Sagan Summer Workshop
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Beyond Bare Detection to Biological and Geological Indicators

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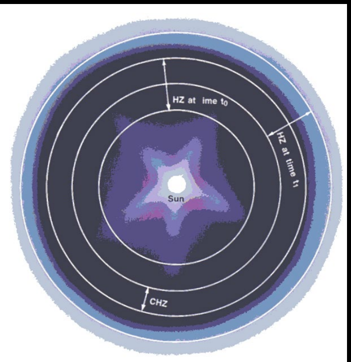
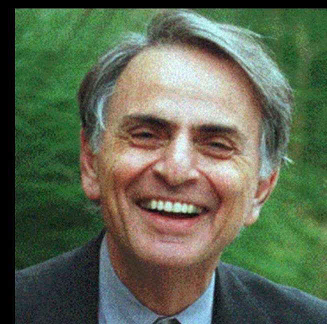
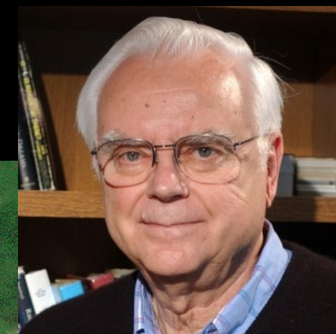
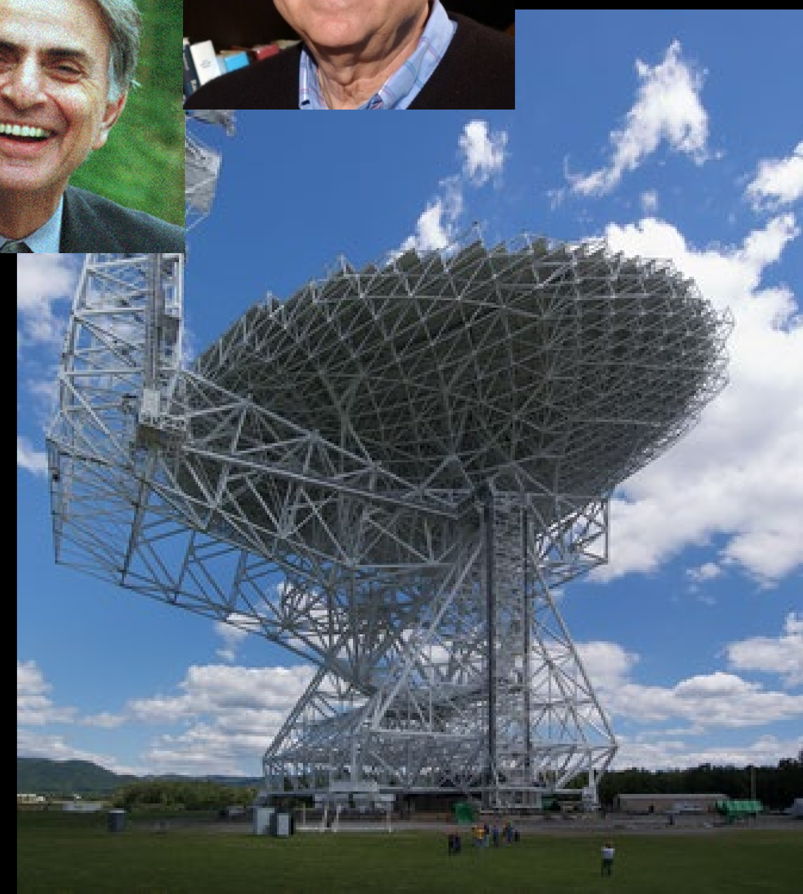


SETI: The Search for Intelligent Life

- Astronomers have actually been searching for evidence of extraterrestrial life for several decades
  - Carl Sagan and Frank Drake convened a meeting at the Green Bank Radio Observatory in 1961 to discuss this problem, and SETI searches started soon afterwards
- The search for intelligent life has *preceded* the search for simple life because radio telescopes are easier to build than the ones we need for this latter task







Talk Outline

- Part 1—Basic requirements for life
- Part 2—Definition and boundaries of the habitable zone
- Part 3—Atmospheric biosignatures and how to look for them

Requirements for life

1. A planet with a liquid or solid surface
   -- No gas giants allowed
2. A thermodynamic free energy gradient to drive metabolism and growth
   -- Stellar radiation provides most of the free energy on Earth today
3. Availability of carbon and other bioessential elements (CHNOPS)
   -- This assumes life 'as we know it'

Fourth 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)

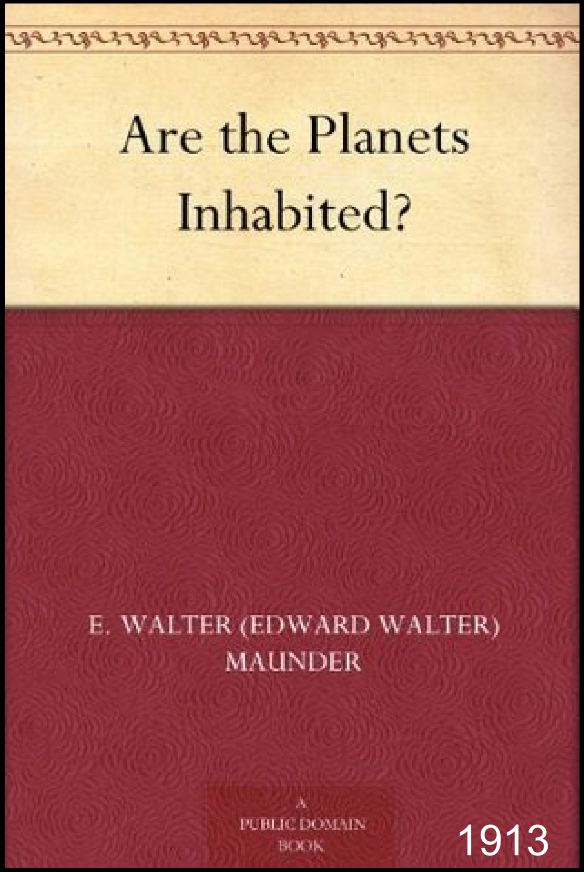
Definition of η_{Earth}

- η_{Earth}—the fraction of stars that have at least one rocky planet in their *habitable zone*
  - This is what we need to know in order to design a space telescope to look for such planets around nearby stars
  - We should be *conservative* when calculating η_{Earth} for this purpose, because we don't want to undersize the telescope

- Part 2—Definition and boundaries of the habitable zone

First use of the term ‘habitable zone’

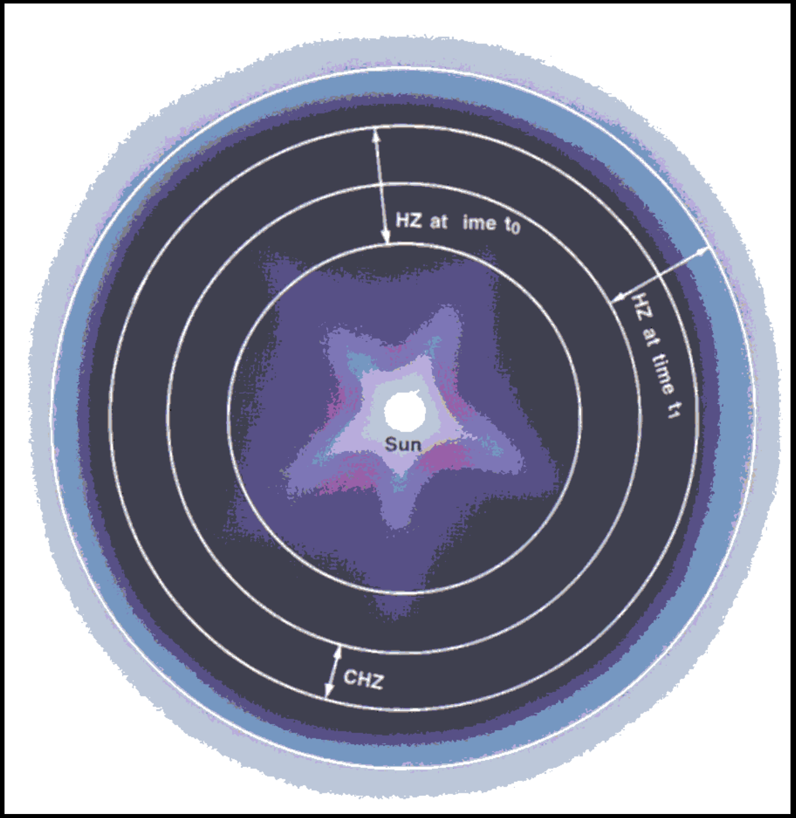
- I am indebted to Ralph Lorenz (and Jason Wright) for finding this reference to the first use of the term ‘habitable zone’
- Maunder, of course, is famous amongst solar physicists for his research on the ‘Maunder minimum’ -- the apparent near absence of sunspots between 1645 and 1715



Definitions

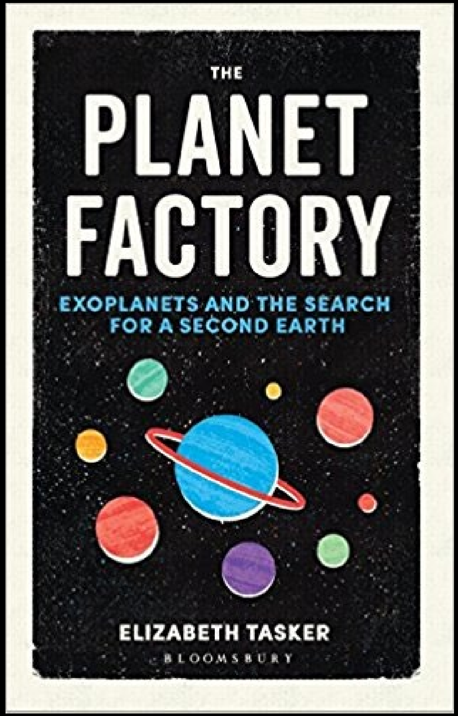
(from Michael Hart, *Icarus*, 1978)

- *Habitable zone (HZ)* -- the region around a star in which an Earth-like planet could maintain liquid water *on its surface* at some instant in time
- *Continuously habitable zone (CHZ)* -- the region in which a planet could remain habitable for some specified period of time (e.g., 4.6 billion years)



Alternative names for the habitable zone

- Lots of different names have been suggested for the habitable zone
  - The liquid-water belt (Shapley, 1953)
  - The ecosphere (Strughold, 1953)
  - The Goldilocks zone (Margulis, ~1996)
  - The hunting zone (Forget, 2017)
  - The temperate zone (Tasker, 2017)
- Regardless of what we call it, we are all talking about the same thing



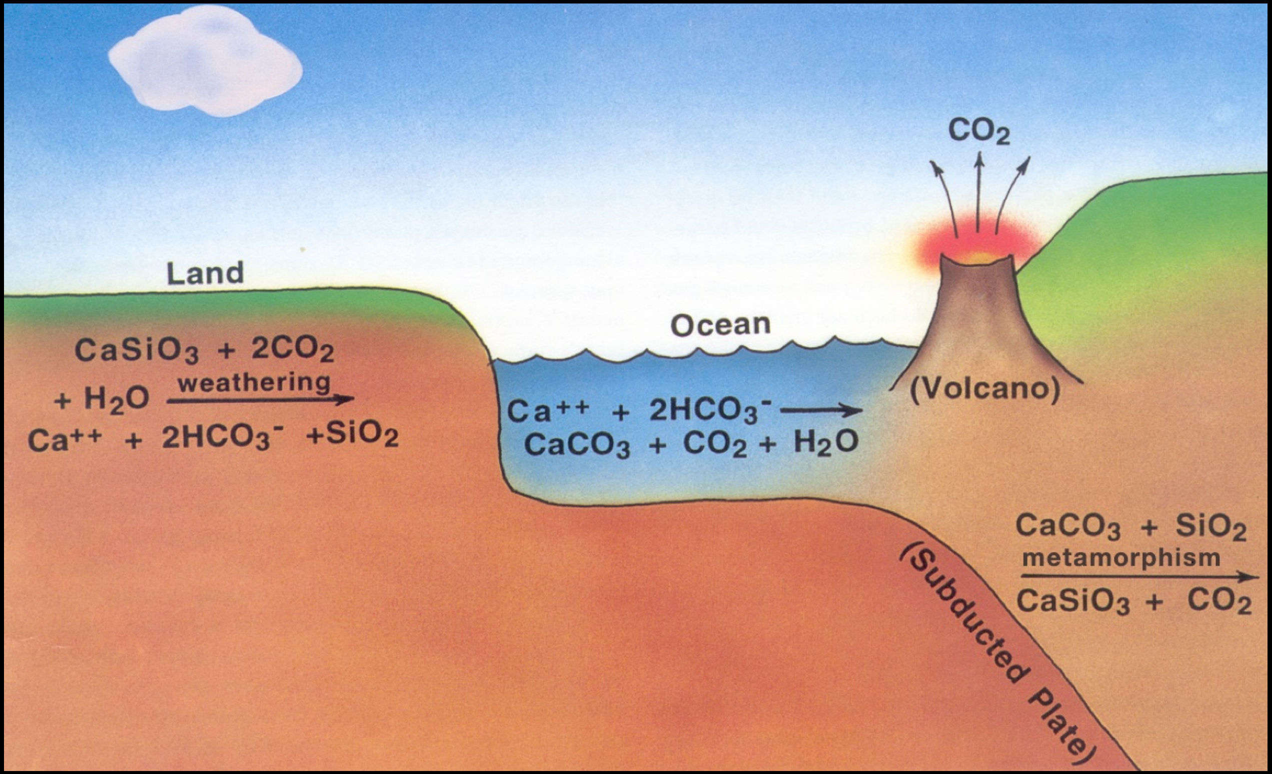
Michael Hart's calculations (*Icarus*, 1978, 1979)

- 4.6-Gyr CHZ around our own Sun is quite narrow
  - 0.95 AU: Runaway greenhouse
  - 1.01 AU: Runaway glaciation
- CHZ's around other spectral types are even narrower
  - Corollary: Earth may be the only habitable planet in our galaxy

Problems with Hart's model

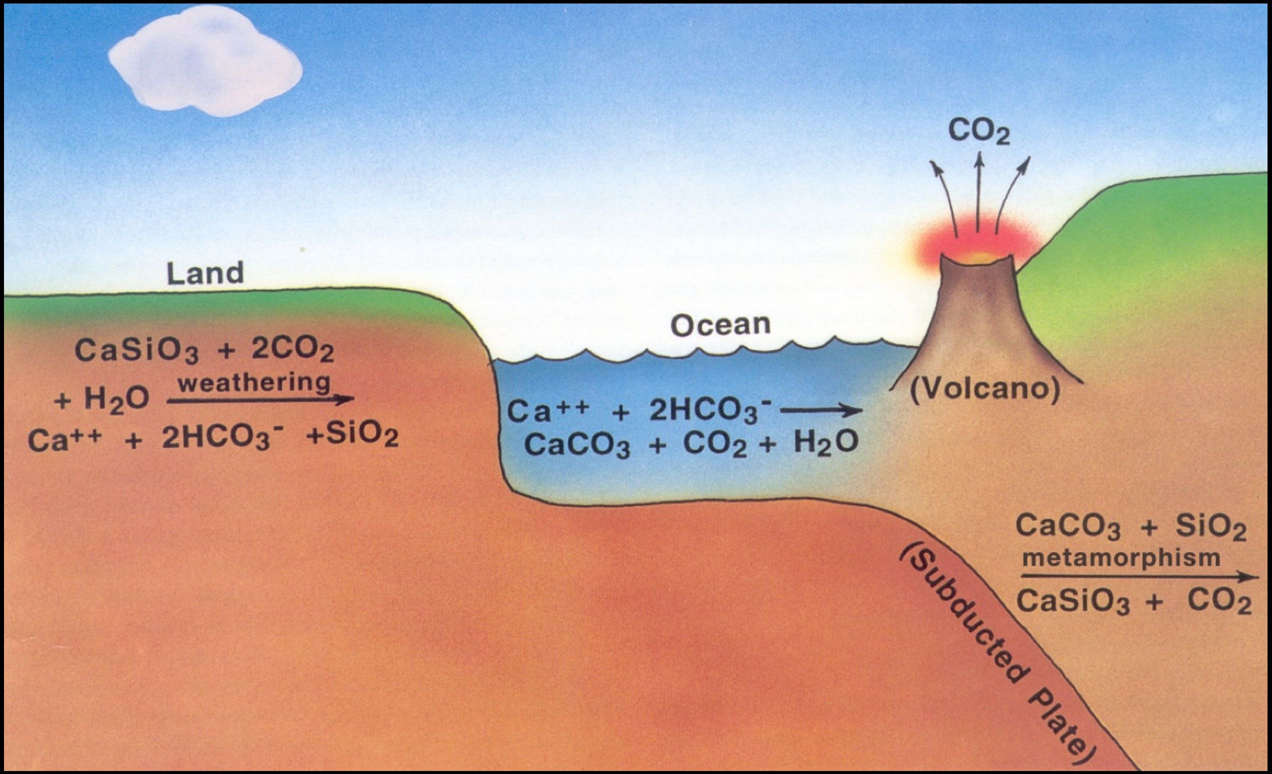
- He concluded, incorrectly, that a fully glaciated planet could never deglaciate by building up CO_2
- There is strong evidence that this actually happened on Earth several times in the aftermath of Snowball Earth glaciations
- Furthermore, there is a well-known negative feedback that causes CO_2 to accumulate on frozen planets…

The carbonate-silicate cycle



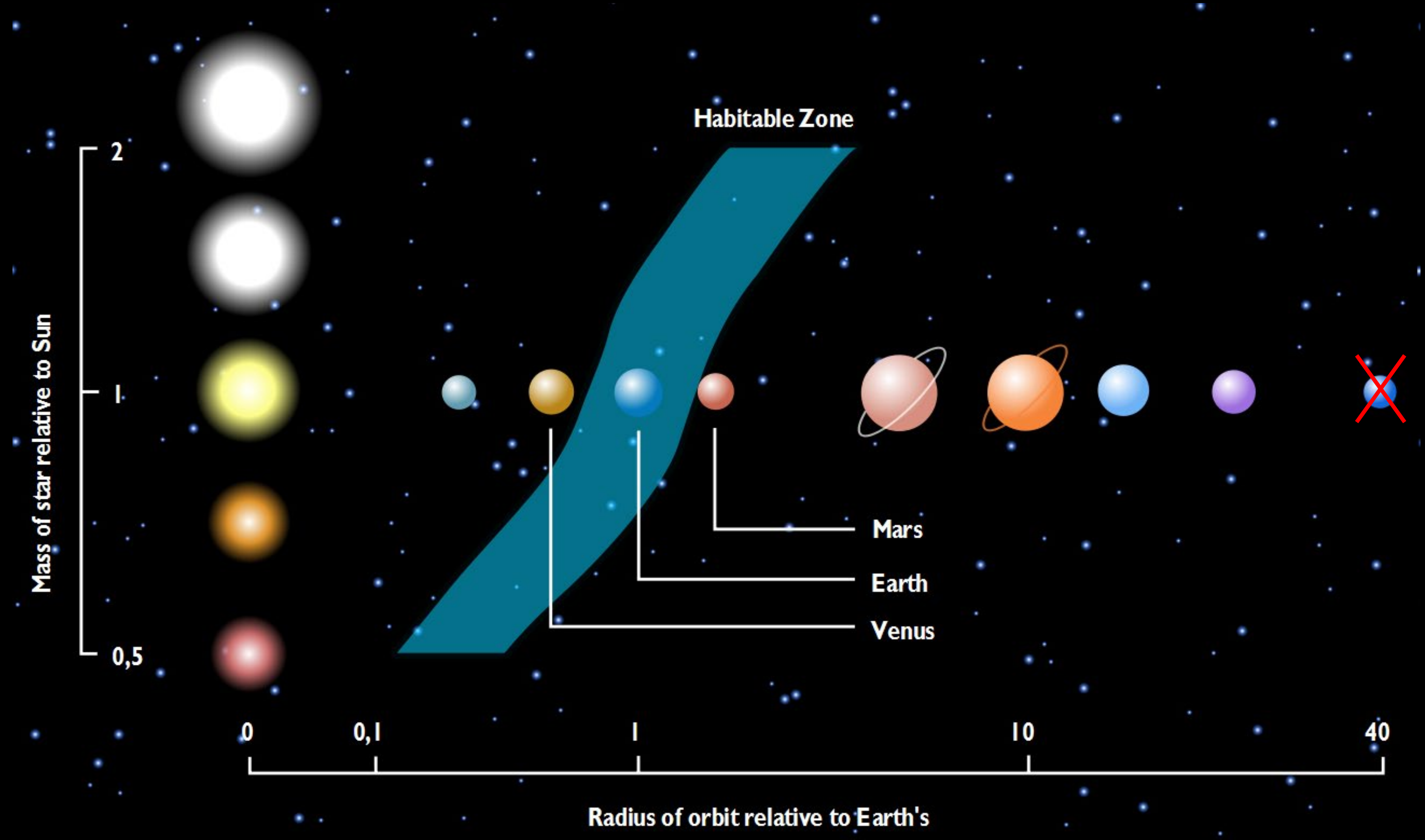
- The habitable zone is relatively wide because of negative feedbacks in the carbonate-silicate cycle: Atmospheric CO_2 should build up as the planet cools
- Higher CO_2 is also at least part of the solution to the faint young Sun problem on Earth

The carbonate-silicate cycle



- <u>Caveat</u>: For planets with low volcanic outgassing rates and with low stellar insolation, it may not be possible to maintain warm climates all the time. Instead, one may get *limit cycling* behavior, in which the climate alternates between warm and globally glaciated states (see, *e.g.*, Kadoya and Tajika, 2014; Menou, 2015; Haqq-Misra et al., 2016)

The ZAMS habitable zone



- With this in mind, one gets a habitable zone that is fairly wide compared to the mean planetary spacing
- 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/

Outer edge of the HZ

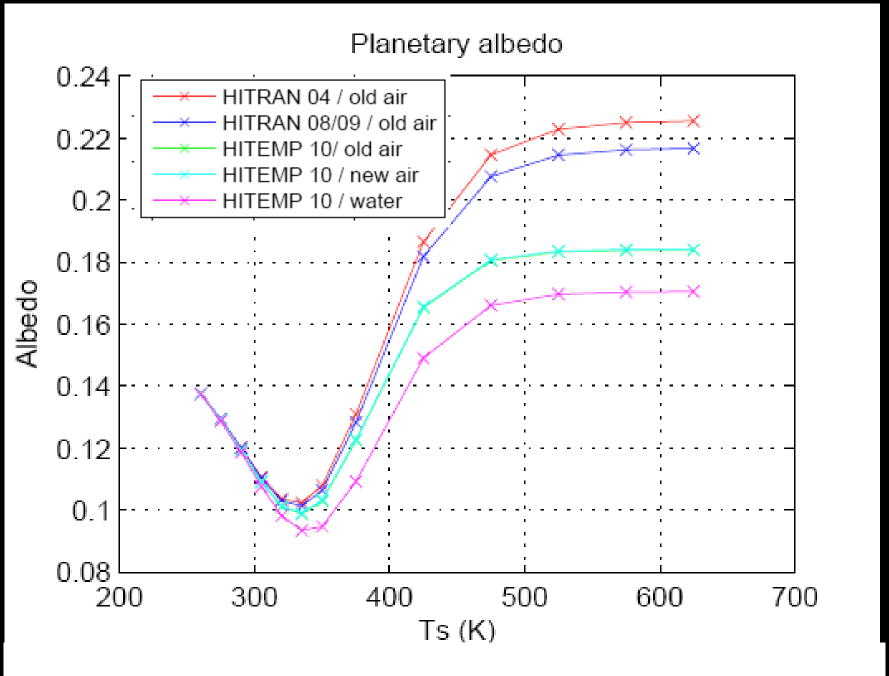
- There is a limit, though, at which the CO_2 starts to condense. This reduces the greenhouse effect by lowering the *tropospheric lapse rate*
- Rayleigh scattering by CO_2 raises the planet's *albedo* and therefore also competes against the greenhouse effect
- This leads to something termed the *'maximum greenhouse limit',* which one can calculate using a 1-D climate model (~1.67 AU for a Sun-like star)

Inner edge of the HZ

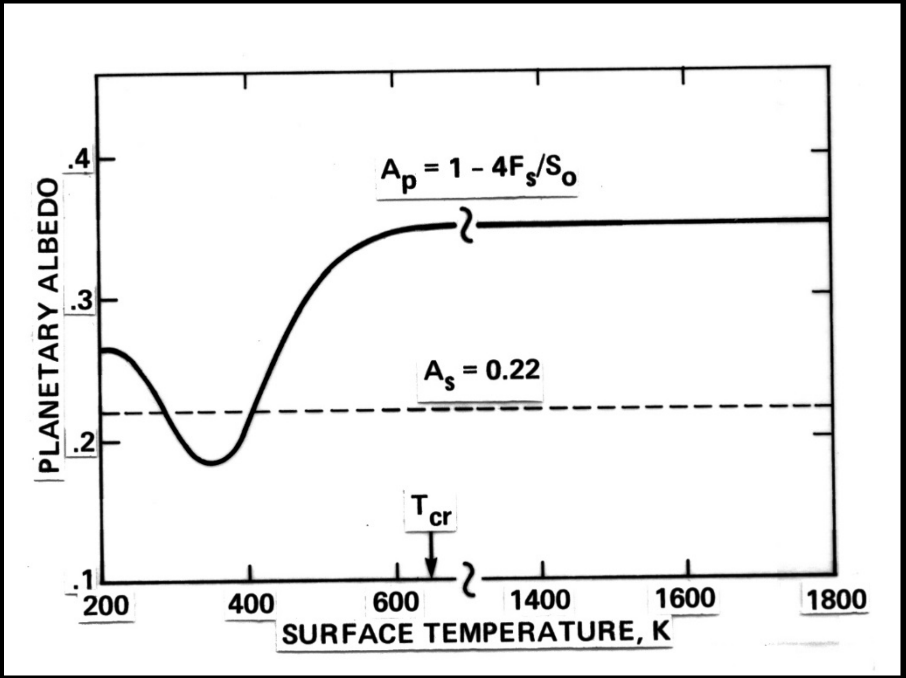
- Near the inner edge of the HZ, the problem is just the opposite: a planet can develop either a *runaway* or *moist greenhouse*
- Runaway greenhouse: The oceans evaporate entirely
  - Old limit was 0.85 AU*
- Moist greenhouse: The ocean remains liquid, but the stratosphere becomes wet, leading to rapid photolysis of water and escape of hydrogen to space
  - Old limit was 0.95 AU*

*Kasting et al. (1993)

New albedo calculations using the HITEMP database



Goldblatt et al. (2013)

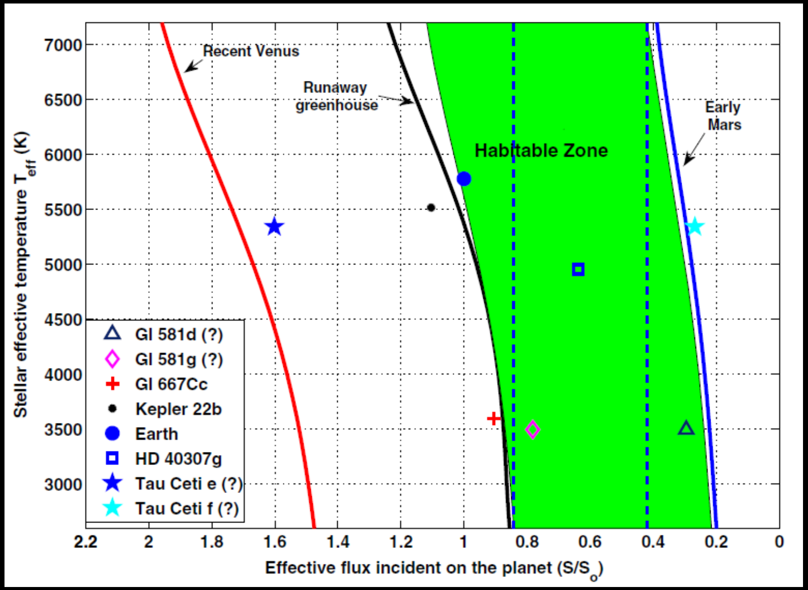


Kasting (1988) model

- As first pointed out by Colin Goldblatt (U. Victoria), our old climate model may have seriously underestimated absorption of visible/near-IR radiation by H_2O. New data are available from the HITEMP database

Is the modern Earth habitable?

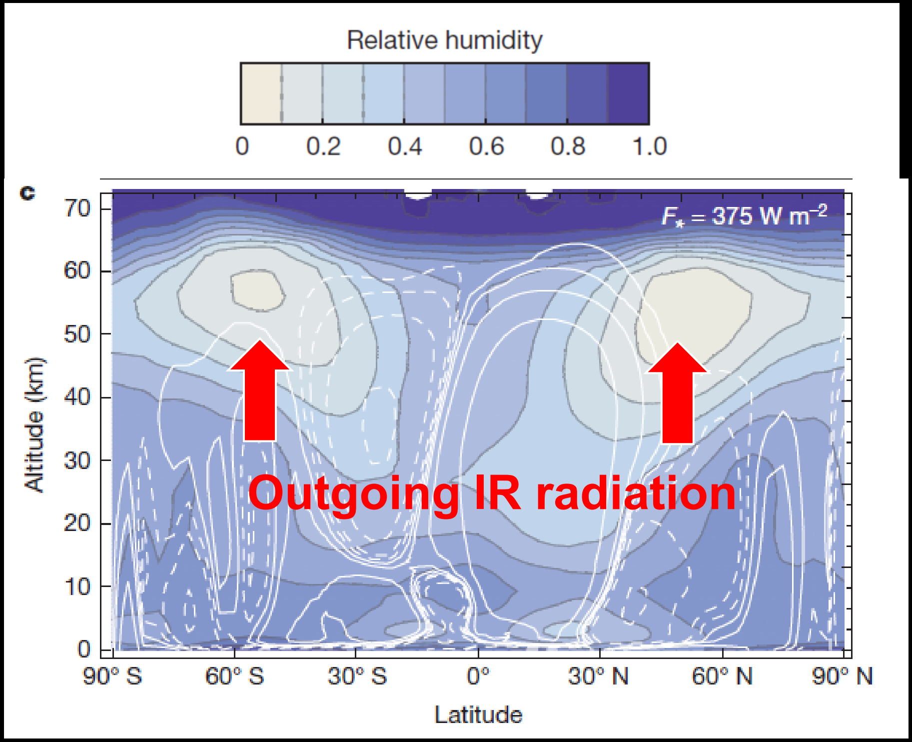
- Unfortunately, making this change in our climate model moved the inner edge of the habitable zone from 0.95 AU out to ~1.00 AU, implying that Earth is on the verge of becoming uninhabitable
- We know, however, that our estimates are overly pessimistic because we assume a fully saturated troposphere in our 1-D, globally averaged climate model



Kopparapu et al., ApJ (2013)

3-D modeling of habitable zone boundaries

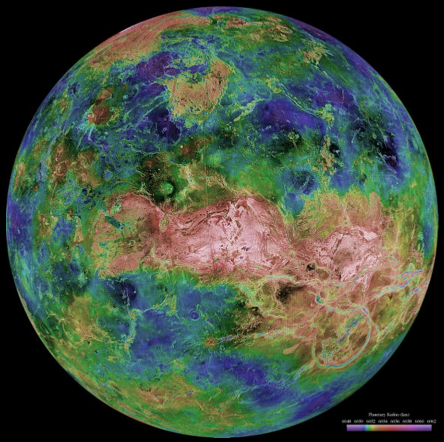
- Fortunately, new studies using 3-D climate models predict that the runaway greenhouse threshold is increased by ~10% because the tropical Hadley cells act like radiator fins
  - This was pointed out 20 years ago by Ray Pierrehumbert (JAS, 1995) in a paper dealing with Earth's tropics
- We have adjusted our (1-D) HZ inner edge back inward to 0.95 AU to account for this behavior

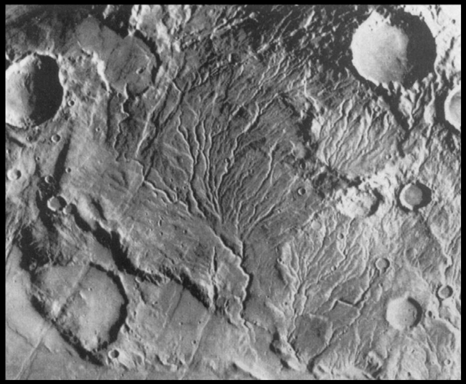


Leconte et al., Nature (2013)

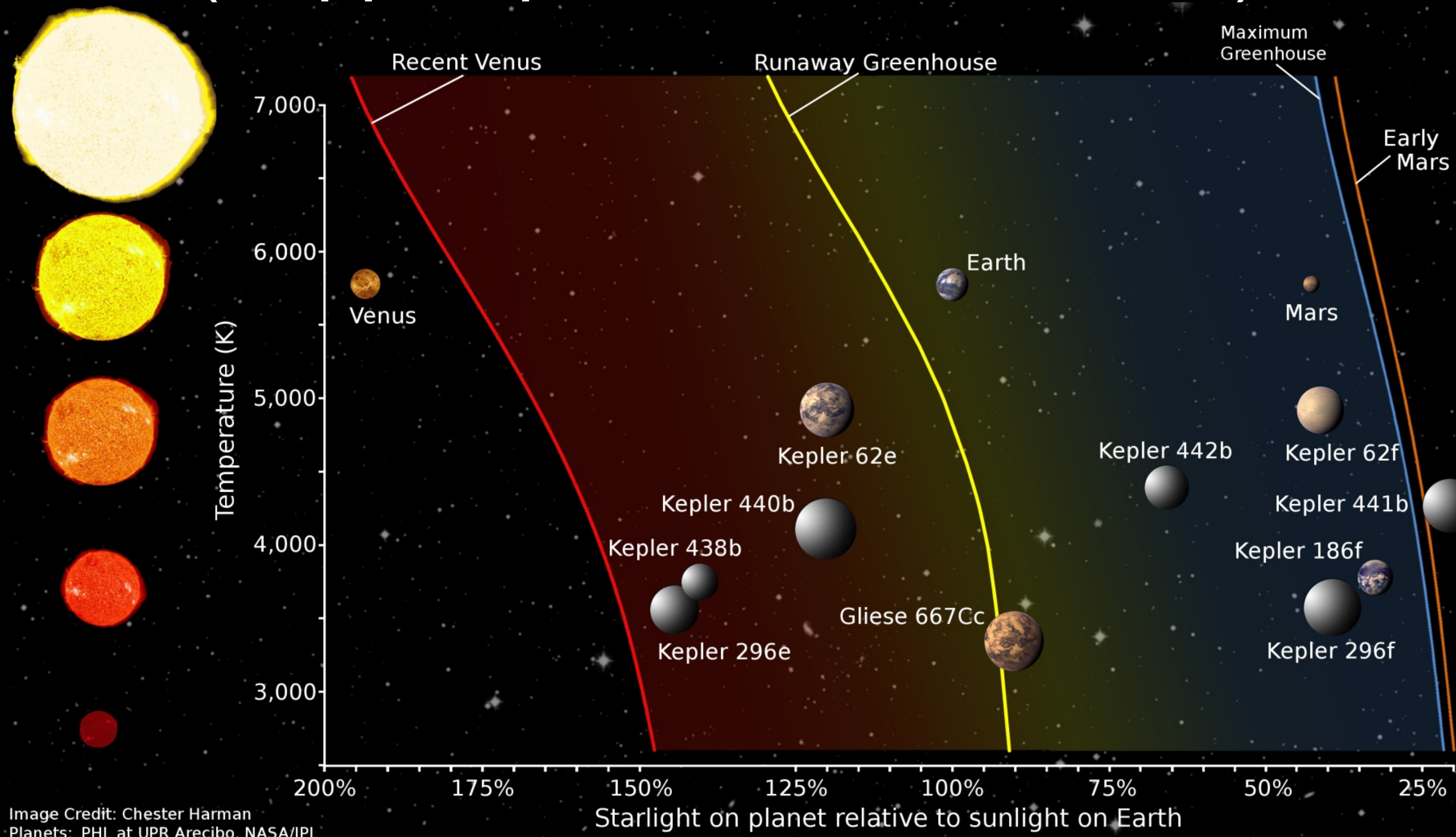
Empirical HZ limits

- Some researchers don't trust theorists
- We can also define *empirical* limits on the HZ
  - From looking at its surface, we can discern that Venus has not had liquid water for at least the last 1 b.y.
  - Mars, on the other hand, looks as if it *was* habitable at about 3.8 Ga





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

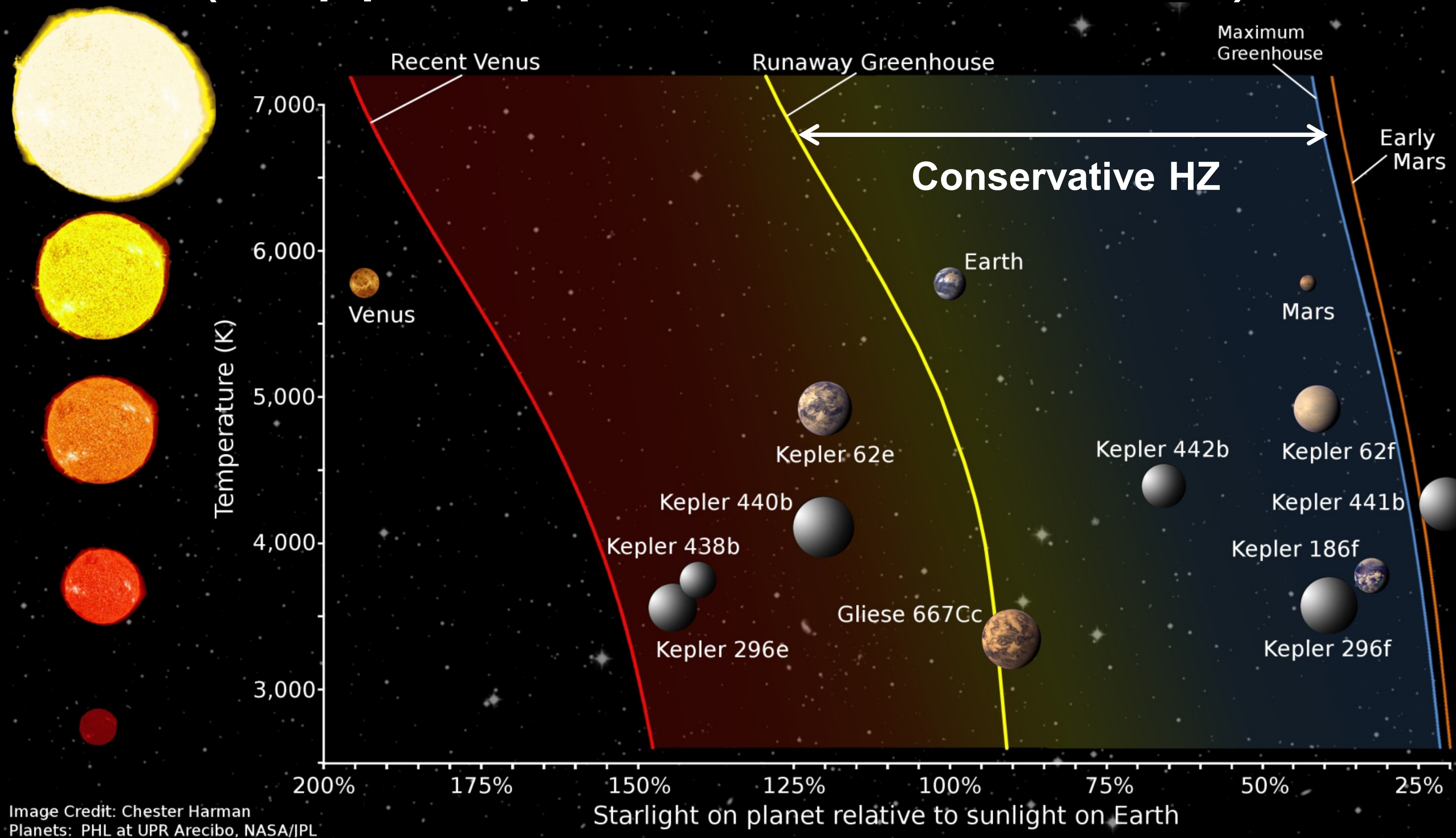


- Note the change in the x-axis from distance units to stellar flux units. This makes it easier to compare where different objects lie

Credit: Sonny Harman

Updated habitable zone

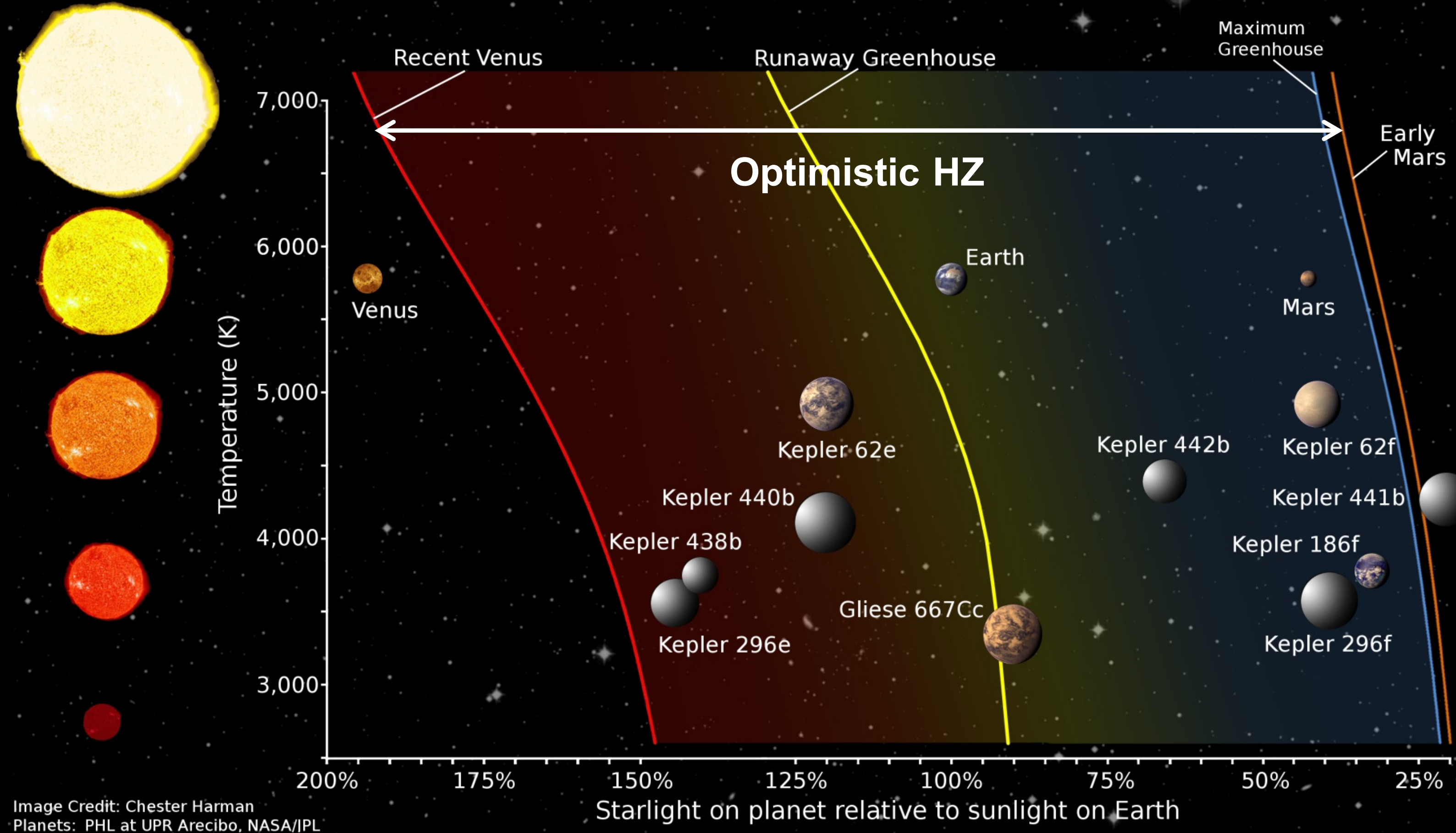
(Kopparapu et al., 2013, 2014)



- We should define the HZ *conservatively* when designing our space telescopes, so that we don't underestimate the problem

Credit: Sonny Harman

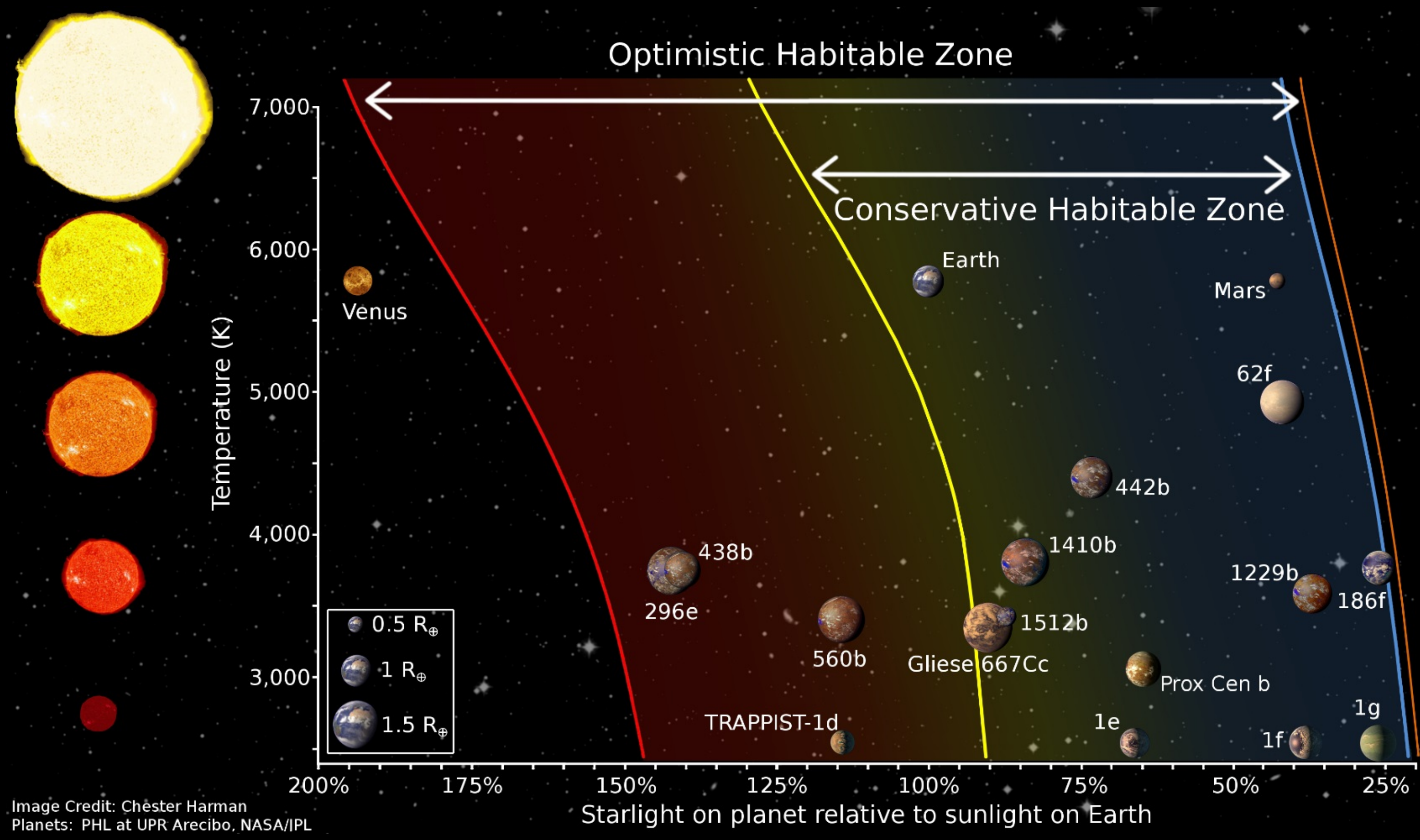
Updated habitable zone
(Kopparapu et al., 2013, 2014)



- Once we've got these telescopes built and launched, we can afford to be more *optimistic*, so that we don't overlook interesting planets

Credit: Sonny Harman

Most recent habitable zone



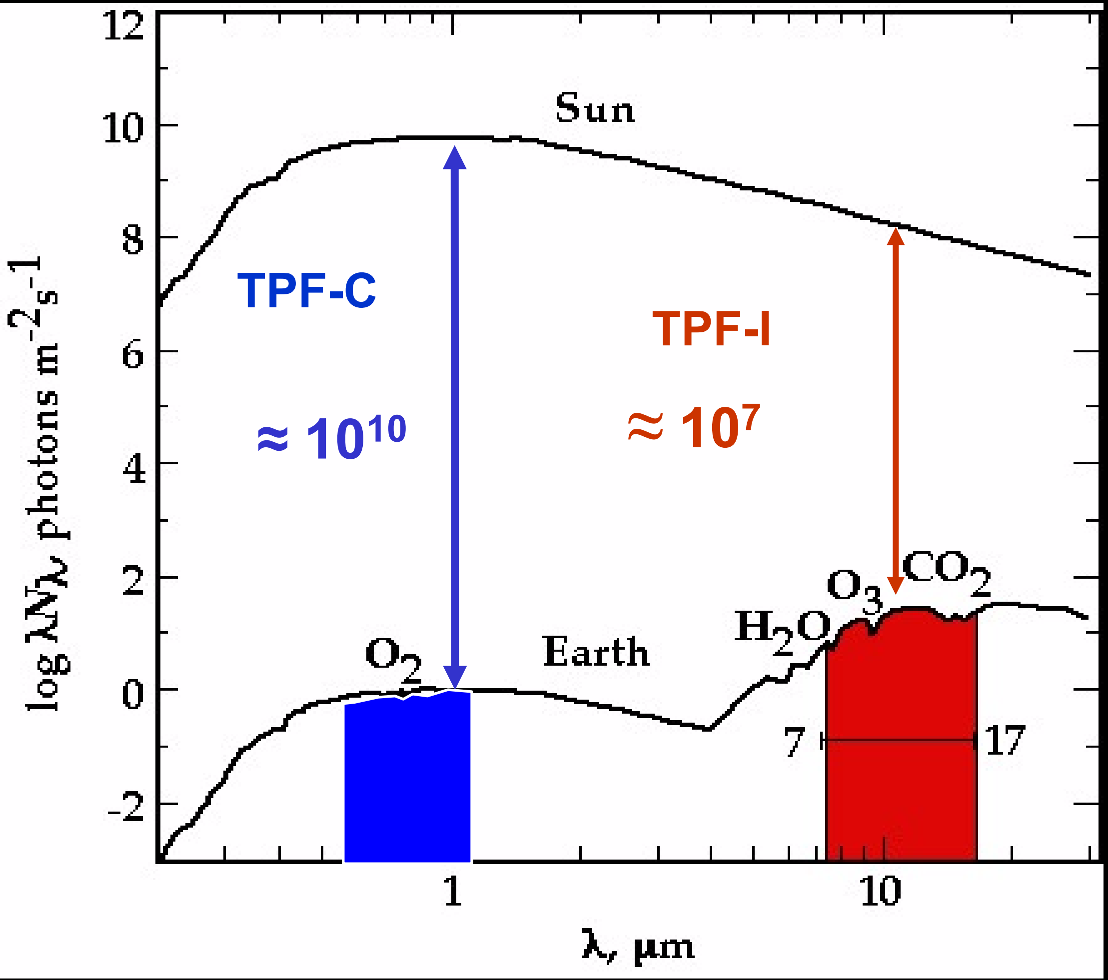
- Excludes planets >1.6 R_E
- Three of the seven Trappist-1 planets fall within the conservative HZ, as does Proxima Centauri b

- Part 3—Atmospheric biosignatures and how to look for them

Direct imaging of exoplanets

- So far, we have only been able to obtain spectra of a few *transiting* exoplanets
  - JWST will do a better job on this, but it can still only look at transiting planets
- In direct imaging, one tries to block out the light from the star and look for the reflected light (or emitted IR radiation) from the planets around it

Terrestrial Planet Finder (TPF)



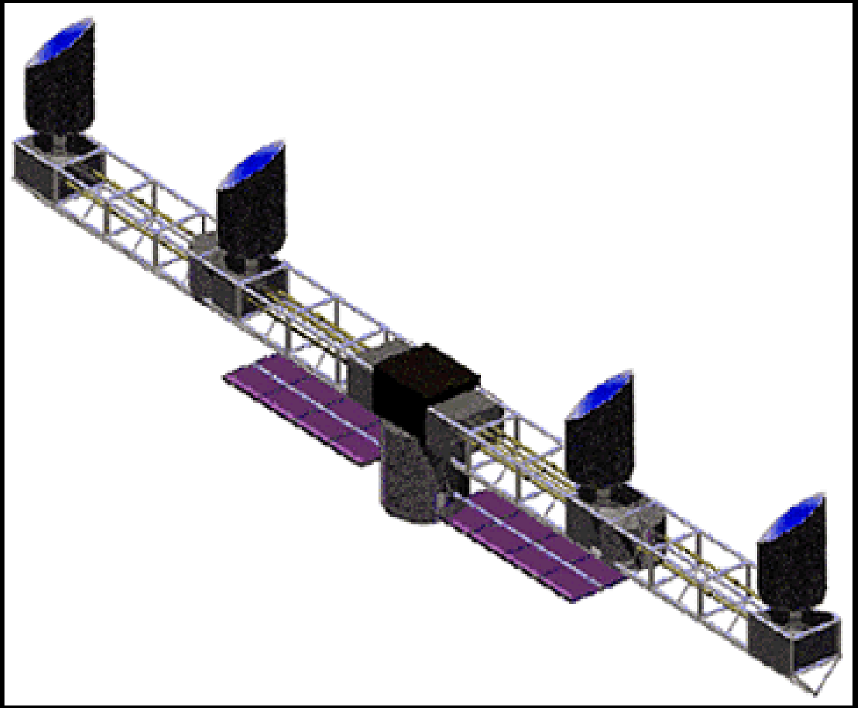
Visible or thermal-IR?

- Contrast ratio:
  10^{10} in the visible
  10^{7} in the thermal-IR
- Resolution: $\theta = \lambda/D$
  -- Real telescopes operate at some multiple of this value
- Required aperture:
  ~8 m in the visible
  80 m in the IR

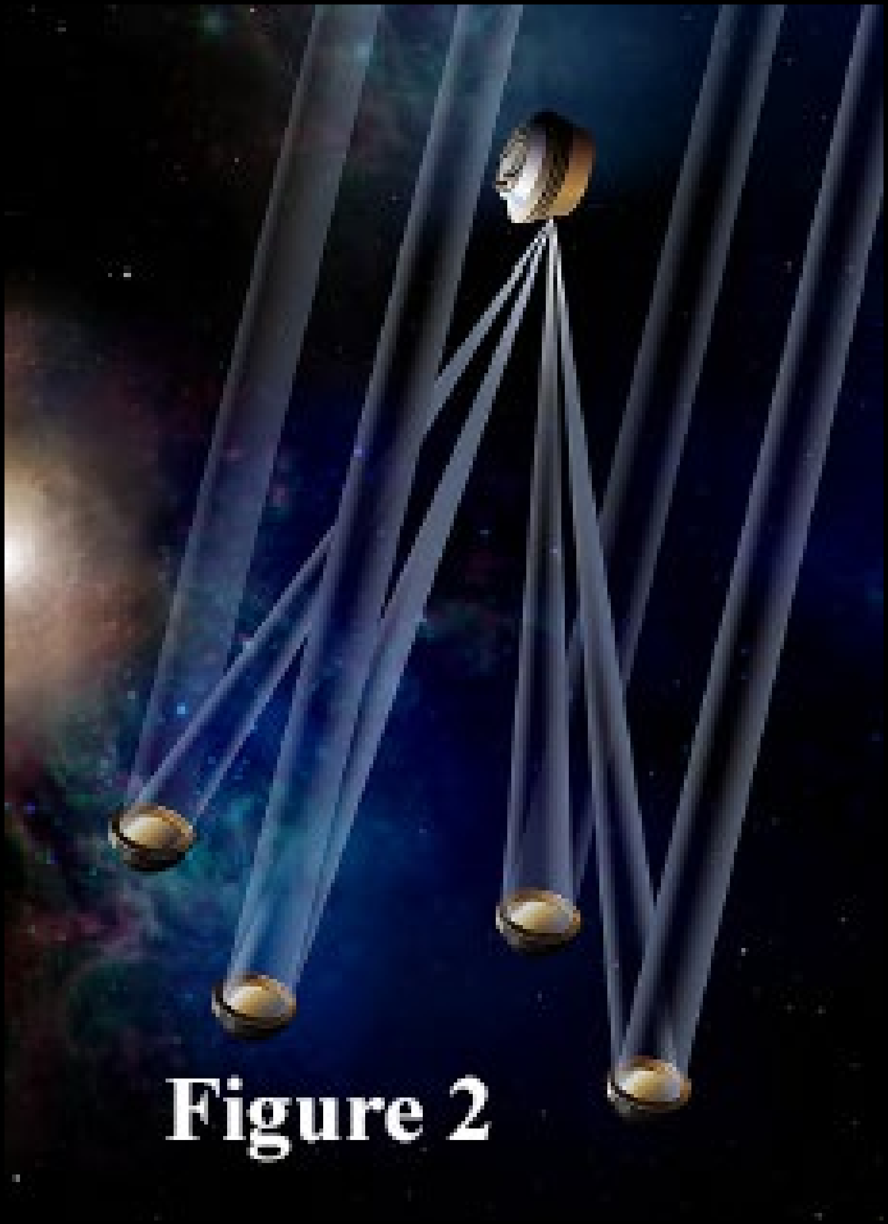
Courtesy: Chas Beichman, JPL

Evolution of the TPF flight design concepts

- The original idea was to fly a thermal-infrared interferometer on a fixed 80-m boom, similar to SIM, but bigger (and cooled)
  - SIM (the Space Interferometry Mission) would have looked for planets using precise astrometry (measuring stellar positions)
- Disadvantages:
  - Vibrations
  - Fixed baseline



The original TPF-I concept (circa 2002)

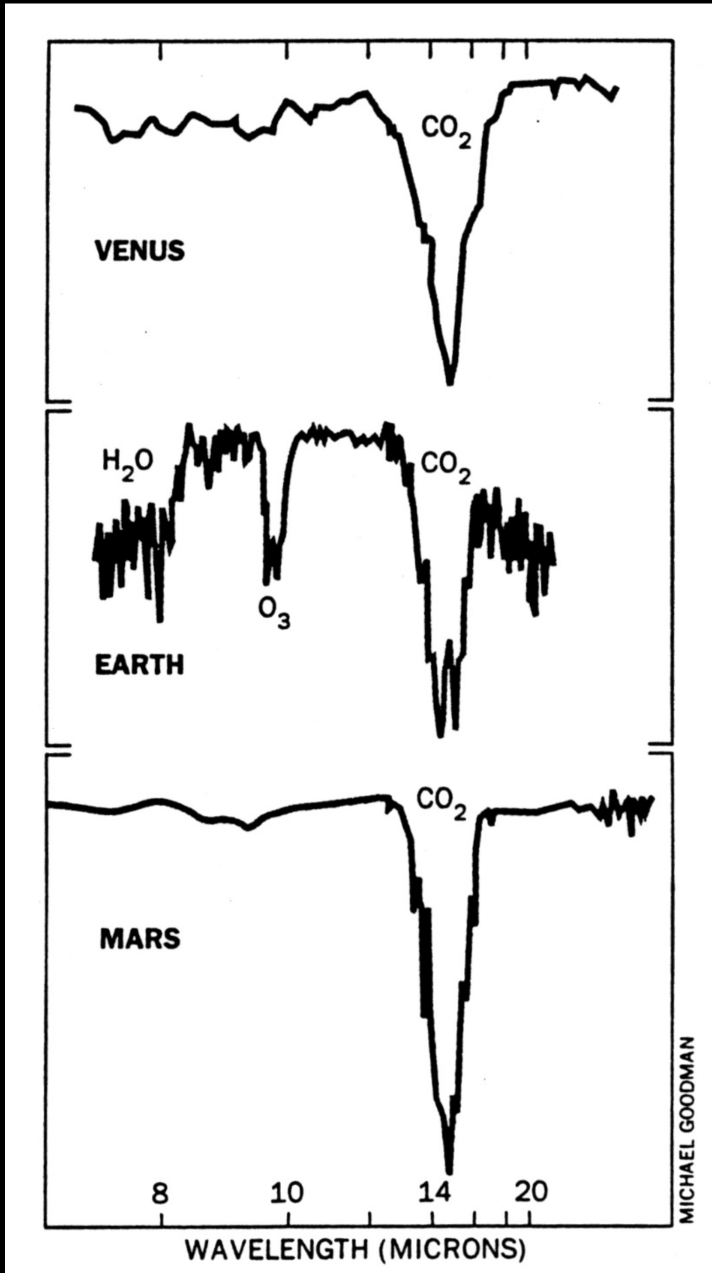


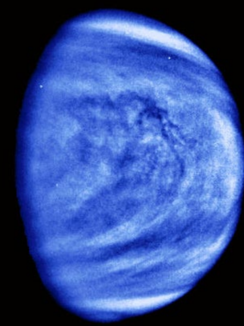
Peter Lawson TPF-I white paper

"Emma" design For TPF-I/Darwin

- After many years of study, ESA's Darwin mission eventually got cancelled
- This concept is now being studied once again by ESA under the acronym LIFE: Large Interferometer For Exoplanets

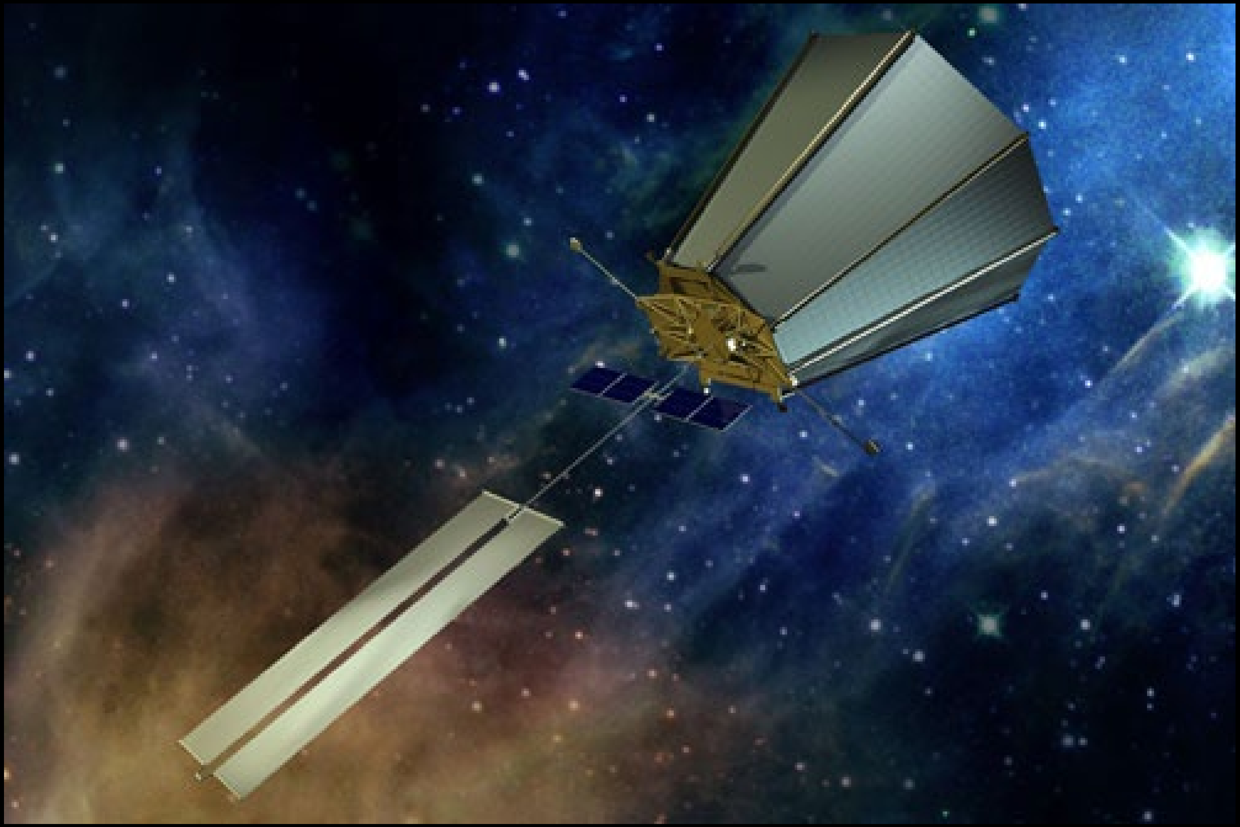
Thermal-IR spectra





Source:
R. Hanel, Goddard Space Flight Center

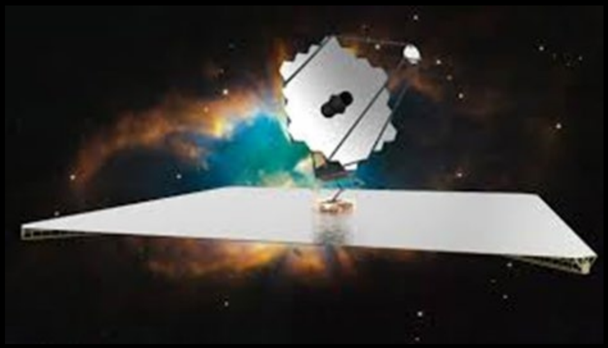
TPF-C: Visible/near-IR coronagraph (circa 2005)



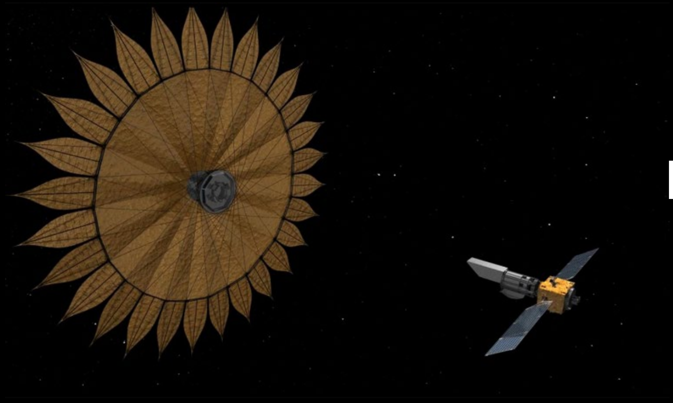
- It may be easier, however, to do TPF in the visible, using a single telescope and spacecraft
- Advantages: single spacecraft and telescope
- Disadvantages: high contrast ratio between planet and star

Modern direct imaging concepts

- LUVOIR: the Large UV-Optical-IR Space Telescope
- HabEx: the Habitable Planets Explorer
  - LUVOIR is bigger (8-15 m)
  - HabEx is smaller, but still not tiny (4 m)
  - Both telescopes are being studied as potential flagship missions for the 2030's
  - These missions can also look for signs of life

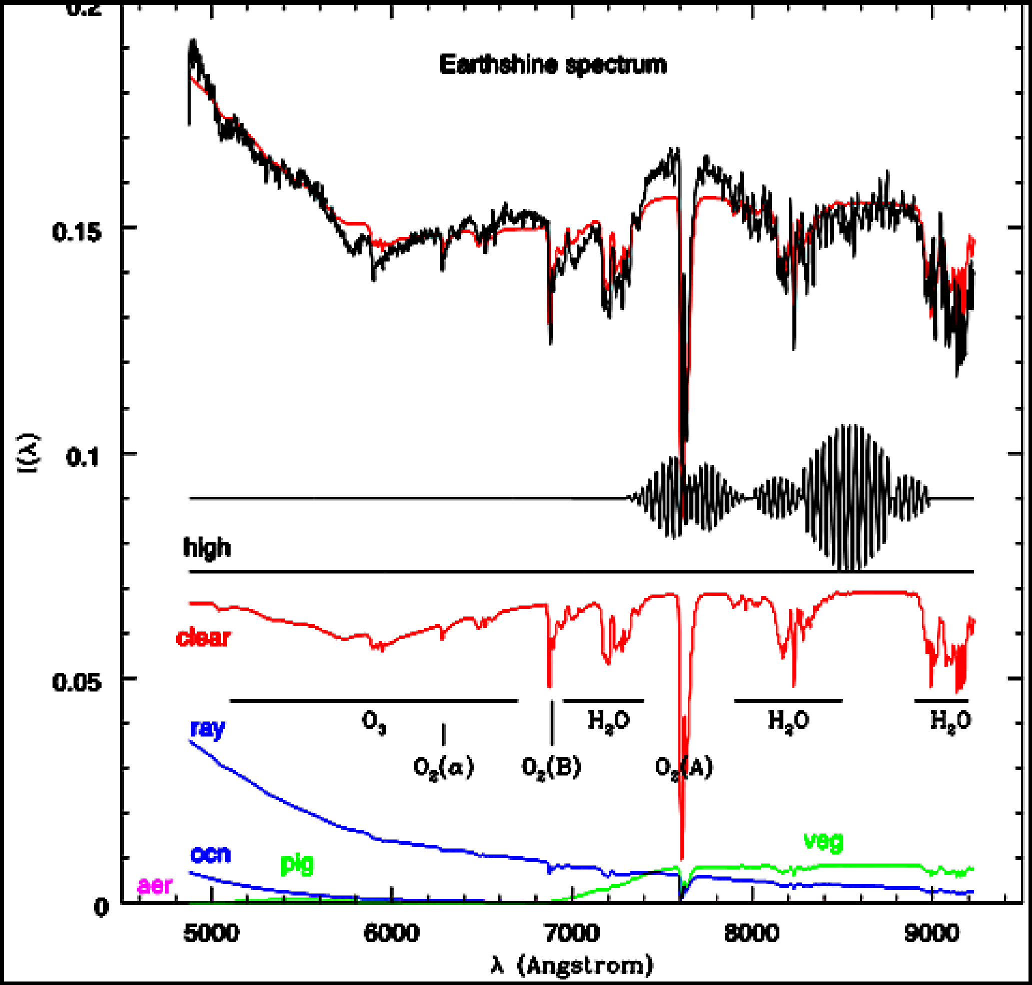


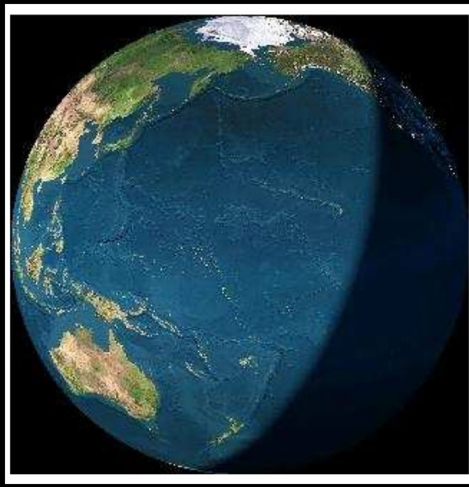
LUVOIR



HabEx

Visible Spectrum of Earth





Integrated light of Earth, reflected from dark side of moon; Rayleigh, chlorophyll, O_2, O_3, H_2O.

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

Conclusions

- Detectable life requires, at a minimum, a planet with a solid (or liquid) surface, a source of thermodynamic free energy, 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
  - 3-D climate models are needed to further refine the boundaries of the HZ
- In the long run, both NASA and, hopefully, ESA want to do space-based direct imaging of exoplanets using telescopes such as HabEx or LUVOIR. This is our best chance for finding Earth-like planets and for looking for signs of life