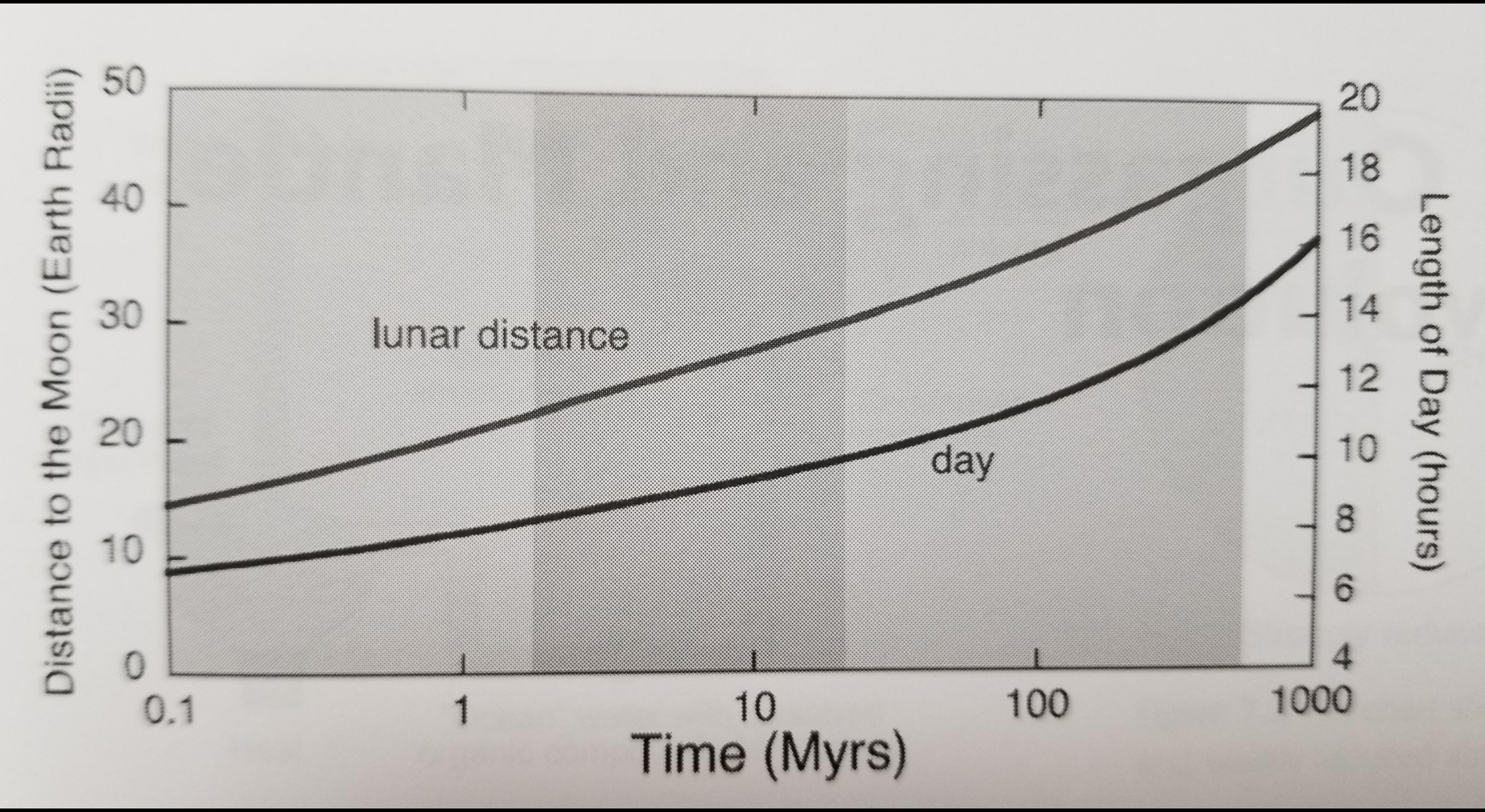
- The Earth-moon system contains significant angular momentum. If transferred to Earth, the rotation period would be 4 hours.

- Why doesn't Venus have a moon?

# Effects of Moon-Forming Impact

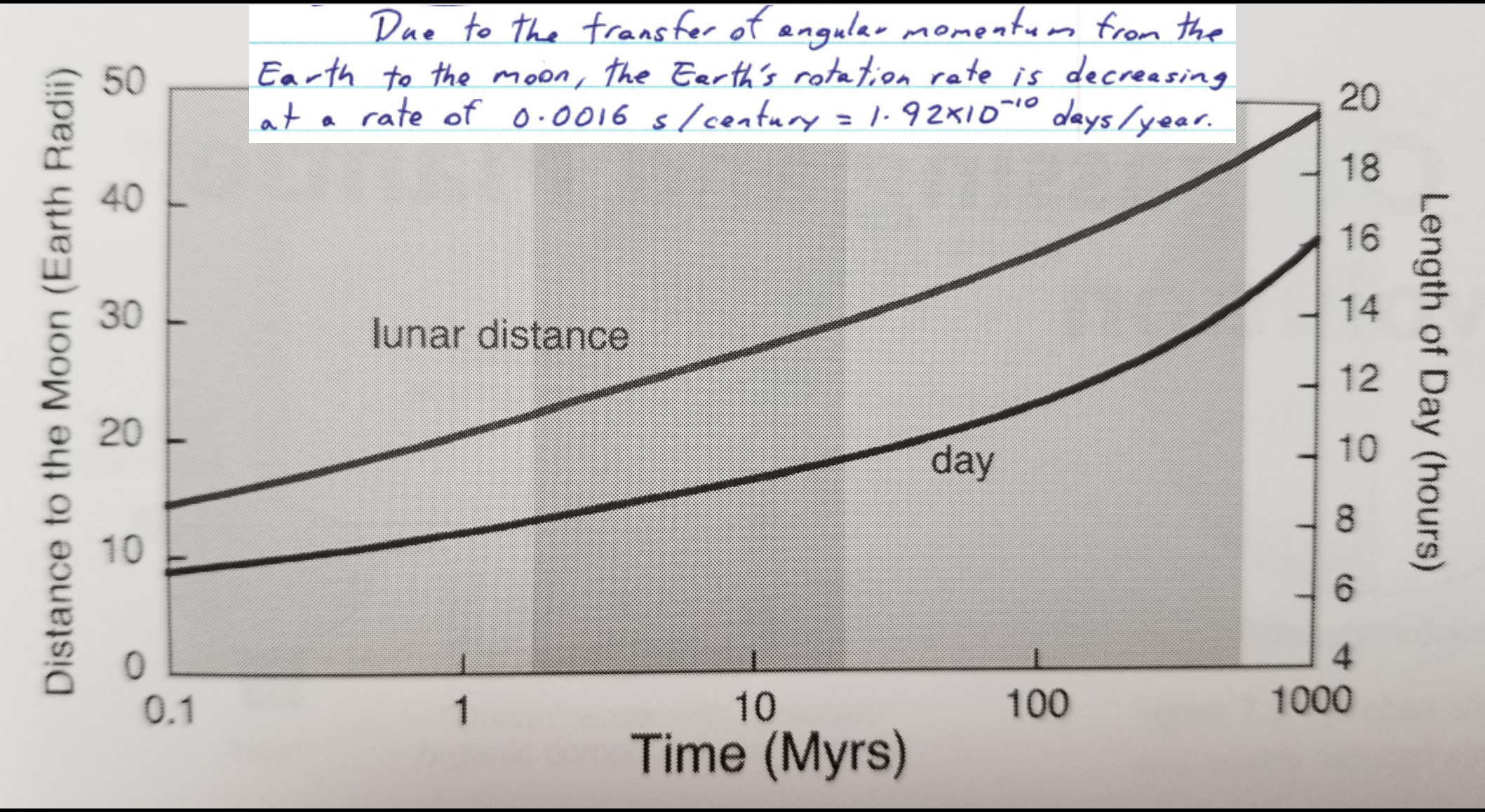


# Effects of Moon-Forming Impact



# Effects of Moon-Forming Impact

Due to the transfer of angular momentum from the Earth to the moon, the Earth's rotation rate is decreasing at a rate of 0.0016 s/century = $1.92 \times 10^{-10}$ days/year.



# Emergence of a Habitable Planet

Show affiliations

Zahnle, Kevin ; Arndt, Nick ; Cockell, Charles ; Halliday, Alex ; Nisbet, Euan ; Selsis, Franck ; Sleep, Norman H.

We address the first several hundred million years of Earth's history. The Moon-forming impact left Earth enveloped in a hot silicate atmosphere that cooled and condensed over ~1,000 yrs. As it cooled the Earth degassed its volatiles into the atmosphere. It took another ~2 Myrs for the magma ocean to freeze at the surface. The cooling rate was determined by atmospheric thermal blanketing. Tidal heating by the new Moon was a major energy source to the magma ocean. After the mantle solidified geothermal heat became climatologically insignificant, which allowed the steam atmosphere to condense, and left behind a ~100 bar, ~500 K $CO_2$ atmosphere. Thereafter cooling was governed by how quickly $CO_2$ was removed from the atmosphere. If subduction were efficient this could have taken as little as 10 million years. In this case the faint young Sun suggests that a lifeless Earth should have been cold and its oceans white with ice. But if carbonate subduction were inefficient the $CO_2$ would have mostly stayed in the atmosphere, which would have kept the surface near ~500 K for many tens of millions of years. Hydrous minerals are harder to subduct than carbonates and there is a good chance that the Hadean mantle was dry. Hadean heat flow was locally high enough to ensure that any ice cover would have been thin (<5 m) in places. Moreover hundreds or thousands of asteroid impacts would have been big enough to melt the ice triggering brief impact summers. We suggest that plate tectonics as it works now was inadequate to handle typical Hadean heat flows of 0.2-0.5 $W/m^2$. In its place we hypothesize a convecting mantle capped by a ~100 km deep basaltic mush that was relatively permeable to heat flow. Recycling and distillation of hydrous basalts produced granitic rocks very early, which is consistent with preserved >4 Ga detrital zircons. If carbonates in oceanic crust subducted as quickly as they formed, Earth could have been habitable as early as 10-20 Myrs after the Moon-forming impact.

**Publication:** Space Science Reviews, Volume 129, Issue 1-3, pp. 35-78

**Pub Date:** March 2007

**DOI:** 10.1007/s11214-007-9225-z

**Bibcode:** 2007SSRv..129...35Z

**Keywords:** Hadean Earth; Moon-forming impact; Origin of Earth; Magma oceans; Planetary atmospheres; Late heavy bombardment

# Origin of the Moon in a giant impact near the end of the Earth's formation

Show affiliations

Canup, Robin M. ; Asphaug, Erik

The Moon is generally believed to have formed from debris ejected by a large off-centre collision with the early Earth. The impact orientation and size are constrained by the angular momentum contained in both the Earth's spin and the Moon's orbit, a quantity that has been nearly conserved over the past 4.5 billion years. Simulations of potential moon-forming impacts now achieve resolutions sufficient to study the production of bound debris. However, identifying impacts capable of yielding the Earth-Moon system has proved difficult. Previous works found that forming the Moon with an appropriate impact angular momentum required the impact to occur when the Earth was only about half formed, a more restrictive and problematic model than that originally envisaged. Here we report a class of impacts that yield an iron-poor Moon, as well as the current masses and angular momentum of the Earth-Moon system. This class of impacts involves a smaller-and thus more likely-object than previously considered viable, and suggests that the Moon formed near the very end of Earth's accumulation.

**Publication:** Nature, Volume 412, Issue 6848, pp. 708-712 (2001).

**Pub Date:** August 2001

**Bibcode:** 2001Natur.412..708C

# Brief follow-up on recent studies of Theia's accretion

Show affiliations

Kaib, Nathan A. ; Cowan, Nicolas B.

Kaib and Cowan (Kaib, N.A., Cowan, N.B. [2015]. Icarus 252, 161-174) recently used terrestrial planet formation simulations to conclude that the moon-forming impactor (Theia) had only a ~5% or less chance of having the same oxygen isotope composition as Earth, while Mastrobuono-Battisti et al. (Mastrobuono-Battisti, A., Perets, H.B., Raymond, S.N. [2015]. Nature 520, 212-215) used seemingly similar simulations and methods to arrive at a higher value of ~20% or more. Here we derive the results of both papers from a single set of simulations. Compared to Kaib and Cowan (Kaib, N.A., Cowan, N.B. [2015]. Icarus 252, 161-174), the analysis of Mastrobuono-Battisti et al. (Mastrobuono-Battisti, A., Perets, H.B., Raymond, S.N. [2015]. Nature 520, 212-215) systematically yields more massive Theia analogs and imposes flatter $\Delta 1^7$ O gradients across the original protoplanetary disk. Both of these effects diminish isotopic differences between Earth and Theia analogs. While it is notoriously difficult to produce systems resembling our actual terrestrial planets, the analysis of Kaib and Cowan (Kaib, N.A., Cowan, N.B. [2015]. Icarus 252, 161-174) more often selects and analyzes Earth and Mars analogs at orbital locations near the real planets. Given this, we conclude that the greater isotopic differences between Earth and Theia found in Kaib and Cowan (Kaib, N.A., Cowan, N.B. [2015]. Icarus 252, 161-174) better reflect the predictions of terrestrial planet formation models. Finally, although simulation uncertainties and a terrestrial contribution to Moon formation enhance the fraction of Theia analogs consistent with the canonical giant impact hypothesis, this fraction still remains in the 5-8% range.

**Publication:** Icarus, Volume 258, p. 14-17.

**Pub Date:** September 2015

**DOI:** 10.1016/j.icarus.2015.06.019
10.48550/arXiv.1506.06132

**arXiv:** arXiv:1506.06132

**Bibcode:** 2015Icar..258...14K

**Keywords:** Moon; Terrestrial planets; Planetary formation; interior; Planetesimals; Astrophysics - Earth and Planetary Astrophysics

**E-Print Comments:** 5 pages, 4 figures, accepted to Icarus; doi:10.1016/j.icarus.2015.06.019

# The Habitability of Our Earth and Other Earths: Astrophysical, Geochemical, Geophysical, and Biological Limits on Planet Habitability

Show affiliations

Lineweaver, Charles H. ; Chopra, Aditya

For life-forms like us, the most important feature of Earth is its habitability. Understanding habitability and using that knowledge to locate the nearest habitable planet may be crucial for our survival as a species. During the past decade, expectations that the universe could be filled with habitable planets have been bolstered by the increasingly large overlap between terrestrial environments known to harbor life and the variety of environments on newly detected rocky exoplanets. The inhabited and uninhabited regions on Earth tell us that temperature and the presence of water are the main constraints that can be used in a habitability classification scheme for rocky planets. Our compilation and review of recent exoplanet detections suggests that the fraction of stars with planets is ~100%, and that the fraction with rocky planets may be comparably large. We review extensions to the circumstellar habitable zone (HZ), including an abiogenesis habitable zone and the galactic habitable zone.

**Publication:** Annual Review of Earth and Planetary Sciences, vol. 40, issue 1, pp. 597-623

**Pub Date:** May 2012

**DOI:** 10.1146/annurev-earth-042711-105531

**Bibcode:** 2012AREPS..40..597L

# Distribution of Life on Earth

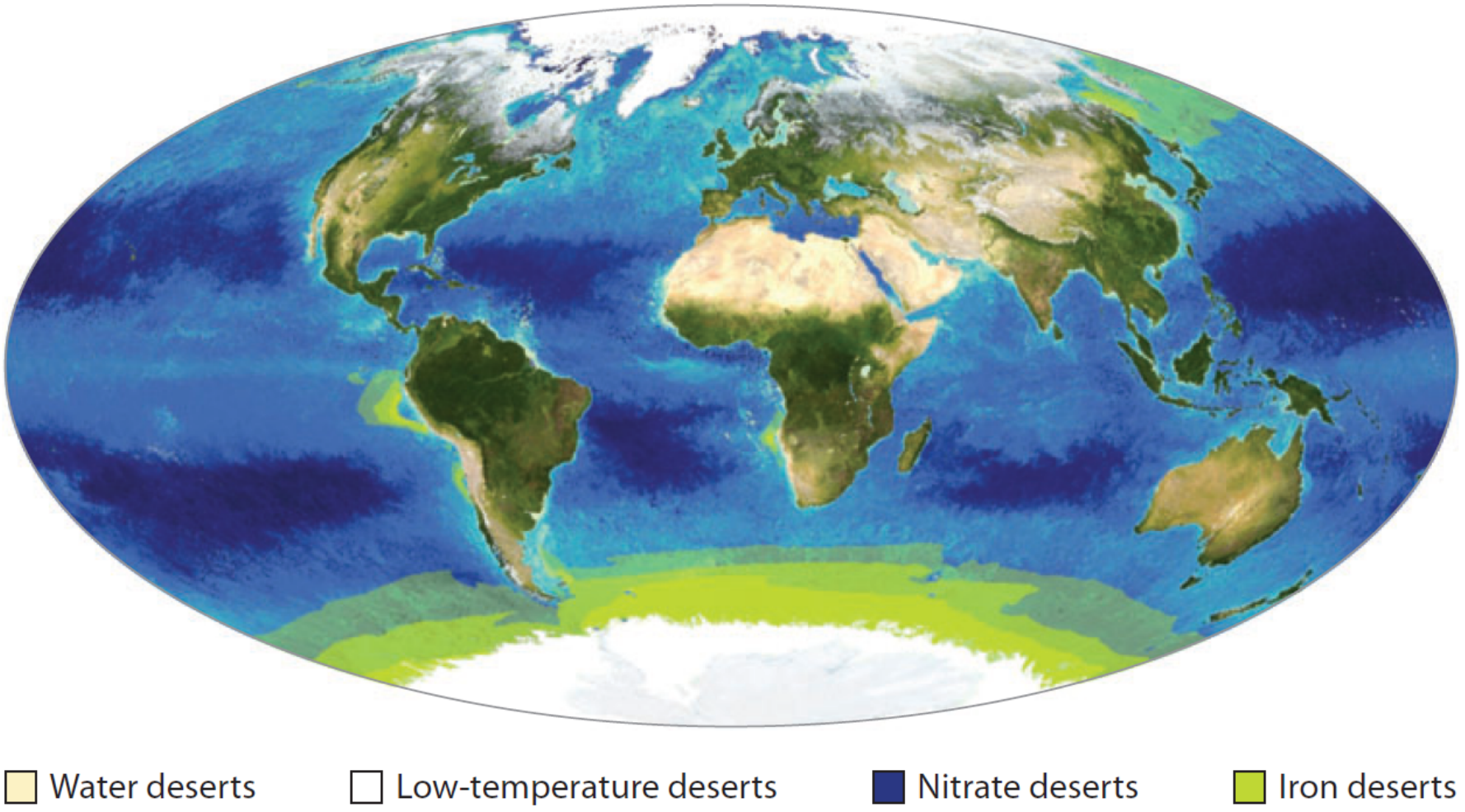



**Figure 3**

Four deserts on Earth's surface. Life is not evenly distributed over the surface of Earth. There are water deserts (*sandy brown*), low-temperature deserts (*white*), nitrate deserts (*dark blue*), and iron deserts (*light green*), where the abundance of life is significantly lower than in surrounding regions. This map was constructed with data from Stockli et al. (2005) and McClain et al. (2006).

# Distribution of Life on Earth

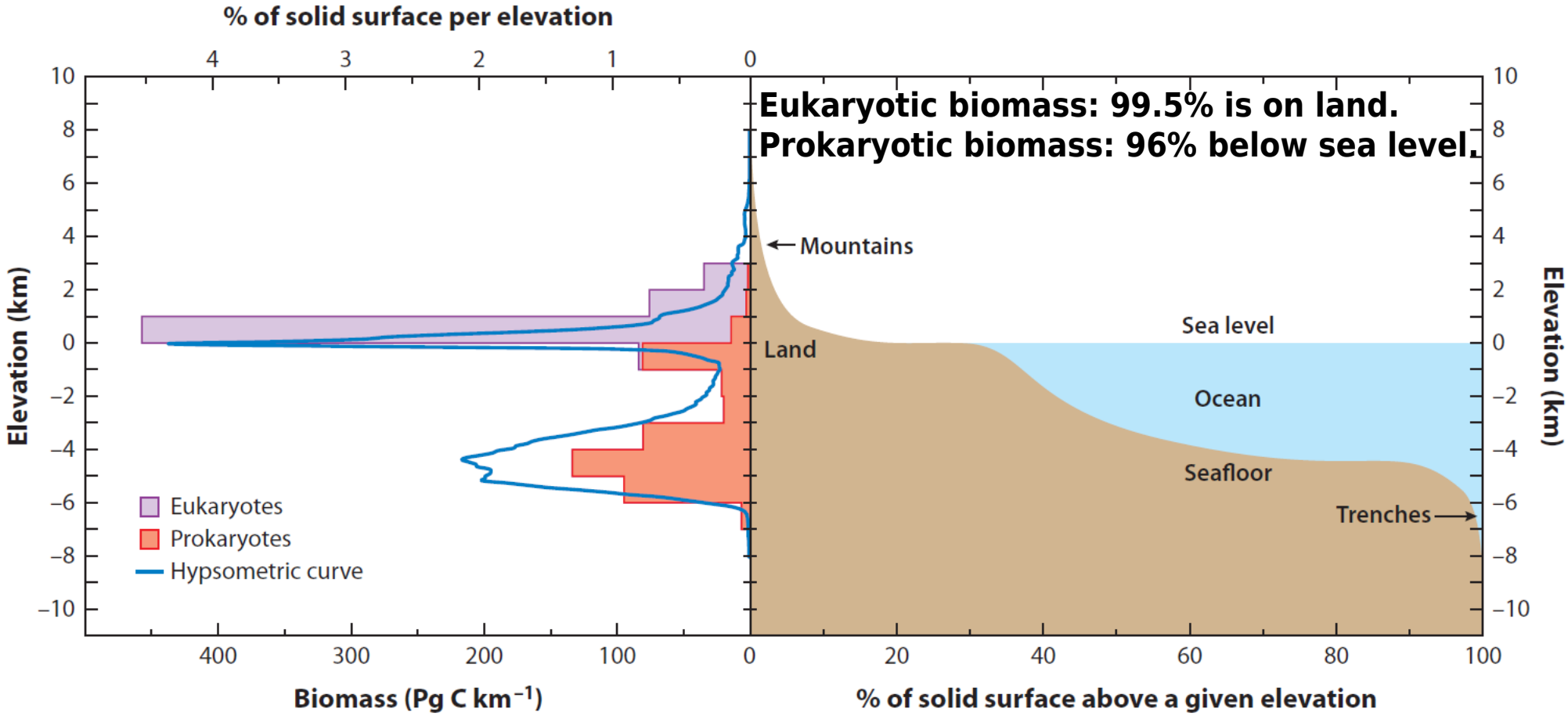
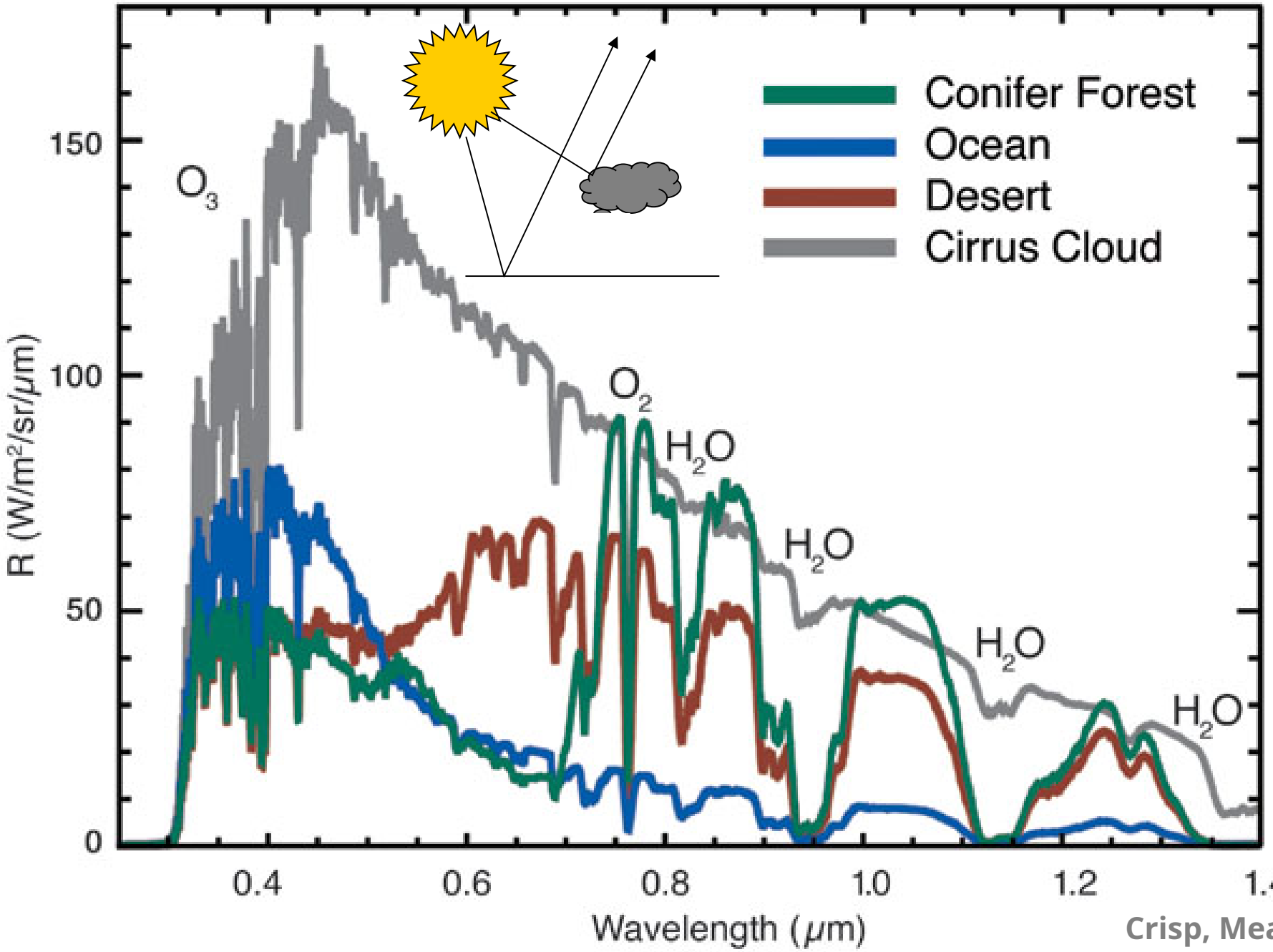


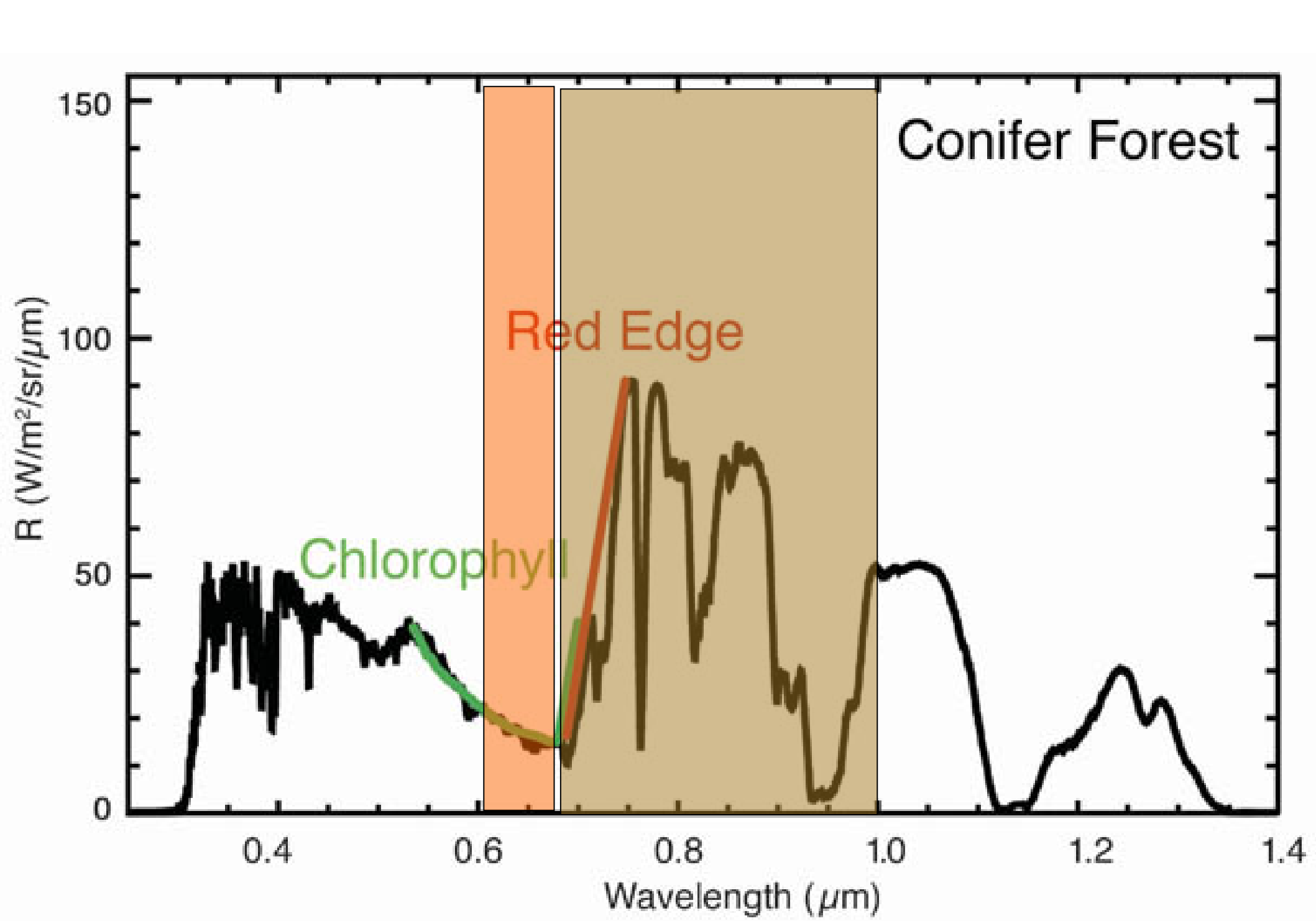

**Figure 4**

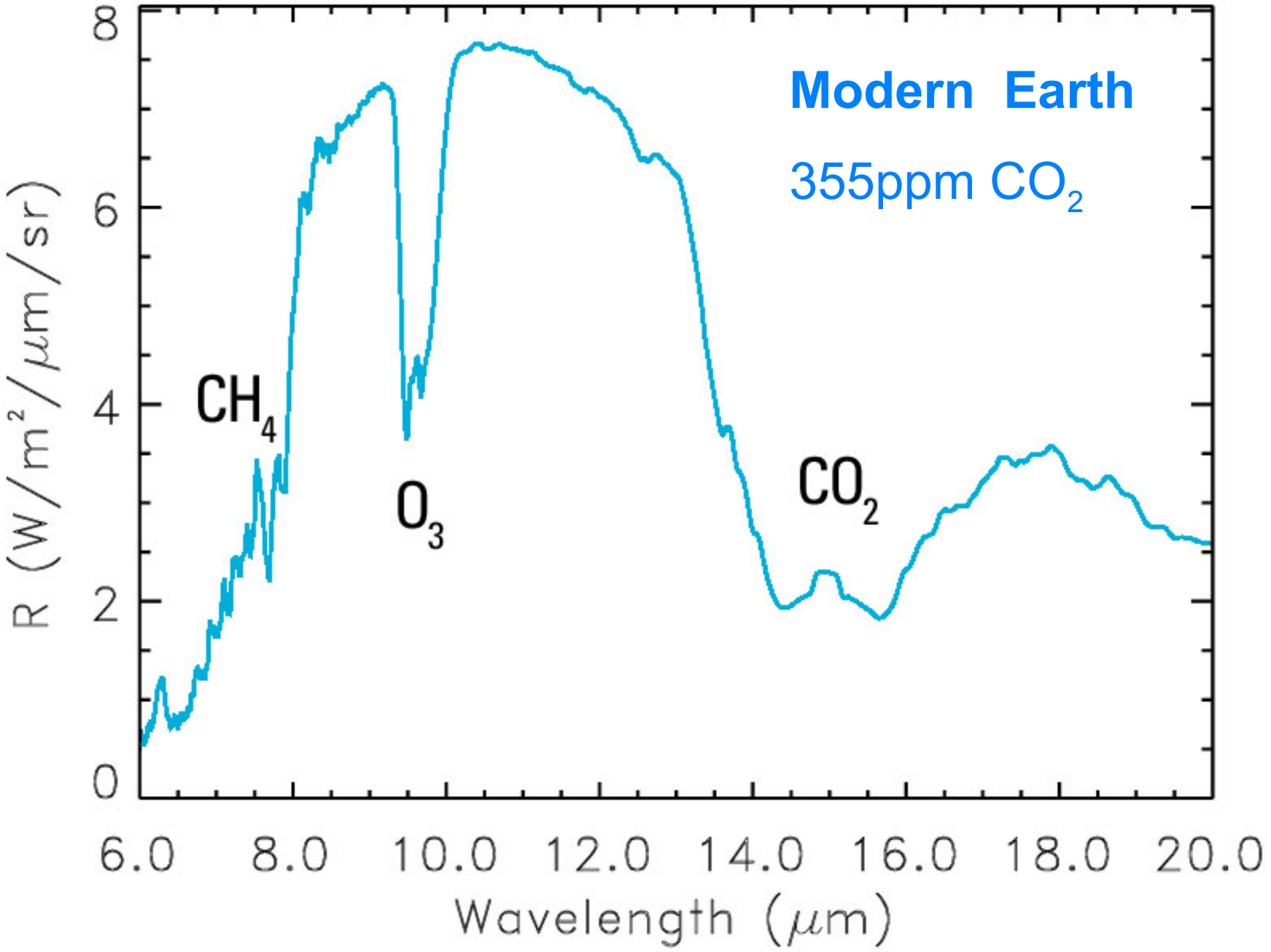
Vertical profile of biomass in the thin terrestrial bioshell (± 10 km). The hypsographic curve on the right shows the fraction of Earth's solid surface above a given elevation. For example, 30% of the solid surface is above sea level, whereas the remaining 70% is below sea level. The hypsometric curve on the left (*blue line*) (Perotti & Rinaldi 2011) shows the fraction of Earth's solid surface at any given elevation. The histogram on the left shows our estimate of the vertical profile of terrestrial biomass (total carbon in terrestrial life forms) derived from combining data from Whitman et al. (1998) and Houghton (2003).

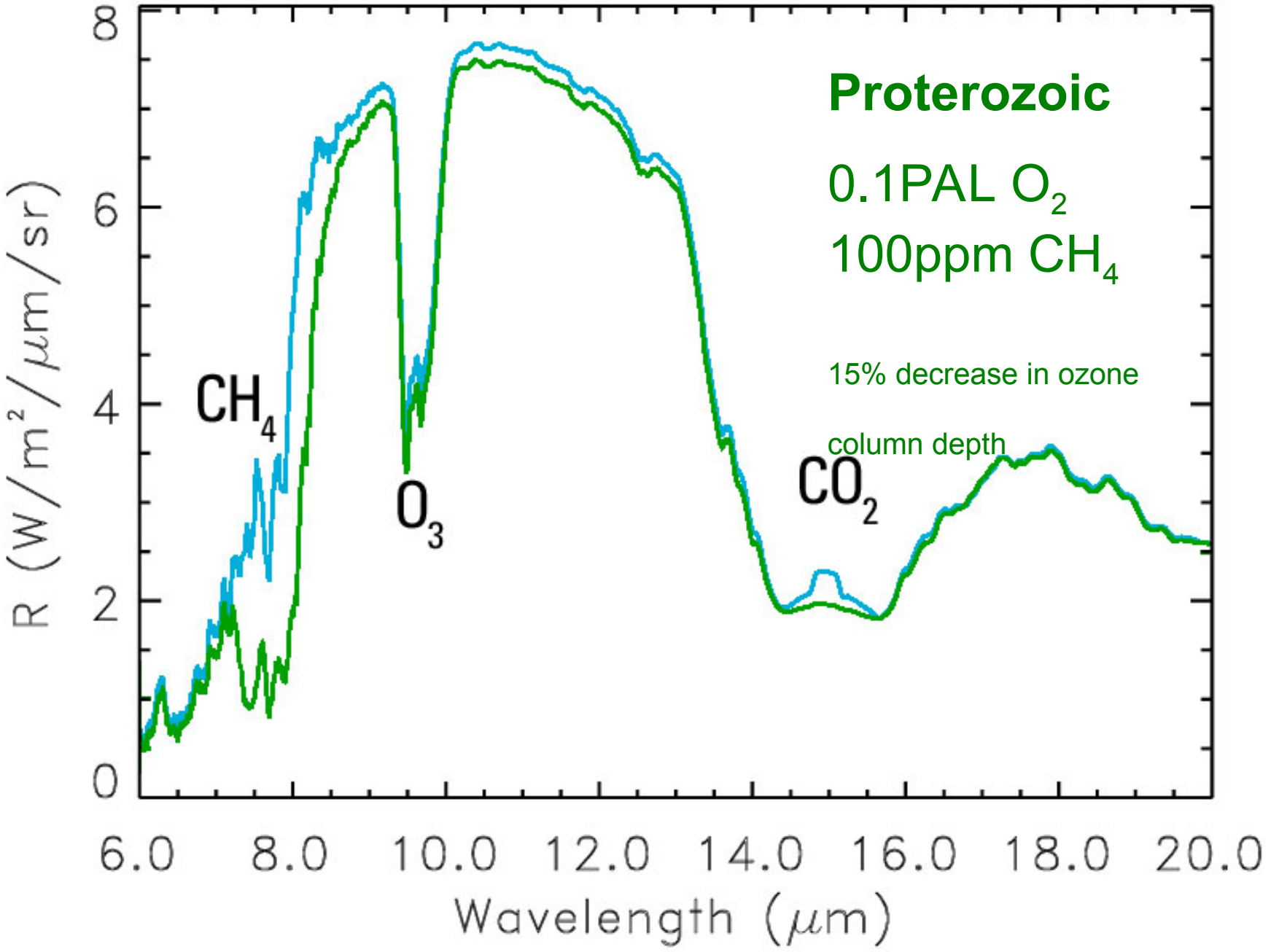
# The Earth From Space In The Visible

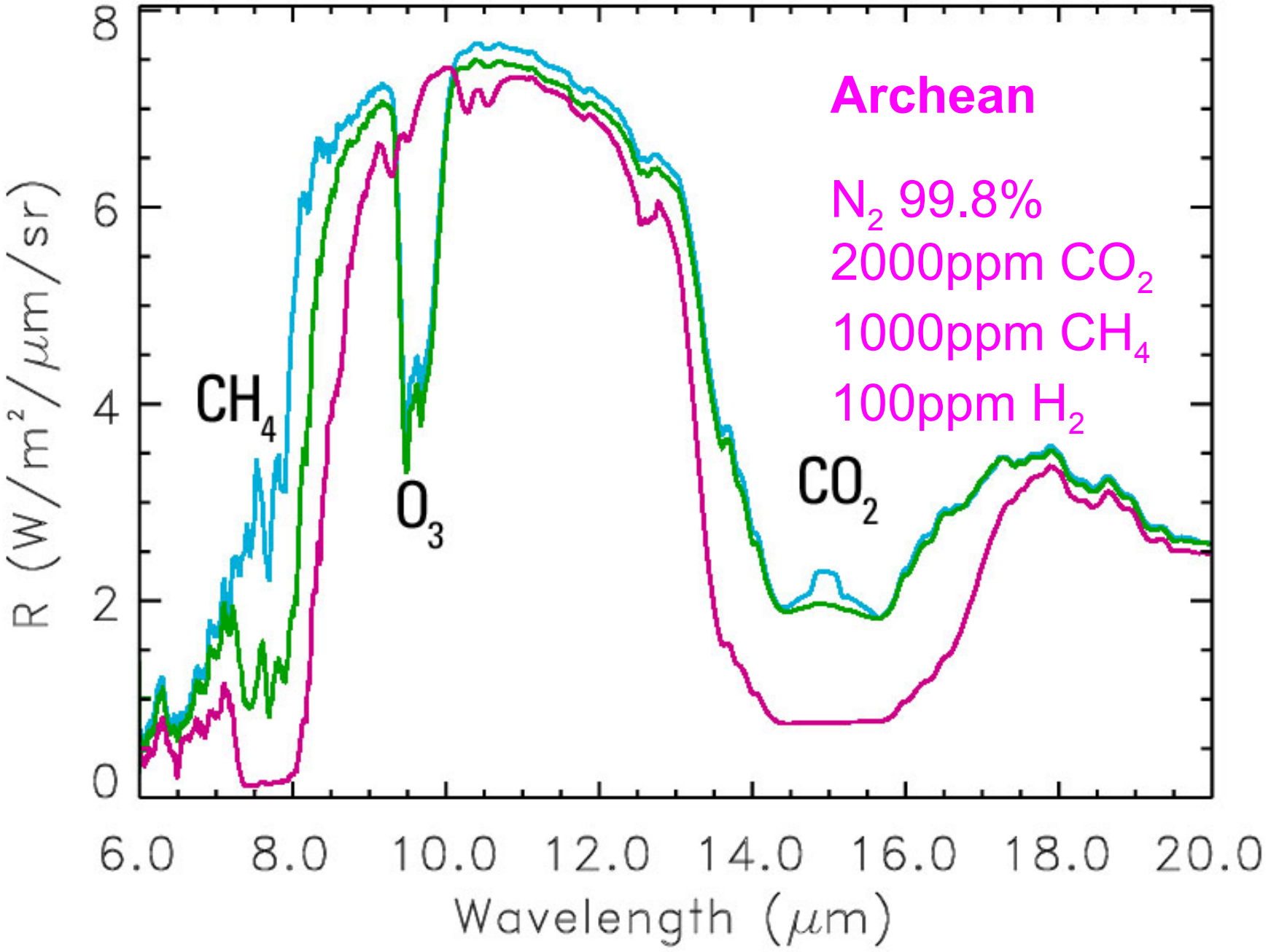



Crisp, Meadows

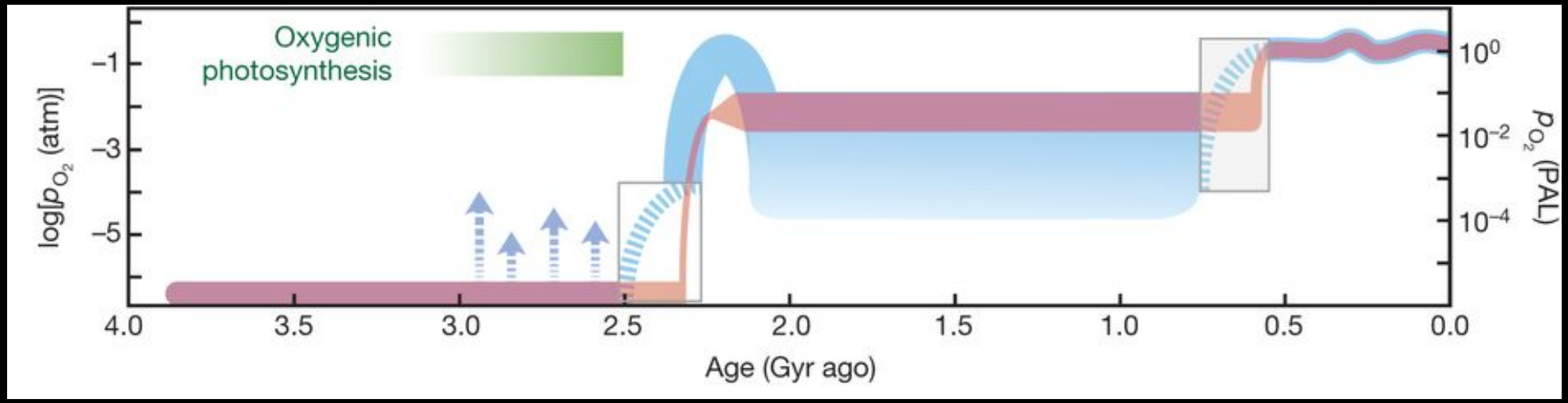

Conifer Forest
Red Edge
Chlorophyll
150
100
50
0
R (W/m²/sr/μm)
0.4
0.6
0.8
1.0
1.2
1.4
Wavelength (μm)


Modern Earth
355ppm $CO_2$
$CH_4$
$O_3$
$CO_2$
R (W/m²/μm/sr)
0
2
4
6
8
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
Wavelength (μm)


Proterozoic
0.1PAL $O_2$
100ppm $CH_4$
15% decrease in ozone column depth
$CH_4$
$O_3$
$CO_2$
R (W/m²/μm/sr)
Wavelength (μm)
0
2
4
6
8
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0


Archean
N2 99.8%
2000ppm CO2
1000ppm CH4
100ppm H2
CH4
O3
CO2
R (W/m²/μm/sr)
Wavelength (μm)
0
2
4
6
8
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0

# Earth's Atmosphere with Time




- **Red curve = classical two-step view.**
- **Blue curve = emerging view, highlighting poorly understood regions.**
- **PAL = Present Atmospheric Level.**

TW Lyons *et al. Nature* **506**, 307-315 (2014) doi:10.1038/nature13068

# Exoplanet Biosignatures: A Review of Remotely Detectable Signs of Life

Show affiliations

Schwieterman, Edward W. ; Kiang, Nancy Y. ; Parenteau, Mary N. ; Harman, Chester E. ; DasSarma, Shiladitya ; Fisher, Theresa M. ; Arney, Giada N. ; Hartnett, Hilairy E. ; Reinhard, Christopher T. ; Olson, Stephanie L. ; Meadows, Victoria S. ; Cockell, Charles S. ; Walker, Sara I. ; Grenfell, John Lee ; Hegde, Siddharth ; Rugheimer, Sarah ; Hu, Renyu ; Lyons, Timothy W.

In the coming years and decades, advanced space- and ground-based observatories will allow an unprecedented opportunity to probe the atmospheres and surfaces of potentially habitable exoplanets for signatures of life. Life on Earth, through its gaseous products and reflectance and scattering properties, has left its fingerprint on the spectrum of our planet. Aided by the universality of the laws of physics and chemistry, we turn to Earth's biosphere, both in the present and through geologic time, for analog signatures that will aid in the search for life elsewhere. Considering the insights gained from modern and ancient Earth, and the broader array of hypothetical exoplanet possibilities, we have compiled a state-of-the-art overview of our current understanding of potential exoplanet biosignatures including gaseous, surface, and temporal biosignatures. We additionally survey biogenic spectral features that are well-known in the specialist literature but have not yet been robustly vetted in the context of exoplanet biosignatures. We briefly review advances in assessing biosignature plausibility, including novel methods for determining chemical disequilibrium from remotely obtainable data and assessment tools for determining the minimum biomass required for a given atmospheric signature. We focus particularly on advances made since the seminal review by Des Marais et al. (2002). The purpose of this work is not to propose new biosignatures strategies, a goal left to companion papers in this series, but to review the current literature, draw meaningful connections between seemingly disparate areas, and clear the way for a path forward.

**Publication:** Astrobiology, Volume 18, Issue 6, 2018, pp.663-708

**Pub Date:** June 2018

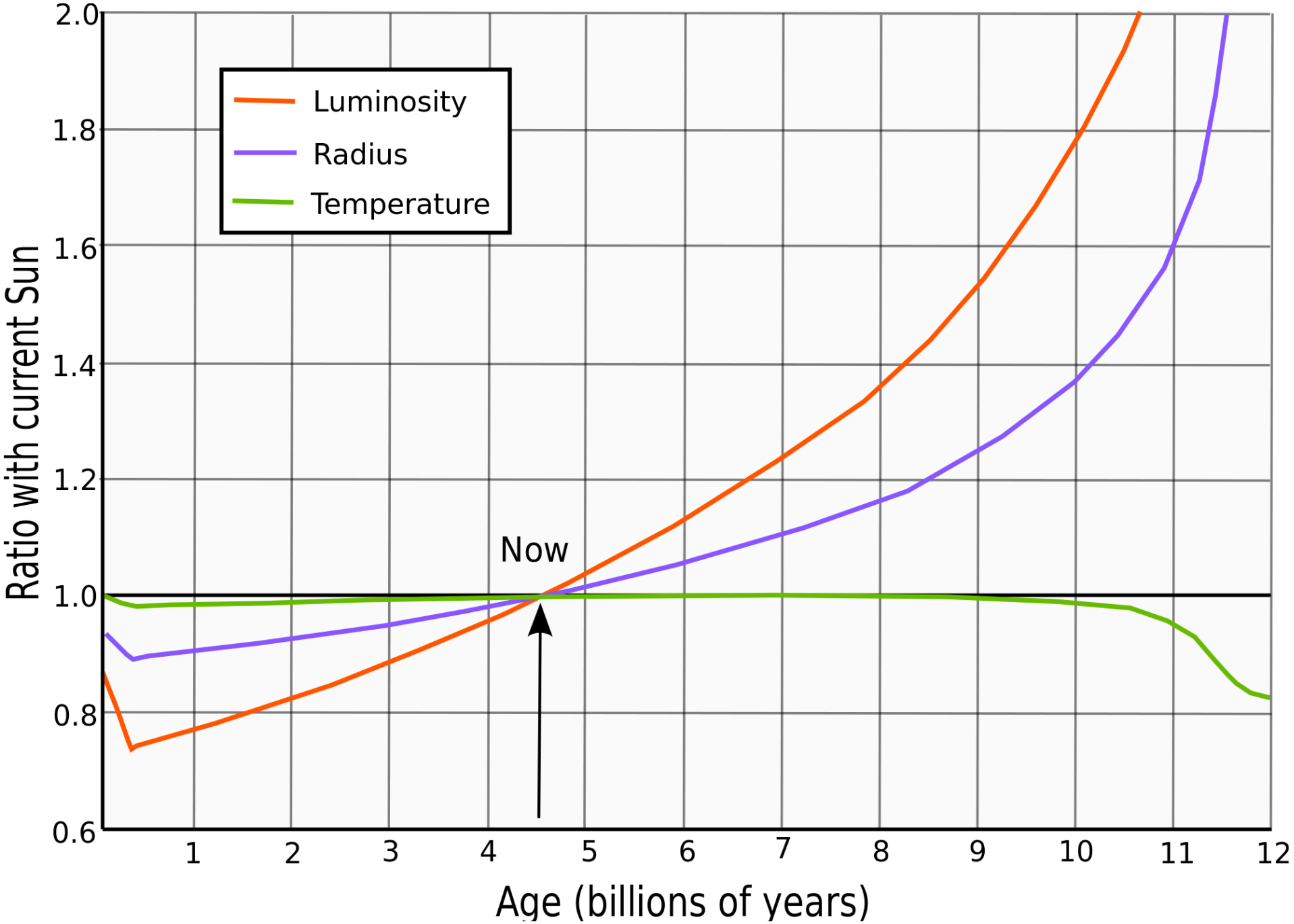
**DOI:** 10.1089/ast.2017.1729
10.48550/arXiv.1705.05791

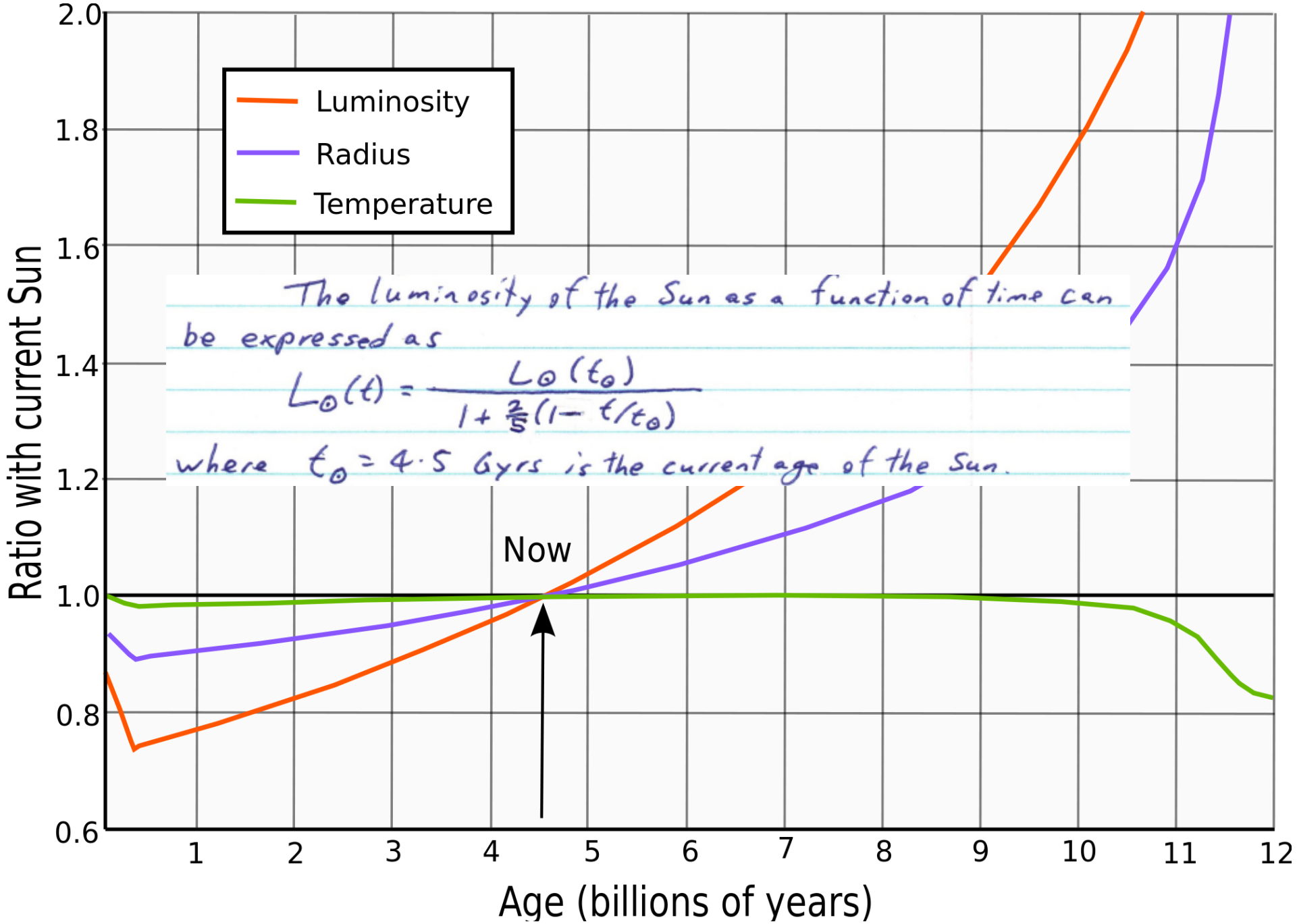
**arXiv:** arXiv:1705.05791

**Bibcode:** 2018AsBio..18..663S

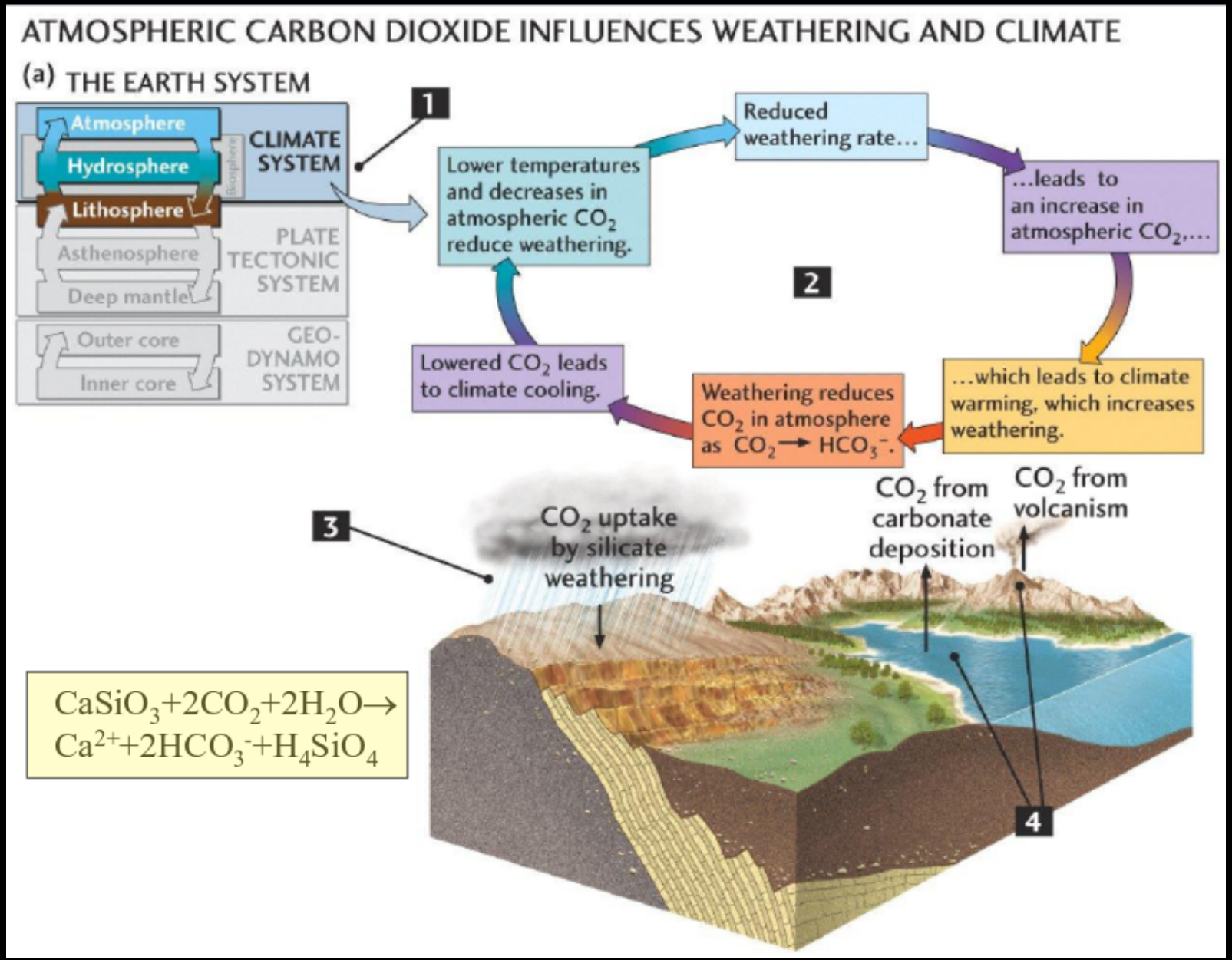
**Keywords:** Review Articles; Astrophysics - Earth and Planetary Astrophysics

**E-Print Comments:** Open Access Article. 46 pages, 13 figures; Schwieterman et al. (2018). Exoplanet Biosignatures: A Review of Remotely Detectable Signs of Life. Astrobiology, 18(6), 663-708; doi:10.1089/ast.2017.1729


Luminosity
Radius
Temperature
Now
Ratio with current Sun
Age (billions of years)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1
2
3
4
5
6
7
8
9
10
11
12


Luminosity
Radius
Temperature
The luminosity of the Sun as a function of time can be expressed as
$L_\odot(t) = \frac{L_\odot(t_\odot)}{1 + \frac{2}{5}(1 - t/t_\odot)}$
where $t_\odot = 4.5$ Gyrs is the current age of the Sun.
Now
Ratio with current Sun
Age (billions of years)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1
2
3
4
5
6
7
8
9
10
11
12

# Earth's Thermostat



# The Faint Young Sun Paradox

**The *faint young Sun paradox* or *faint young Sun problem* describes the apparent contradiction between observations of liquid water early in Earth's history and the astrophysical expectation that the Sun's output would be only 70 percent as intense during that epoch as it is during the modern epoch. The paradox is this: with the young sun's output at only 70 percent of its current output, early Earth would be expected to be completely frozen – but early Earth seems to have had liquid water and supported life. (wikipedia)**

**To solve the problem, you can investigate one of three aspects:**
**1) Increase the concentration of greenhouse gases.**
**2) Decrease the planetary albedo.**
**3) Increase the solar luminosity.**
**Item 3 on the list is generally considered untenable.**

# Is the Faint Young Sun Problem for Earth Solved?

Show affiliations

Charnay, Benjamin ; Wolf, Eric T. ; Marty, Bernard ; Forget, François

Stellar evolution models predict that the solar luminosity was lower in the past, typically 20-25% lower during the Archean (3.8-2.5 Ga). Despite the fainter Sun, there is strong evidence for the presence of liquid water on Earth's surface at that time. This "faint young Sun problem" is a fundamental question in paleoclimatology, with important implications for the habitability of the early Earth, early Mars and exoplanets. Many solutions have been proposed based on the effects of greenhouse gases, atmospheric pressure, clouds, land distribution and Earth's rotation rate. Here we review the faint young Sun problem for Earth, highlighting the latest geological and geochemical constraints on the early Earth's atmosphere, and recent results from 3D global climate models and carbon cycle models. Based on these works, we argue that the faint young Sun problem for Earth has essentially been solved. Unfrozen Archean oceans were likely maintained by higher concentrations of $CO_2$, consistent with the latest geological proxies, potentially helped by additional warming processes. This reinforces the expected key role of the carbon cycle for maintaining the habitability of terrestrial planets. Additional constraints on the Archean atmosphere and 3D fully coupled atmosphere-ocean models are required to validate this conclusion.

**Publication:** Space Science Reviews, Volume 216, Issue 5, article id.90

**Pub Date:** July 2020

**DOI:** 10.1007/s11214-020-00711-9
10.48550/arXiv.2006.06265

**arXiv:** arXiv:2006.06265

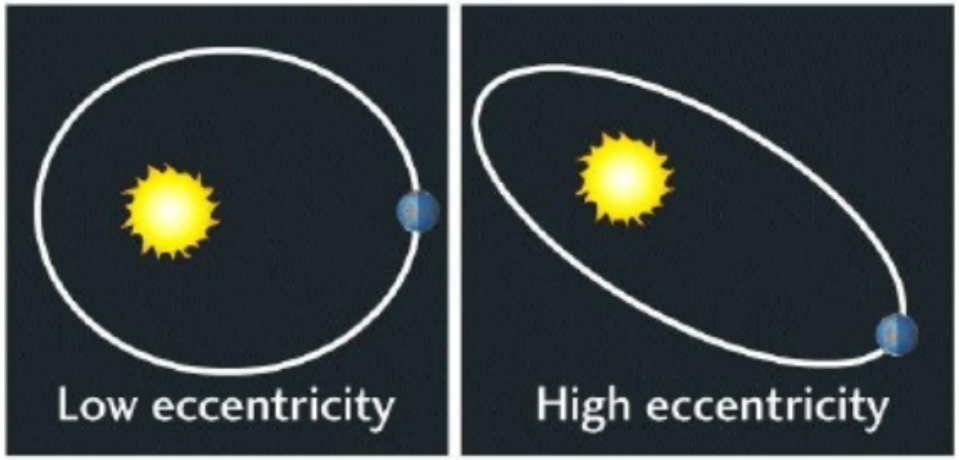
**Bibcode:** 2020SSRv..216...90C

**Keywords:** Early Earth; Paleoclimates; Habitability; Astrophysics - Earth and Planetary Astrophysics; Astrophysics - Solar and Stellar Astrophysics

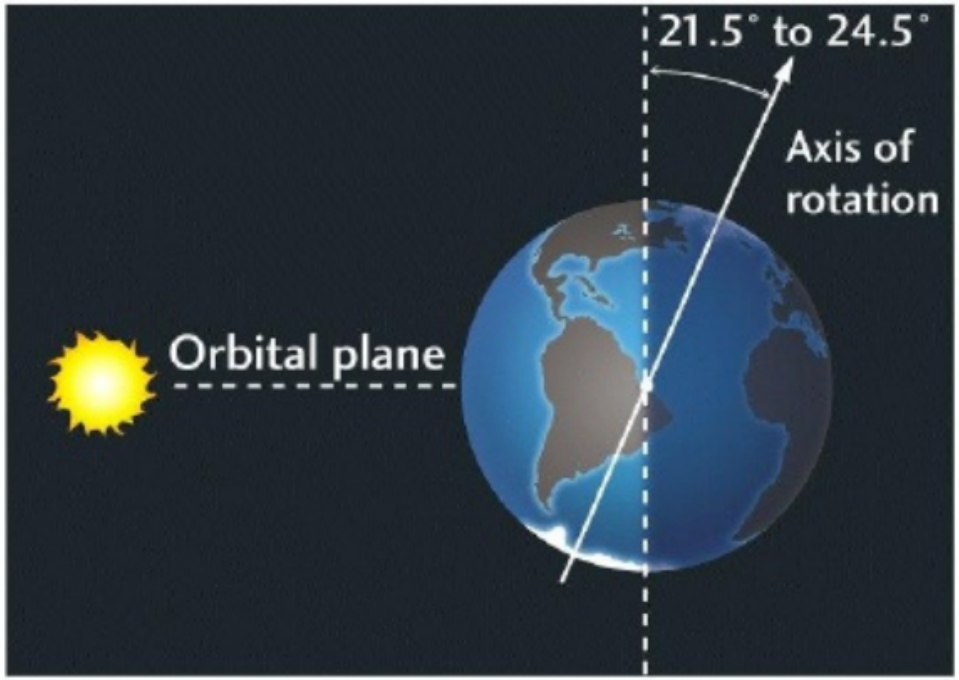
**E-Print Comments:** 22 pages, 7 figures, 1 table. Accepted for publication in Space Science Reviews. Part of ISSI special collection on Diversity of Atmospheres; doi:10.1007/s11214-020-00711-9

# Earth's Orbit

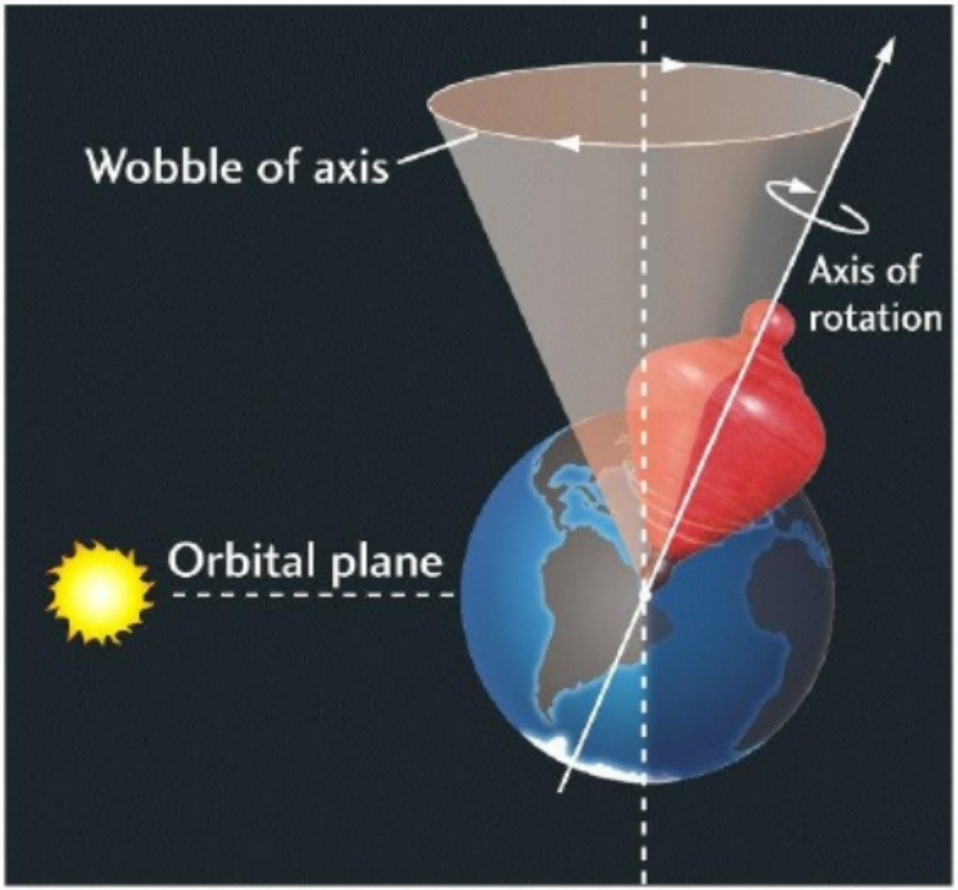
(a) Eccentricity (100,000 years)



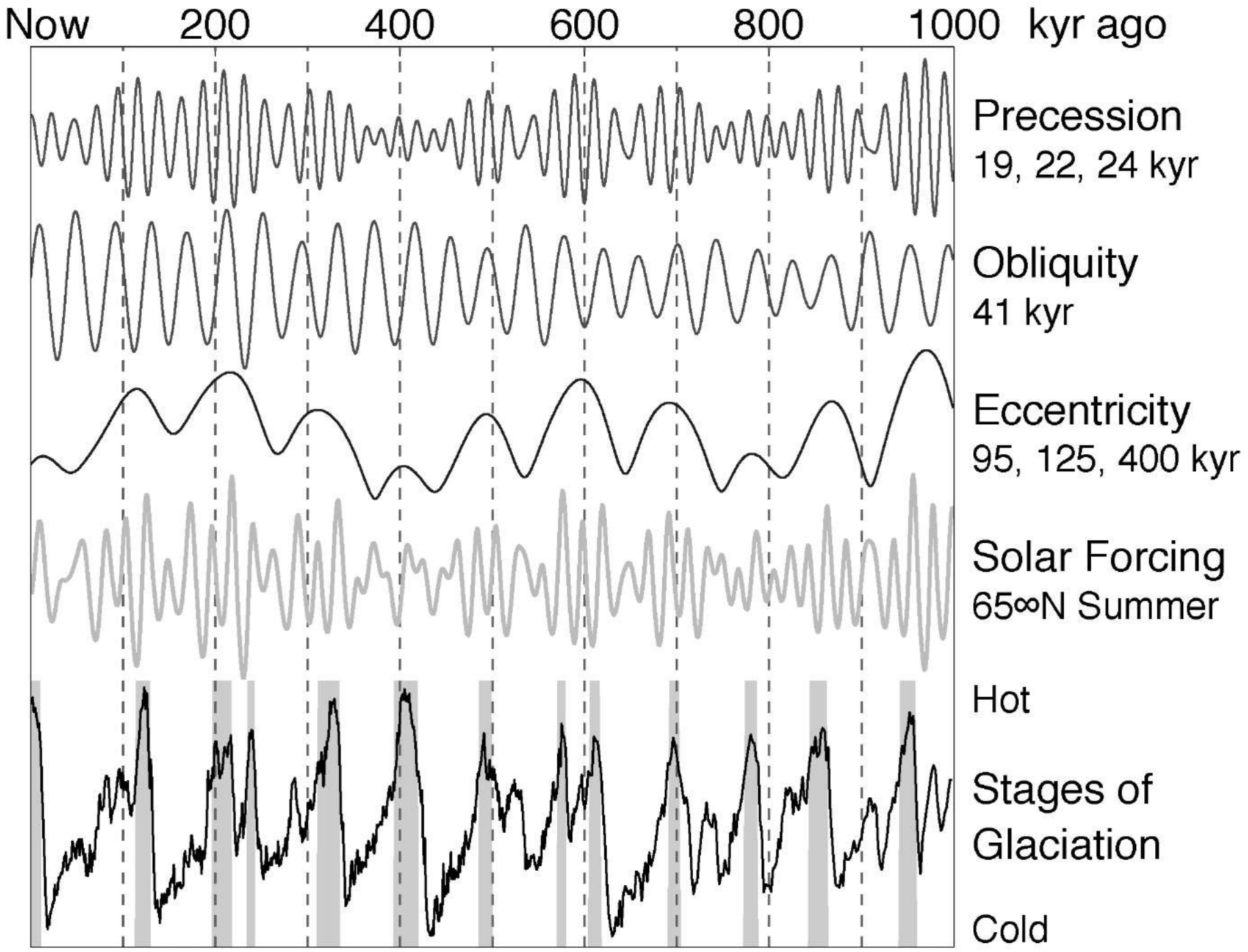

(b) Tilt (41,000 years)




(c) Precession (23,000 years)




Determines how much and where sunlight is received


Now
200
400
600
800
1000
kyr ago
Precession
19, 22, 24 kyr
Obliquity
41 kyr
Eccentricity
95, 125, 400 kyr
Solar Forcing
65∞N Summer
Hot
Stages of
Glaciation
Cold

# System Architecture and Planetary Obliquity: Implications for Long-term Habitability

Show affiliations

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In the search for life beyond our solar system, attention should be focused on those planets that have the potential to maintain habitable conditions over the prolonged periods of time needed for the emergence and expansion of life as we know it. The observable planetary architecture is one of the determinants for long-term habitability as it controls the orbital evolution and ultimately the stellar fluxes received by the planet. With an ensemble of n-body simulations and obliquity models of hypothetical planetary systems, we demonstrate that the amplitude and period of the eccentricity, obliquity, and precession cycles of an Earth-like planet are sensitive to the orbital characteristics of a giant companion planet. A series of transient, ocean-coupled climate simulations show how these characteristics of astronomical cycles are decisive for the evolving surface conditions and long-term fractional habitability relative to the modern Earth. The habitability of Earth-like planets increases with the eccentricity of a Jupiter-like companion, provided that the mean obliquity is sufficiently low to maintain temperate temperatures over large parts of its surface throughout the orbital year. A giant companion closer in results in shorter eccentricity cycles of an Earth-like planet but longer, high-amplitude, obliquity cycles. The period and amplitude of obliquity cycles can be estimated to first order from the orbital pathways calculated by the n-body simulations. In the majority of simulations, the obliquity amplitude relates directly to the orbital inclination whereas the period of the obliquity cycle is a function of the nodal precession and the proximity of the giant companion.

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