Theoretical Perspectives on Rocky Planets

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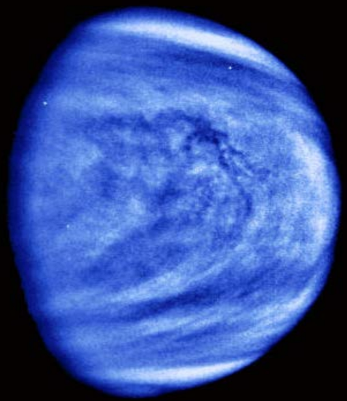


Talk Outline

- Part 1—Some (very brief) thoughts on rocky planets and life
- Part 2—Definition and boundaries of the habitable zone
- Part 3—Biosignatures: What should we be looking for?

- Question: Why do we care so much about rocky exoplanets?

- Obvious answer: Because that is where we think that life might exist..

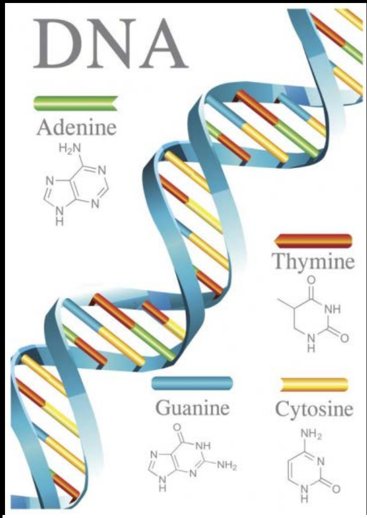
- Requirements for life (in decreasing order of certainty) $\Rightarrow$

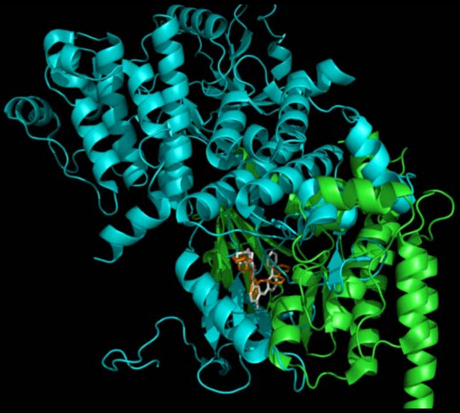
First requirement for life: a liquid or solid surface

- It is difficult, or impossible, to imagine how life could get started on a gas giant planet
  - Need a liquid or solid surface to provide a stable P/T environment
- This requirement is arguably universal

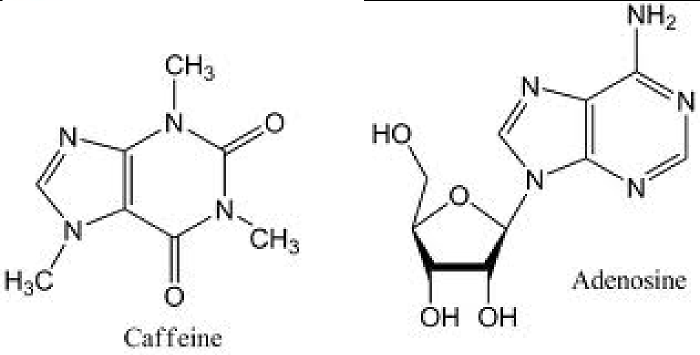
Second requirement for life: carbon

- Carbon is unique among the elements in forming long, complex chains
- Something like 95% of known chemical compounds are composed of organic carbon
- Silicon, which is located right beneath carbon in the Periodic Table, forms strong bonds with oxygen, creating rocks, not life





Proteins

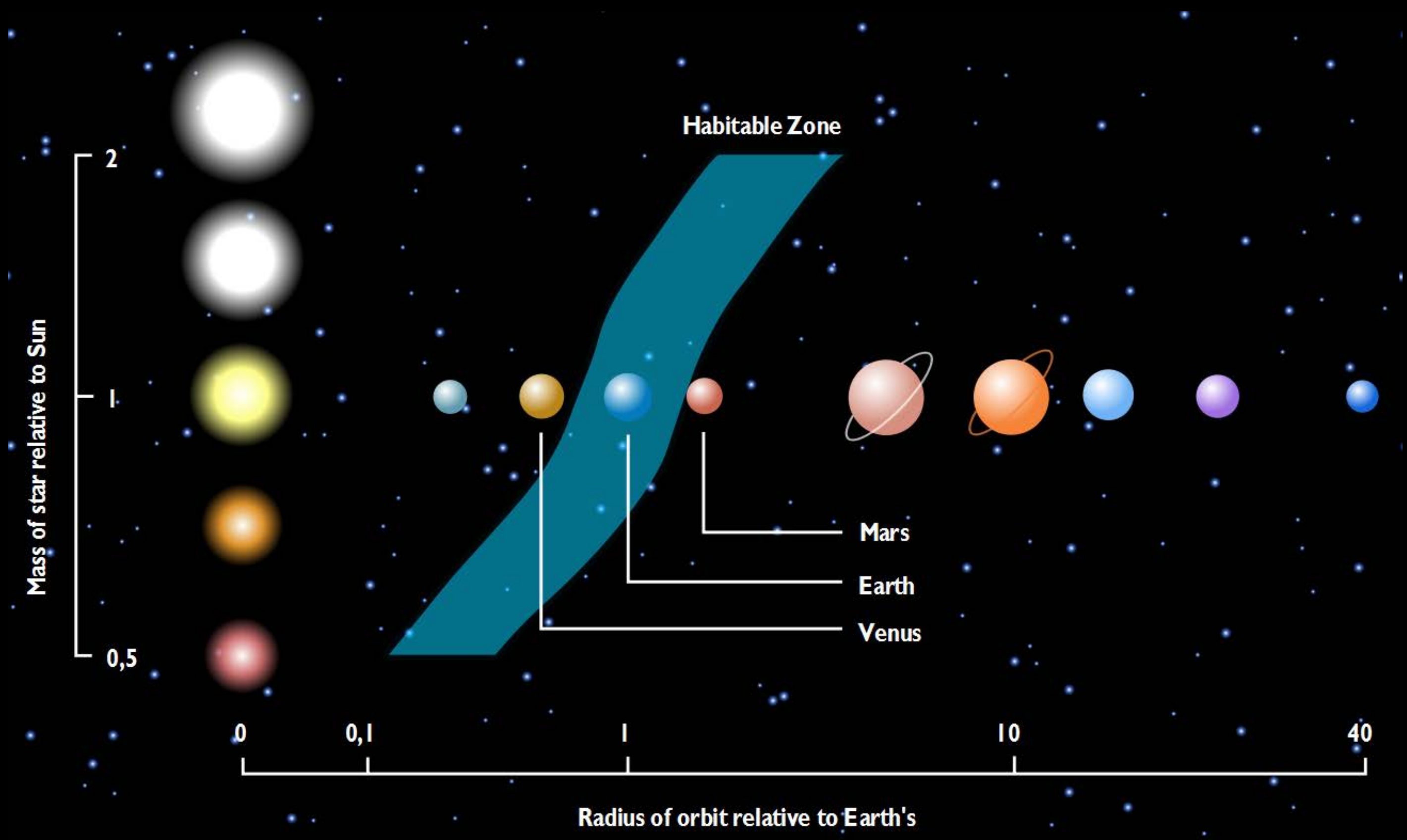


Third requirement for life (as we know it) : Liquid water

- Life on Earth requires liquid water during at least part of its life cycle
- So, our first choice is to look for other planets like Earth
- *Subsurface water* is not relevant for remote life detection because it is unlikely that a subsurface biota could modify a planetary atmosphere in a way that could be observed (at modest spectral resolution)

- Part 2—Definition and boundaries of the habitable zone

The ZAMS habitable zone

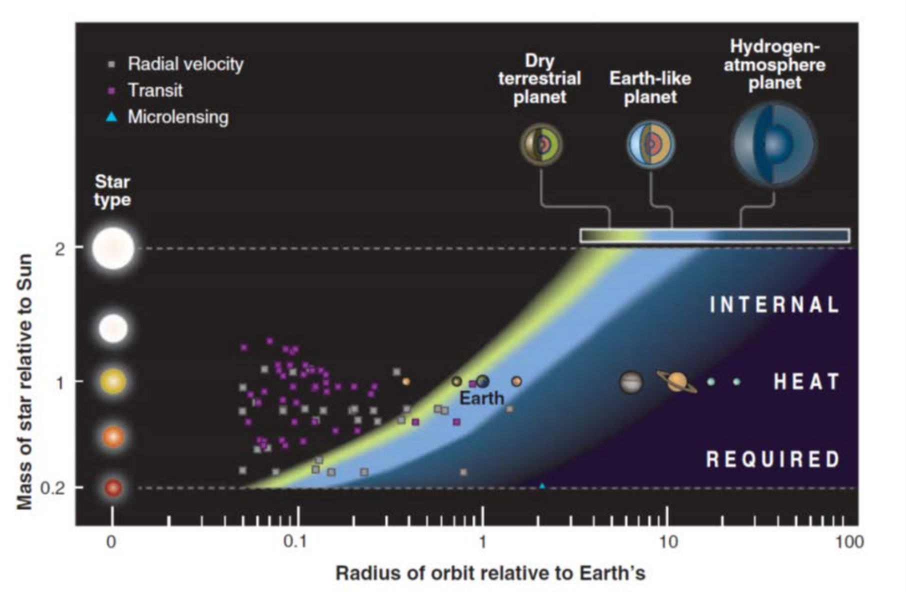


- This leads directly to the concept of the *habitable zone*, also referred to as the *ecosphere*, or (Shapley, 1938) the *liquid water belt*
- Figure applies to zero-age-main-sequence stars; the HZ moves outward with time because all main sequence stars brighten as they age

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

How should the HZ be defined?

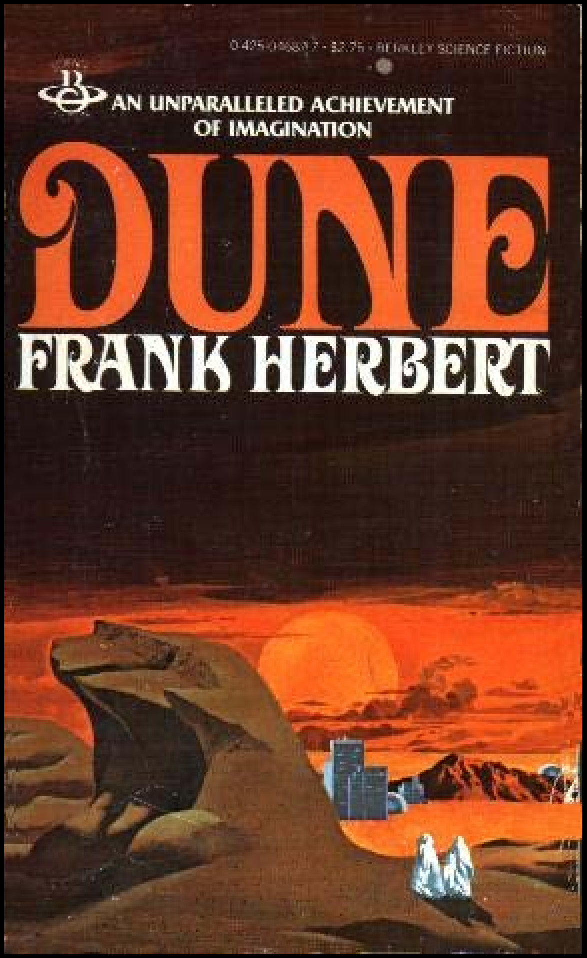
- The HZ depends on greenhouse gases, as well as on distance from the parent star
- Traditionally, CO_2 and H_2O have been the only gases considered
- Seager (2013) suggested including H_2, in which case the HZ outer edge moves out to ~10 AU
  - This is based on a 3-M_E super Earth with a captured 40-bar H_2 atmosphere (Pierrehumbert and Gaidos, 2011)



S. Seager, Science (2013)

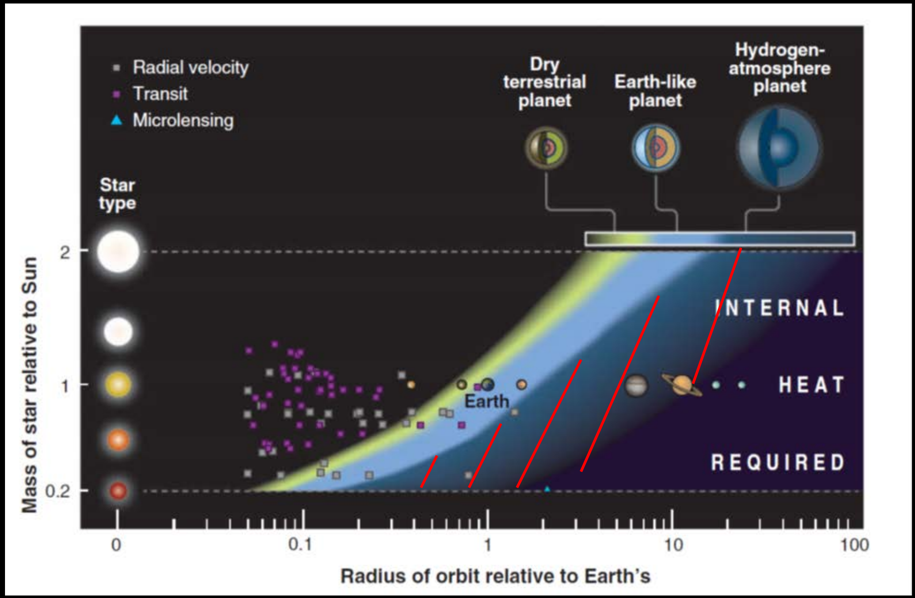
"Dune" planets

- Similarly, Abe et al., *Astrobiology* (2011) suggested that dry planets with water oases at their poles might remain habitable well inside the inner edge of the conventional HZ
  - S_{eff} = 1.7, or 0.77 AU
- These authors used a 3-D climate model, which in one sense represents an advance over 1-D models
- Do such planets really exist, though, or would the water react with the planet's crust to form hydrated silicates?



How should the HZ be defined?

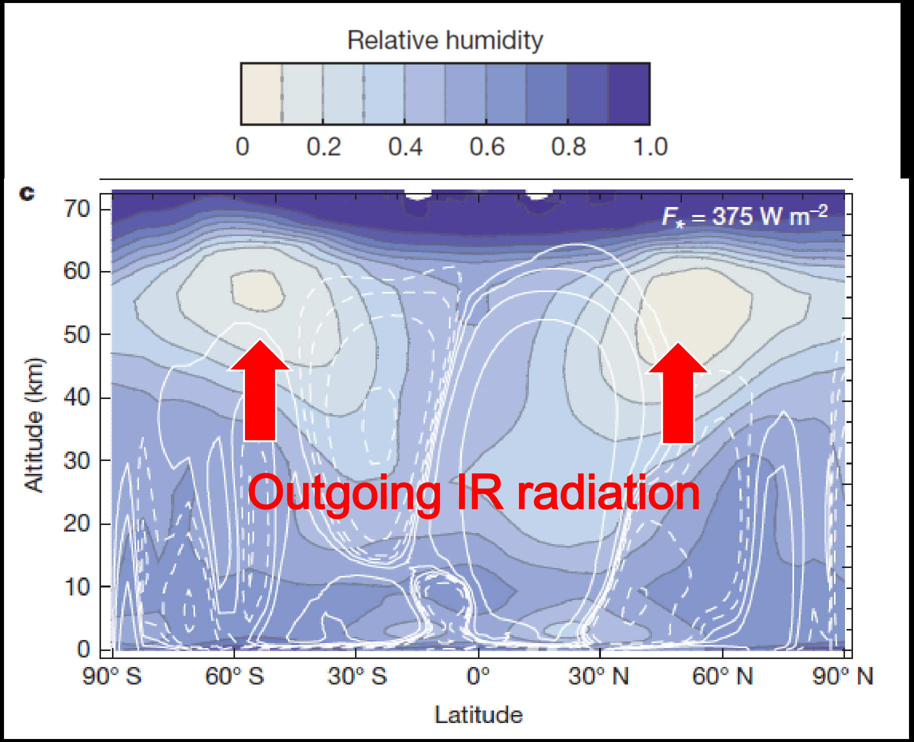
- We would argue that the appropriate definition of the HZ depends on the purpose for which it is being used
- If one is using it to help define η_{Earth} and to set the design parameters for a large, direct-imaging space telescope, then one ought to be *conservative* and just look for planets that are more or less like Earth



S. Seager, Science (2013)

3-D modeling of habitable zone boundaries

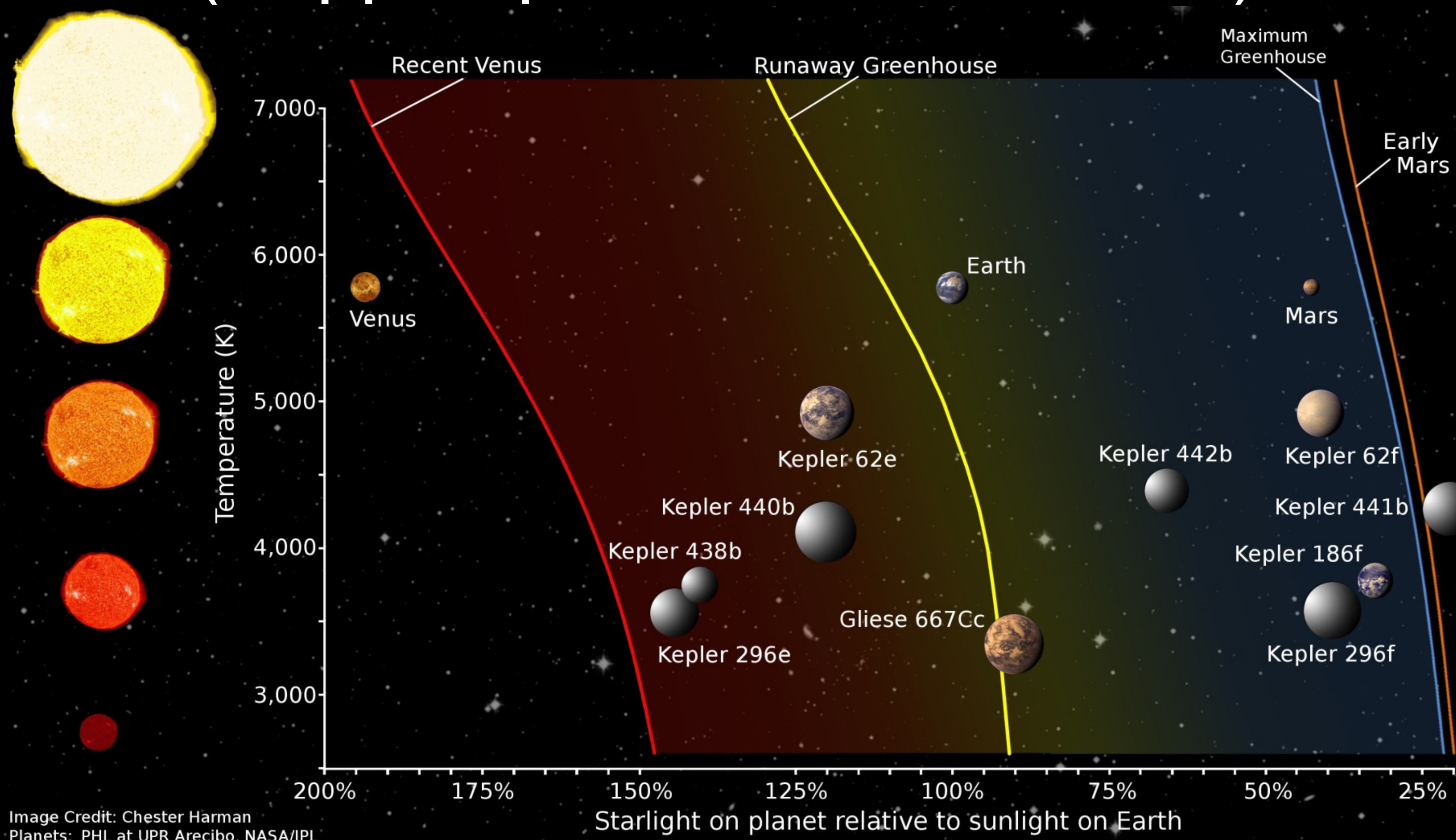
- That said, 3-D climate models are useful
- The runaway greenhouse flux threshold is increased by ~10% because the tropical Hadley cells act like radiator fins
  - This was pointed out 20 years ago by Ray Pierrehumbert (JAS, 1995) in a paper dealing with Earth's tropics
- We have adjusted our (1-D) HZ inner edge inward to account for this behavior



Leconte et al., Nature (2013)

Updated habitable zone

(Kopparapu et al., 2013, 2014)

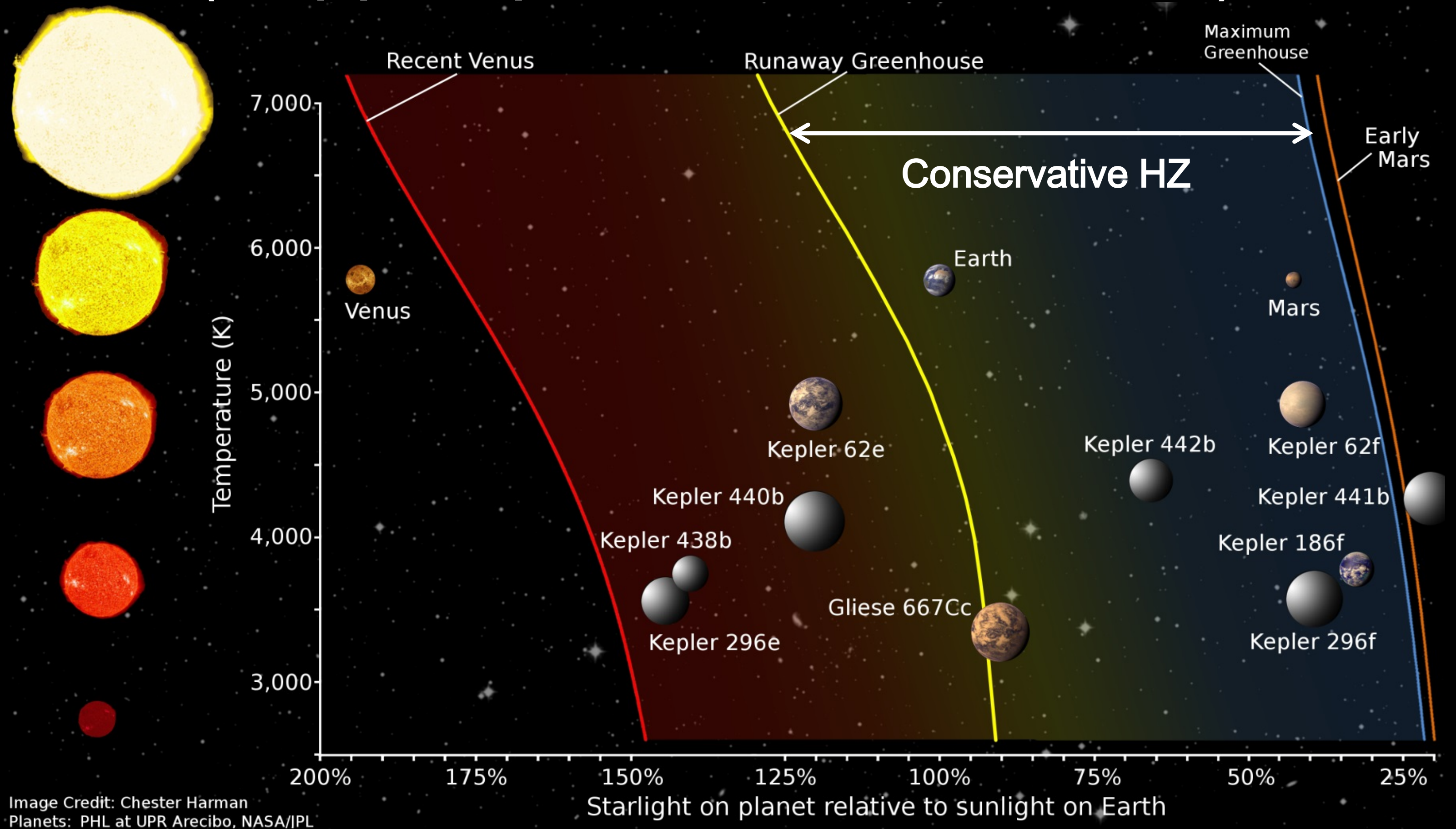


- Note the change in the x-axis from distance units to stellar flux units. This makes it easier to compare where different objects lie

Credit: Sonny Harman

Updated habitable zone

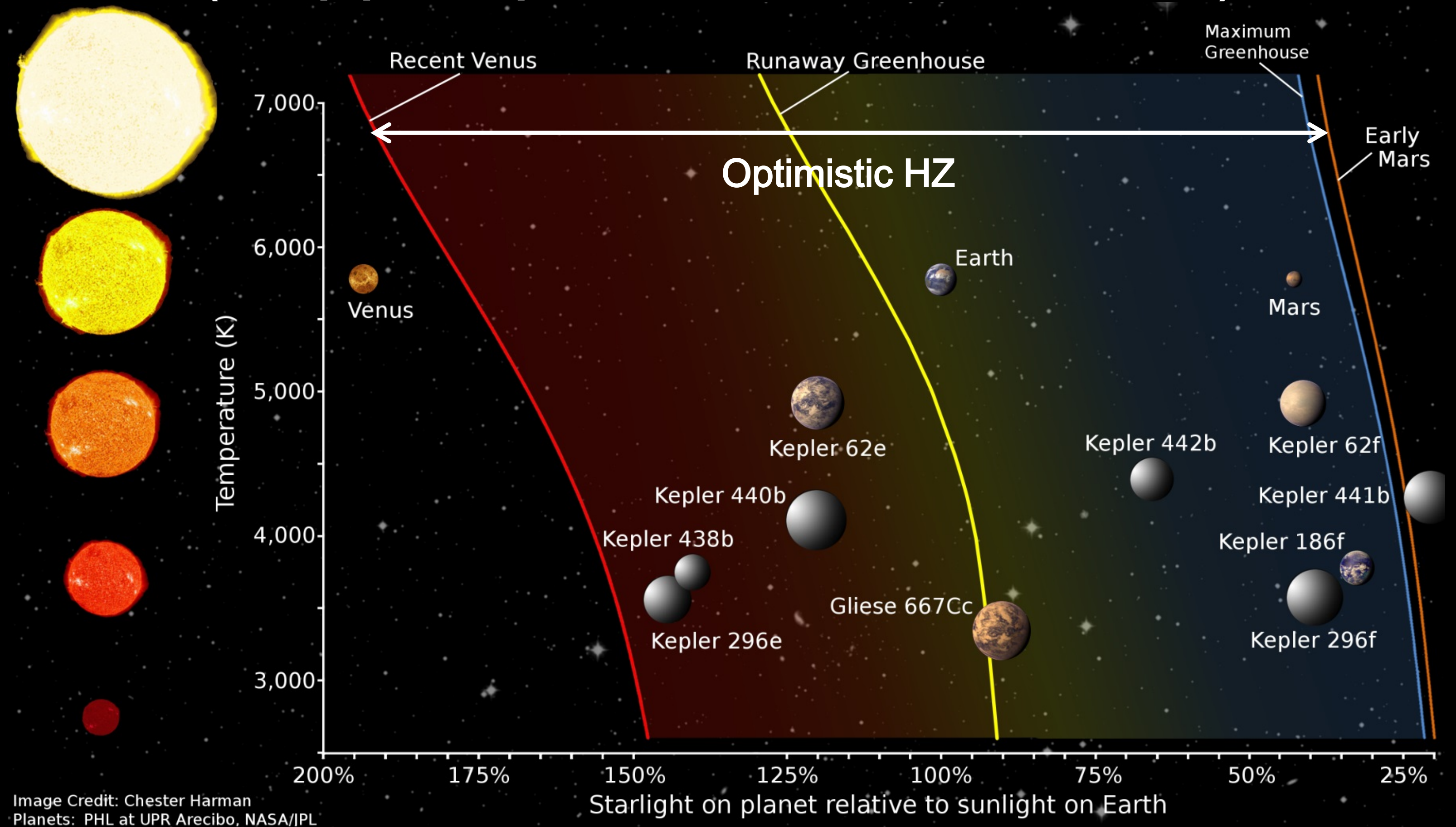
(Kopparapu et al., 2013, 2014)



- Also note that there is still a lot of uncertainty regarding the location of the inner edge

Credit: Sonny Harman

Updated habitable zone
(Kopparapu et al., 2013, 2014)



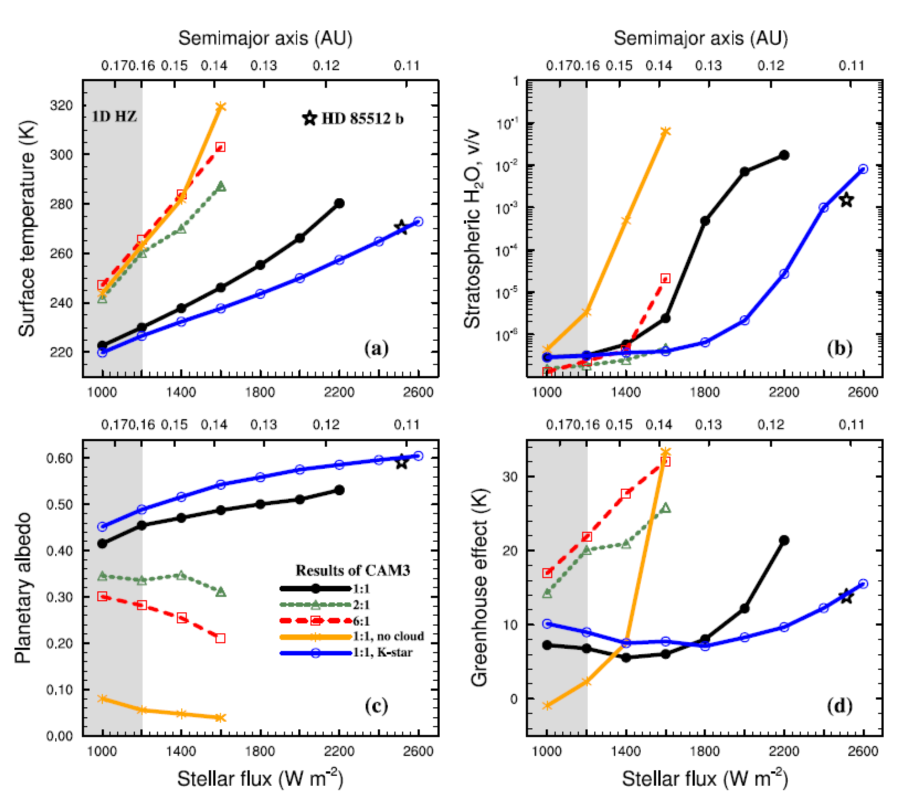
- Also note that there is still a lot of uncertainty regarding the location of the inner edge

Credit: Sonny Harman

- The effect of going to 3-D is even bigger for synchronously rotating planets orbiting late-K and M stars $\Rightarrow$

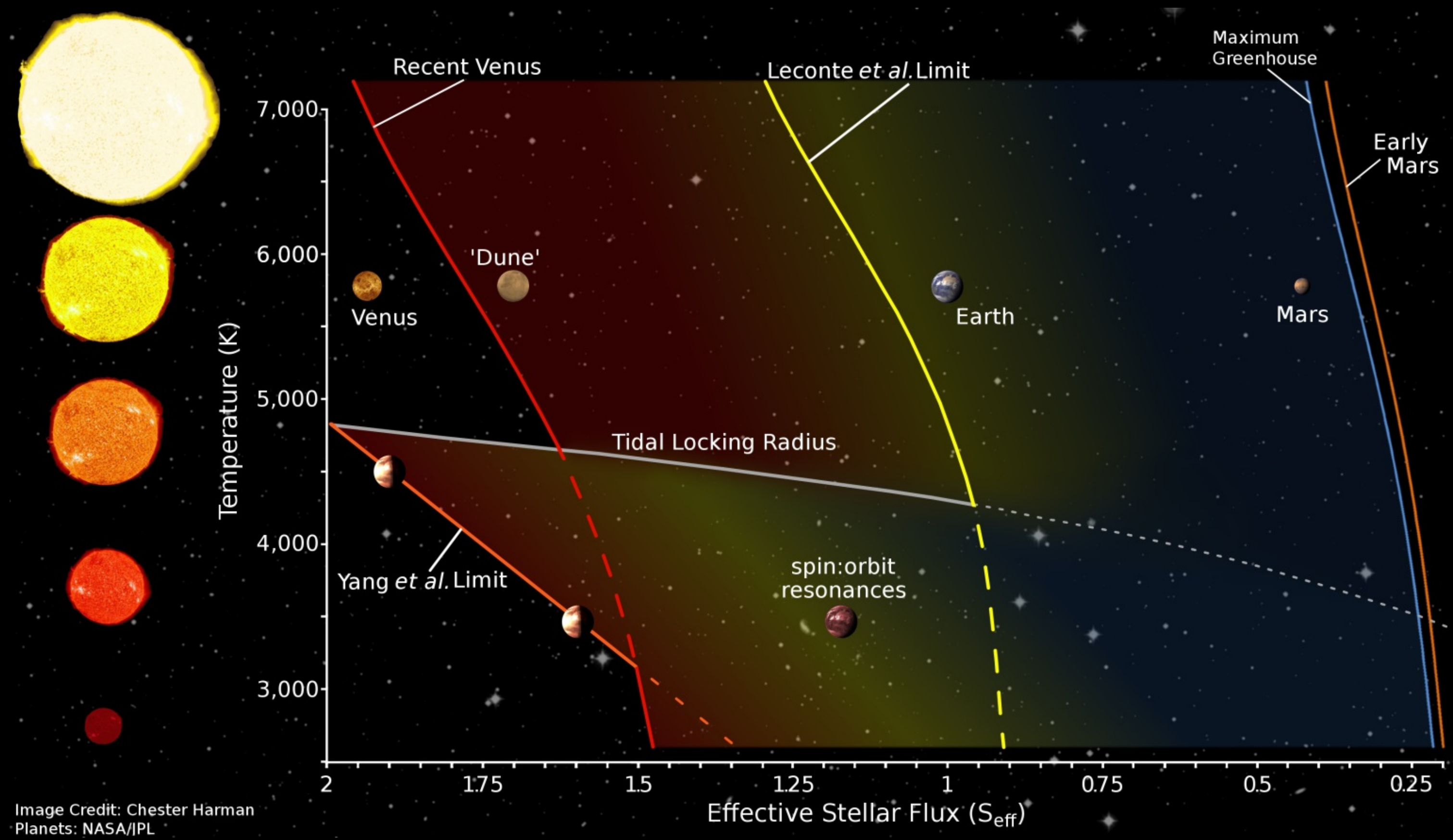
3-D climate model calculations for M- and K-star planets

- Clouds dominate the sunny side of tidally locked planets orbiting M and late-K stars, raising their albedos
- The inner edge of the HZ is therefore pushed way in
  - $S_{eff} \cong 2$ for a synchronously rotating planet around a K star (dark blue curves)
  - These planets all had fixed, 60-day orbital periods
  - When one follows Kepler's laws, they spin faster and the cloud feedback weakens (Kopparapu et al., in prep.)



Yang et al., ApJ Lett (2013)

Most recent habitable zone



- Thus, our current estimate of the habitable zone looks something like this. The inner edge is still highly uncertain

Kopparapu et al., ApJ Lett (2014)

Part 3—Biosignatures: What should we be looking for?

Looking for life via the by-products of metabolism

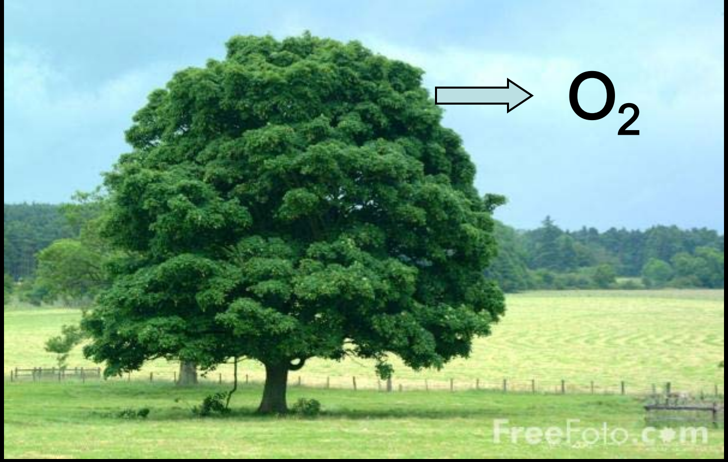
- Green plants and algae (and cyanobacteria) produce oxgyen from photosynthesis:

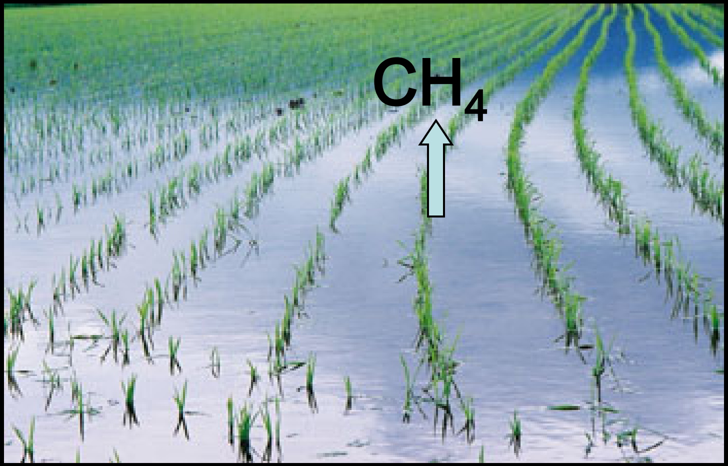
  $CO_2 + H_2O \rightarrow CH_2O + O_2$

- Methanogenic bacteria produce methane

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

- CH_4 and O_2 are out of thermodynamic equilibrium by 20 orders of magnitude!* *Hence, their simultaneous presence is strong evidence for life*

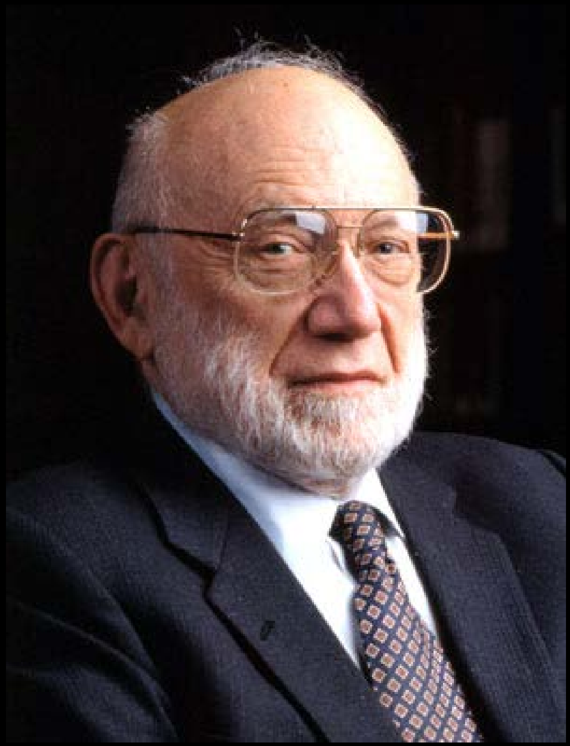




*Lovelock, Nature (1965); Lippincott et al., ApJ (1967)

Is thermodynamic disequilibrium a reliable biosignature?

- Earlier that same year (1965) Joshua Lederberg broadened the criteria for remote life detection to include extreme thermodynamic disequilibrium in general
- But is this really a robust criterion?



Is thermodynamic disequilbrium a reliable biosignature?

- CO can be produced in large quantities by impacts into a CO_2-H_2 atmosphere (J.F. Kasting, Origins of Life, 1990)

  $$2\,CO_2 \rightarrow 2\,CO + O_2$$

- O_2 can then be photolyzed to produce atomic oxygen

  $$O_2 + h\nu \rightarrow O + O$$

Is thermodynamic disequilbrium a reliable biosignature?

- Recombination of O with CO is spin forbidden, however:

  $CO + O + M \not\rightarrow CO_2 + M$

- So, CO can accumulate, even though it is a high-free-energy compound

Is thermodynamic disequilbrium a reliable biosignature?

- What prevents this from happening on Earth (and on Mars) is that CO recombination is catalyzed by the by-products of water vapor photolysis

$$H_2O + h\nu \rightarrow H + OH$$

$$CO + OH \rightarrow CO_2 + H$$

Is thermodynamic disequilbrium a reliable biosignature?

- What CO really wants to do thermodynamically at low T is to form methane

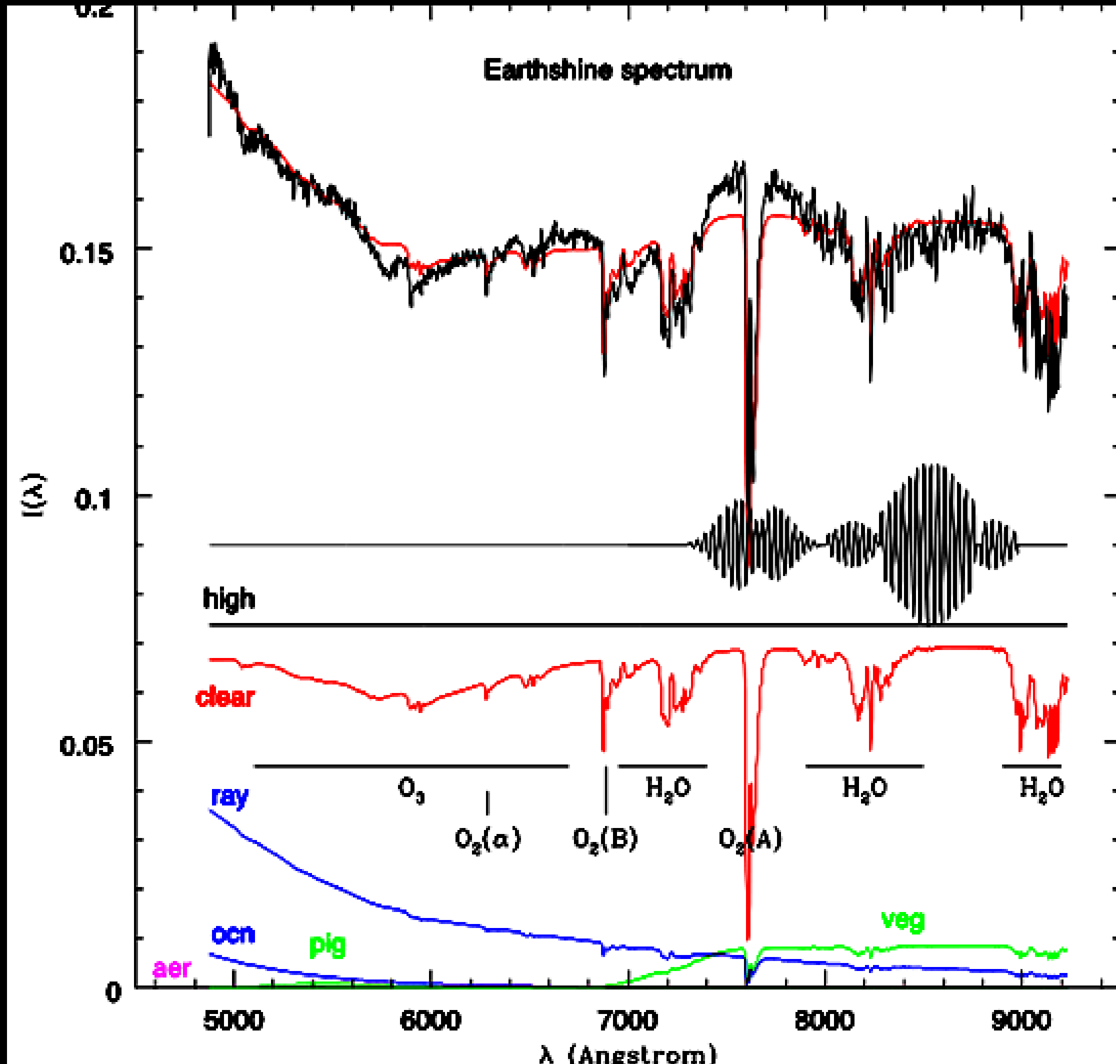
  $CO + 3\,H_2 \not\rightarrow CH_4 + H_2O$

- But this reaction also doesn't go, because there are few abiotic pathways for forming CH_4
- So, the criterion of extreme thermodynamic equilibrium as a biomarker is not very general

- What about O_2 by itself as a biosignature?

- If we look at a low- to moderate-resolution visible/near-IR spectrum of the modern Earth, we can see O_2 but not CH_4 $\Rightarrow$

Visible spectrum of Earth



Integrated light of Earth, reflected from dark side of moon: Rayleigh scattering, chlorophyll, O_2, O_3, H_2O

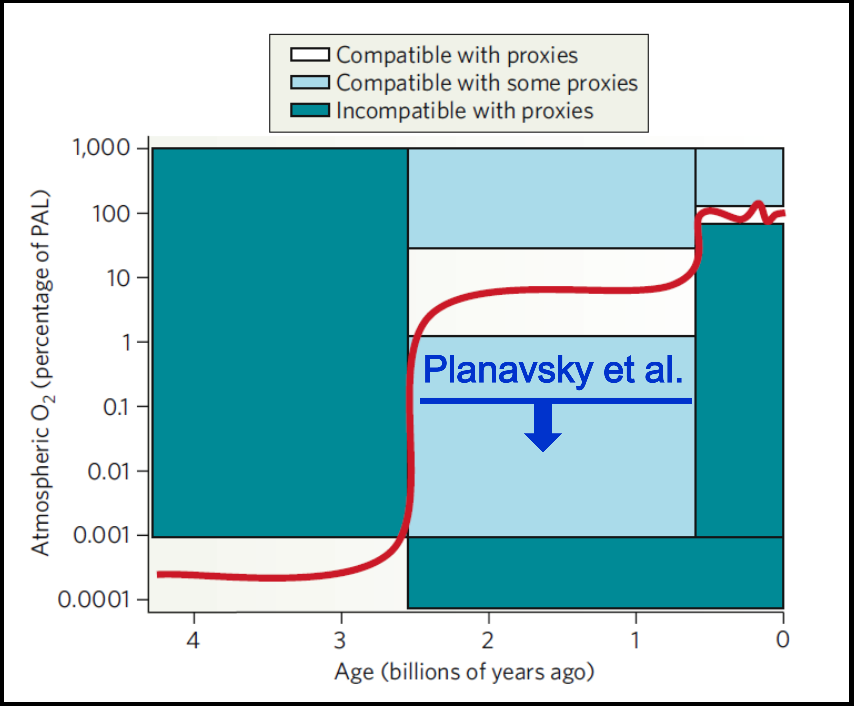
Ref.: Woolf, Smith, Traub, & Jucks, ApJ 2002; also Arnold et al. 2002

False positives for life

- This leads to the question of so-called ‘false positives’ for life
- Can O_2 build up to high levels abiotically, and how high must it build up to be considered a false positive?

The new view of the rise of atmospheric O_2

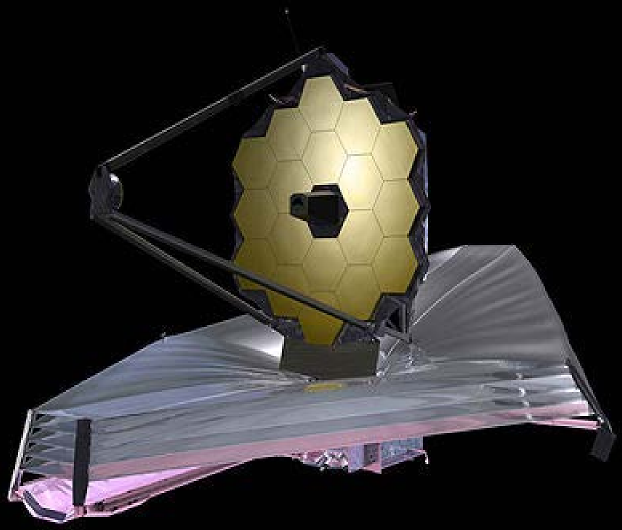
- A new published estimate for Proterozoic O_2 based on Cr isotopes is 0.1% PAL (times the Present Atmospheric Level)
  - This is 100 times lower than the previous best guess
- Life was clearly present on Earth during this time, so any O_2 level higher than 10^{-3} PAL is a potential false positive, even if it could not be detected with a first-generation direct imaging space telescope



L.R. Kump, Nature (2008)
N.J. Planavsky et al., Science (2014)

False positives around M stars?

- Rocky planets around M stars are of interest because they may be observed by JWST
- M-star planets are poor candidates for habitability for a number of reasons
  - Most notably, they may be devolatilized during the star's pre-main sequence phase (Luger and Barnes, Astrobiology, 2015)
- We are nonetheless interested in the question of false positives on such planets



The James Webb Space Telescope

O_2 photochemistry

- O atoms are produced by CO_2 photolysis at wavelengths shortward of 200 nm

$$CO_2 + h\nu \rightarrow CO + O$$

- The reverse reaction, though, is spin-forbidden (as we have already seen)

$$\cancel{CO + O + M \rightarrow CO_2 + M}$$

and, so, O atoms recombine with each other to form O_2

$$O + O + M \rightarrow O_2 + M$$

O_2 photochemistry

- The recombination of O with CO is catalyzed by the byproducts of H_2O photolysis at wavelengths < 240 nm

$$H_2O + h\nu \rightarrow H + OH$$

then

$$CO + OH \rightarrow CO_2 + H$$

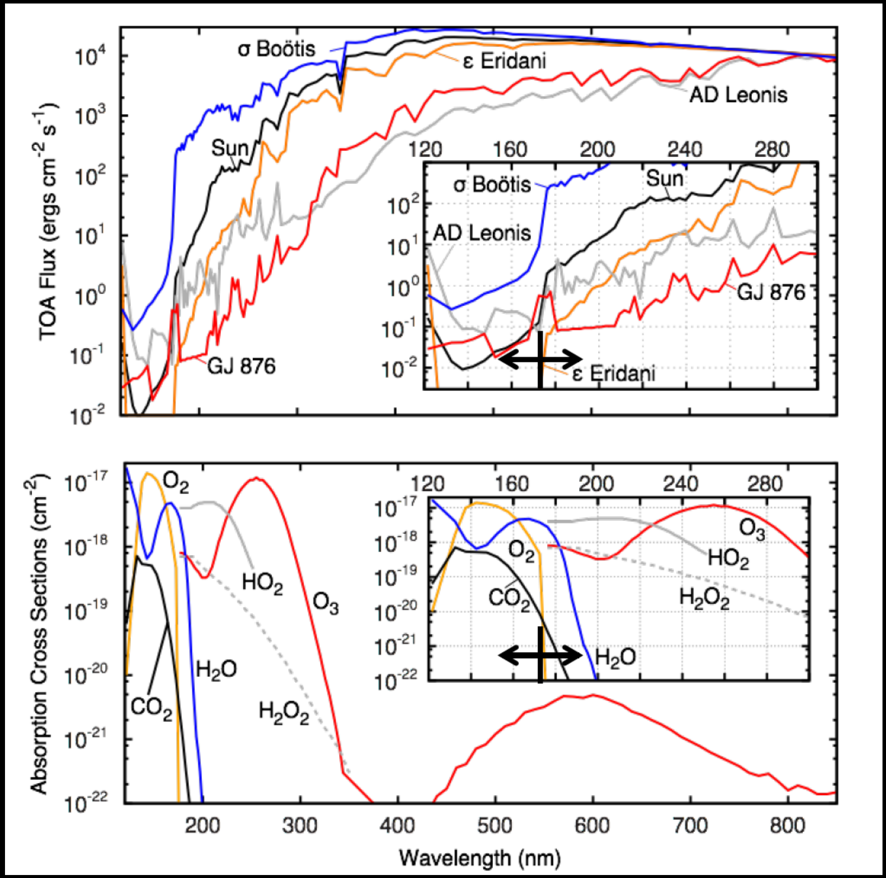
$$H + O_2 + M \rightarrow HO_2 + M$$

$$\underline{O + HO_2 \rightarrow OH + O_2}$$

$$\text{Net:} \quad CO + O \rightarrow CO_2$$

M-star UV spectra

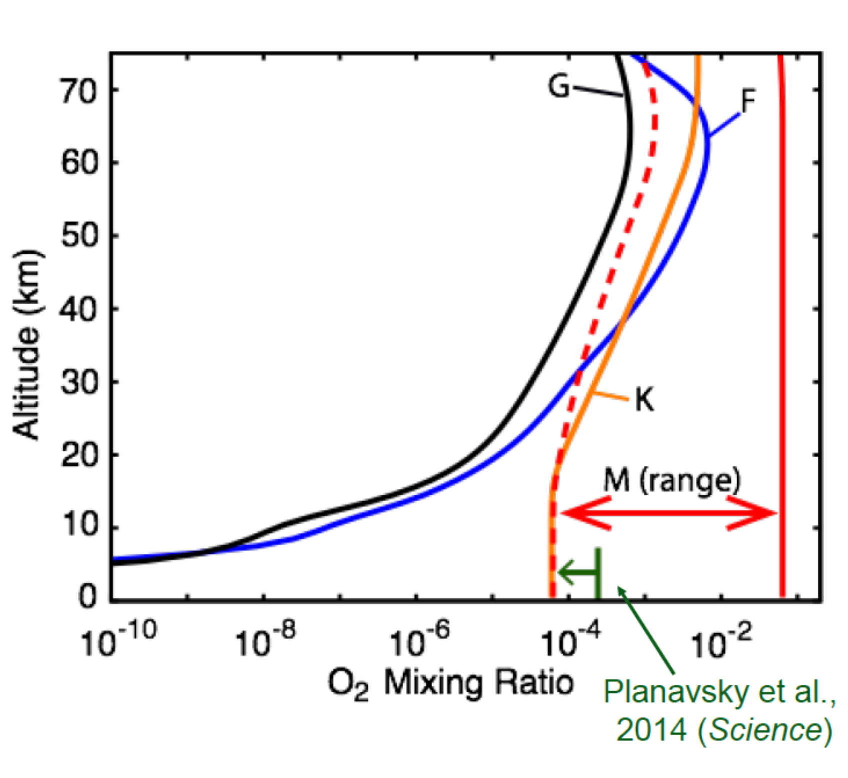
- M stars are deficient in near-UV radiation compared to G stars because of their lower surface temperatures, combined with absorption of radiation by molecules such as TiO in their photospheres
- M stars have lots of magnetic activity and, hence, generate lots of far-UV radiation
- M stars photolyze CO_2 more effectively than H_2O, and thus create higher abiotic O_2 levels



S. Harman et al., in prep.

False positives around M stars?

- The bottom line is that with our models we can create potential false positives on planets around M stars, but not around F and G stars
- K-star planets lie somewhere in between
- A false positive is here defined as any abiotic O_2 level that exceeds the published Proterozoic O_2 level of 0.1% PAL



S. Harman et al., in prep.

Conclusions

- Detectable life requires, at a minimum, a planet with a solid (or liquid) surface, sufficient availability of carbon, and surface liquid water
- Habitable zones should be defined *conservatively* if they are being used to generate design parameters for future space-based telescopes
  - H_2-rich super-Earths and 'Dune' planets could conceivably exist, but we should not simply assume that they do
- Thermodynamic disequilibrium is, in general, *not* a robust biosignature (but O_2 and CH_4 are still useful)
- O_2 by itself *may* be a biosignature, but we should be wary of potential false postives on planets around M stars