How to Find a Habitable Planet

James Kasting
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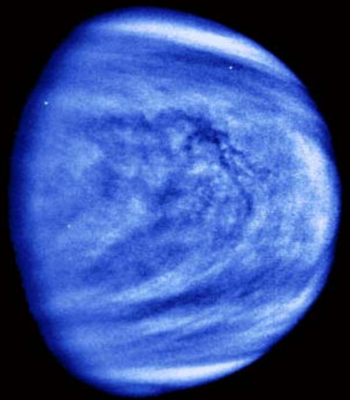
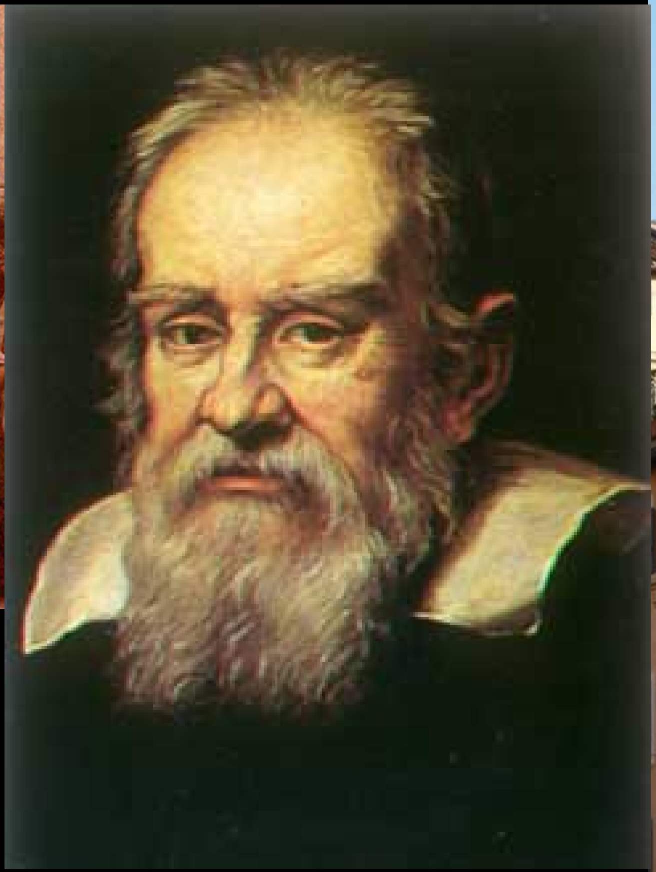
Penn State University



The search for other habitable worlds is ancient



"There are infinite worlds both like and unlike this world of ours..."---
Epicurus (c. 300 BCE)
(died painfully 269 BCE)

"… false and damnable ..."

G. Galilei (b. 1564)

(life imprisonment 1633)

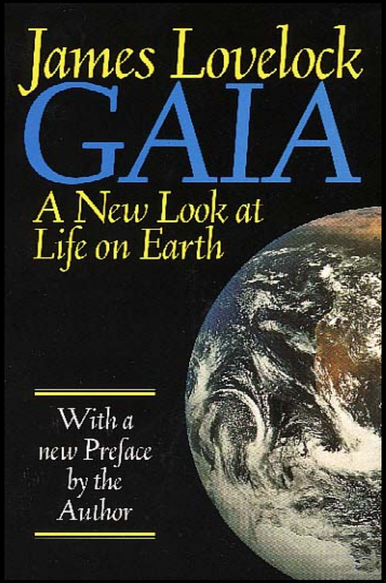
"There are countless suns and countless earths …"
Giordano Bruno (b. 1584)
in De L'infinito Universo E Mondi
(burned at the stake in Campo dei Fiore, Rome, 1600)

From Mike Devirian, *JPL*

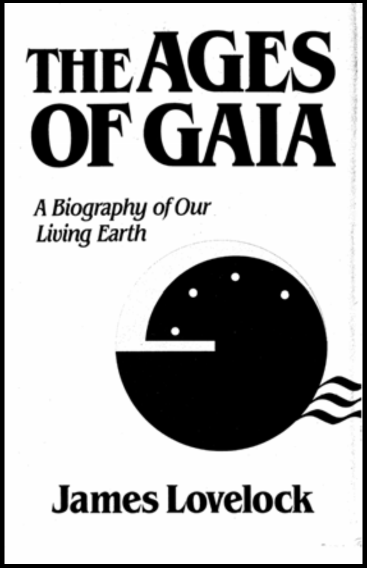
- Even today, opinions differ widely as to whether other Earth-like planets exist…

The Gaia hypothesis

First presented in the 1970s by James Lovelock



1979



1988

http://www.ecolo.org/lovelock

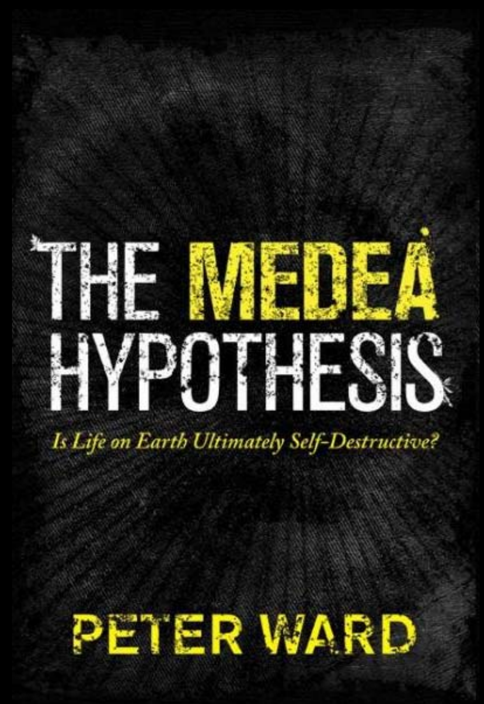
Gaia—The Greek goddess

- According to this hypothesis, *life creates and maintains conditions for its own existence* by stabilizing Earth's climate and other aspects of the Earth system
- If this idea is correct, then only planets that are already inhabited would be habitable

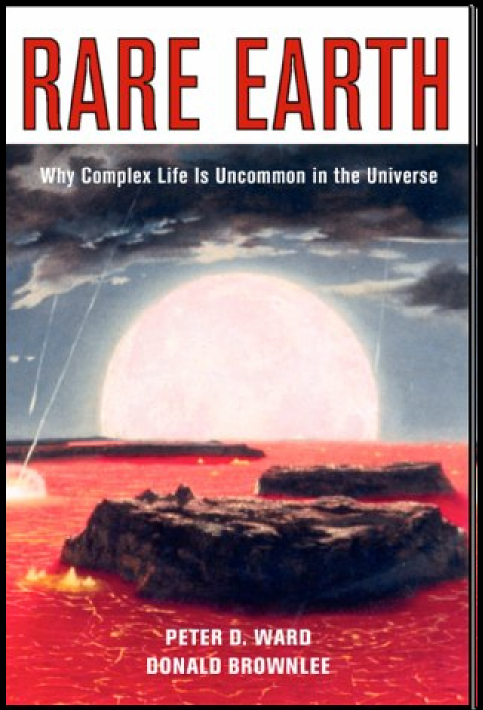
http://www.paleothea.com/Majors.html

The Medea and Rare Earth hypotheses

Peter Ward



2009



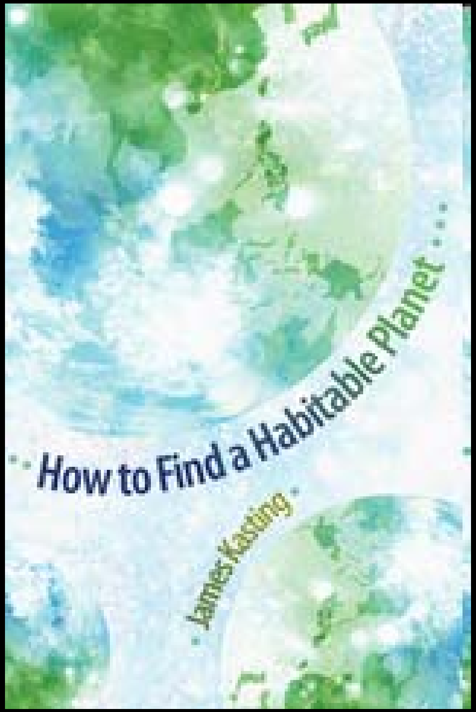
2000

Medea hypothesis: Life is *harmful* to the Earth!

Rare Earth hypothesis: Complex life (animals, including humans) is rare in the universe

The latest addition to this literature

Me



My new book
(Princeton University
Press, 2010)

- As you will see, I am more optimistic than either Peter Ward or Jim Lovelock

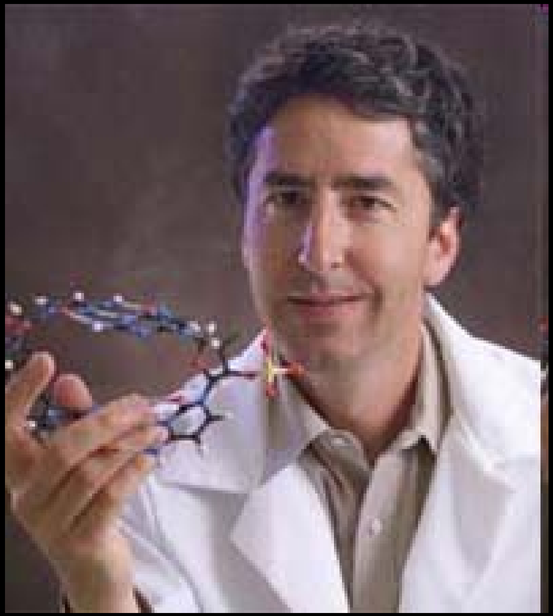
Talk outline

- Introduction (which you heard already)
- Part 1: What makes Earth unique, and what is life?
- Part 2: Can we find Earth-like planets around other stars, and can we detect life remotely?

What is life?

- If we are going to search for life on other planets, we first need to decide what we are looking for
- One definition: "Life is a self-sustained chemical system capable of undergoing Darwinian evolution"

  --*Jerry Joyce*
- This definition, however, is better suited to looking for life in a laboratory experiment than for searching remotely on planets around other stars



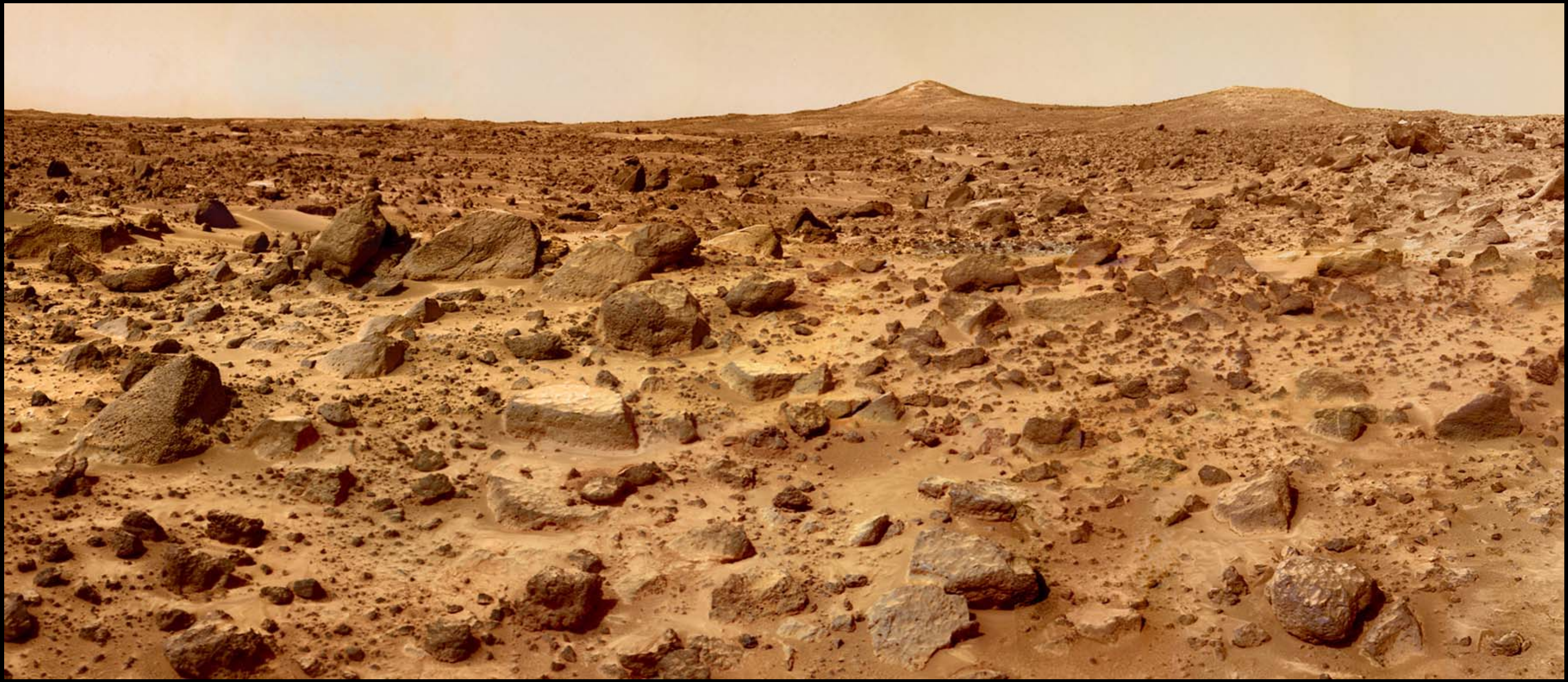
Jerry Joyce, Salk Institute

Liquid water is essential for life

(as we know it)

- Life on Earth is carbon-based (DNA, RNA, and proteins) and requires liquid water
- So, our first choice is to look for other planets like Earth
- However, that water might be subsurface..

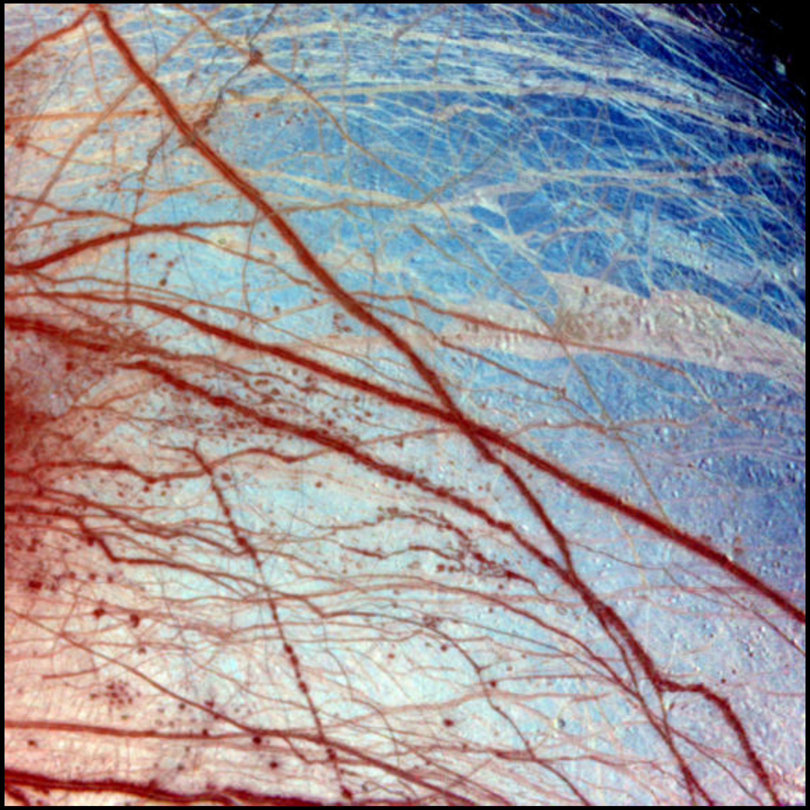
MARS PATHFINDER
Twin peaks view



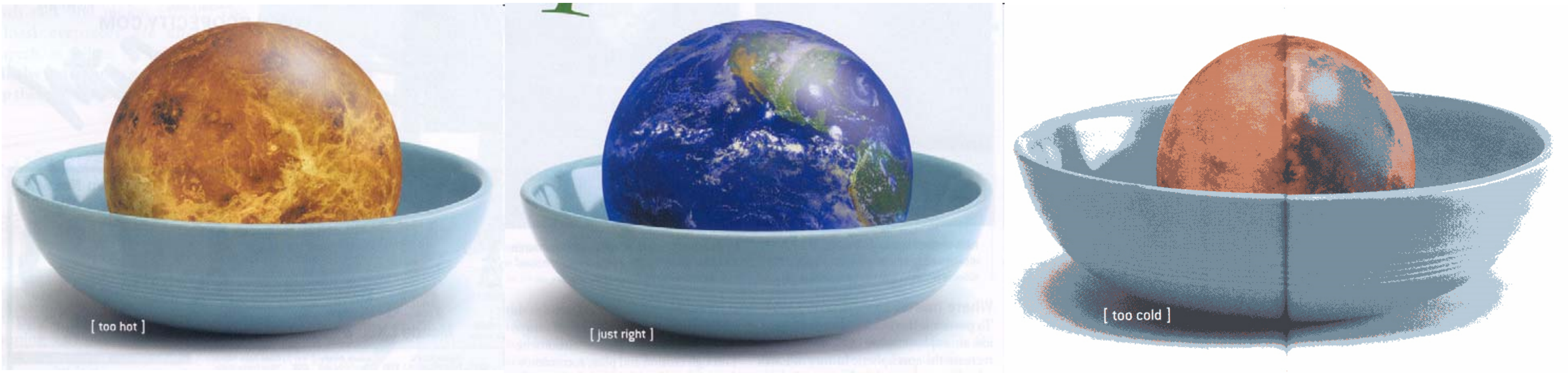
- Mars today is a frozen desert, but it could have liquid water and life beneath its surface

Europa (from Galileo)

- Another place where subsurface liquid water might be present is Jupiter's moon, Europa
- Arthur C. Clarke already scooped NASA on the topic of Europan life in his novel "2010: Odyssey Two"
  - "*ALL THESE WORLDS ARE YOURS EXCEPT EUROPA. ATTEMPT NO LANDINGS THERE.*"
- Again, though, we have no way of knowing without actually going there and melting a hole through the ice



The Goldilocks paradox

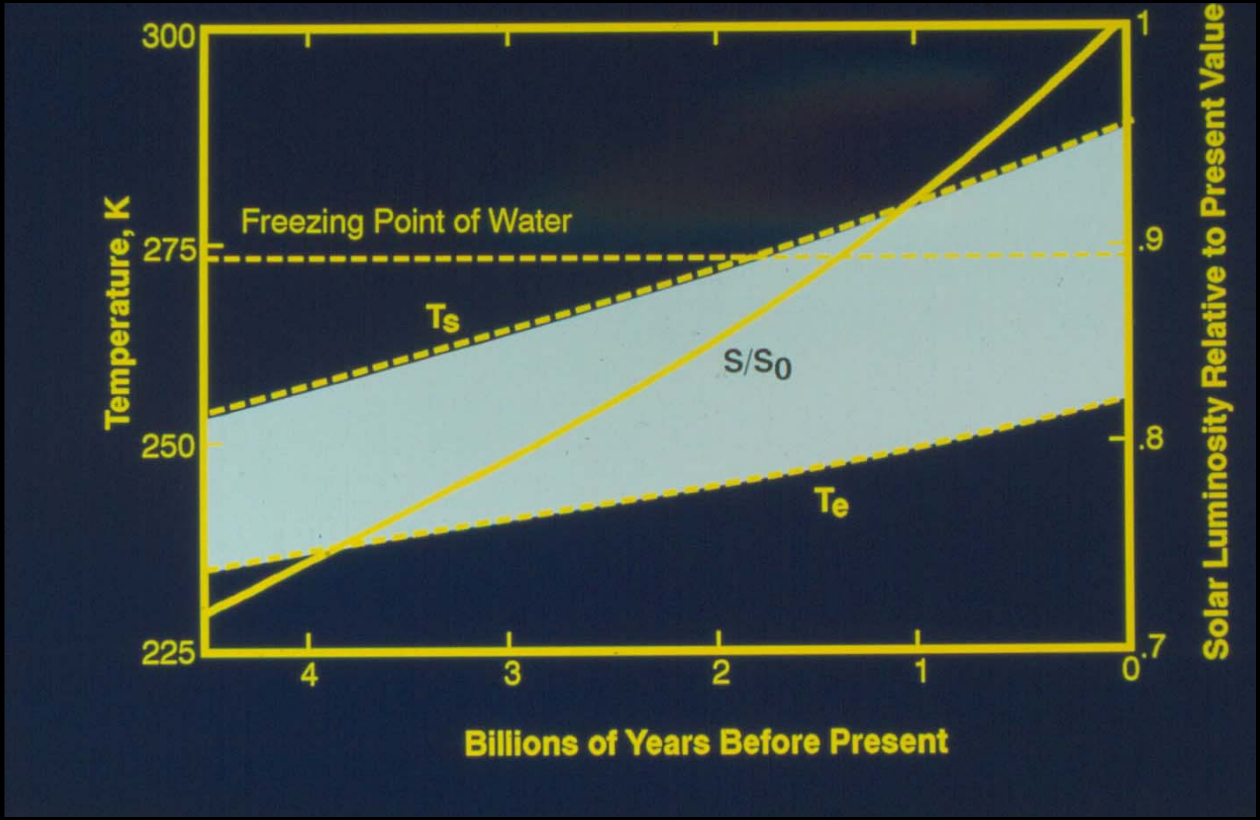


- Why is Venus too hot, Mars too cold, while Earth is just right?

  Lynn Margulis

- The obvious answer concerns their relative distances from the Sun
- However, it turns out that this is only part of the story…

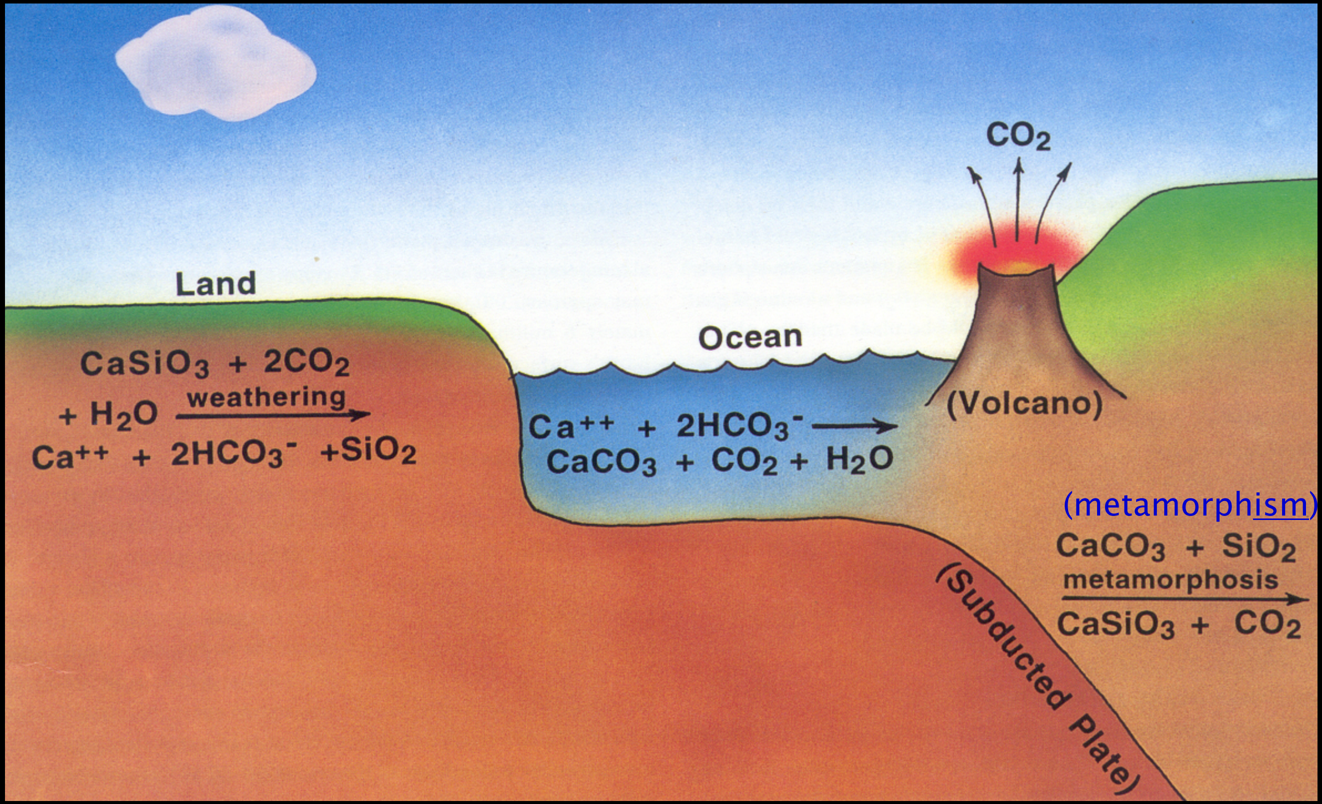
The faint young Sun problem



- Earth's surface temperature would have been below the freezing point of water prior to 2 b.y. ago if its atmosphere was the same as today
- The problem can be resolved if the early atmosphere was rich in *greenhouse gases* such as CO_2 and CH_4

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

The carbonate–silicate cycle



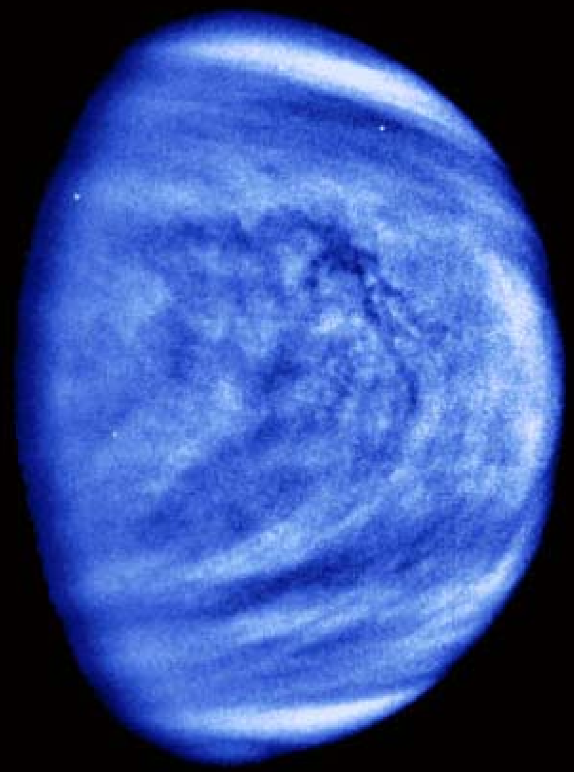
- Atmospheric CO_2 should build up as the planet cools
- This cycle regulates Earth's atmospheric CO_2 level over long time scales and has acted as a planetary *thermostat* during much of Earth's history
- *Biology* affects this cycle, but the feedback should still operate on an abiotic planet

Why isn't Mars habitable?

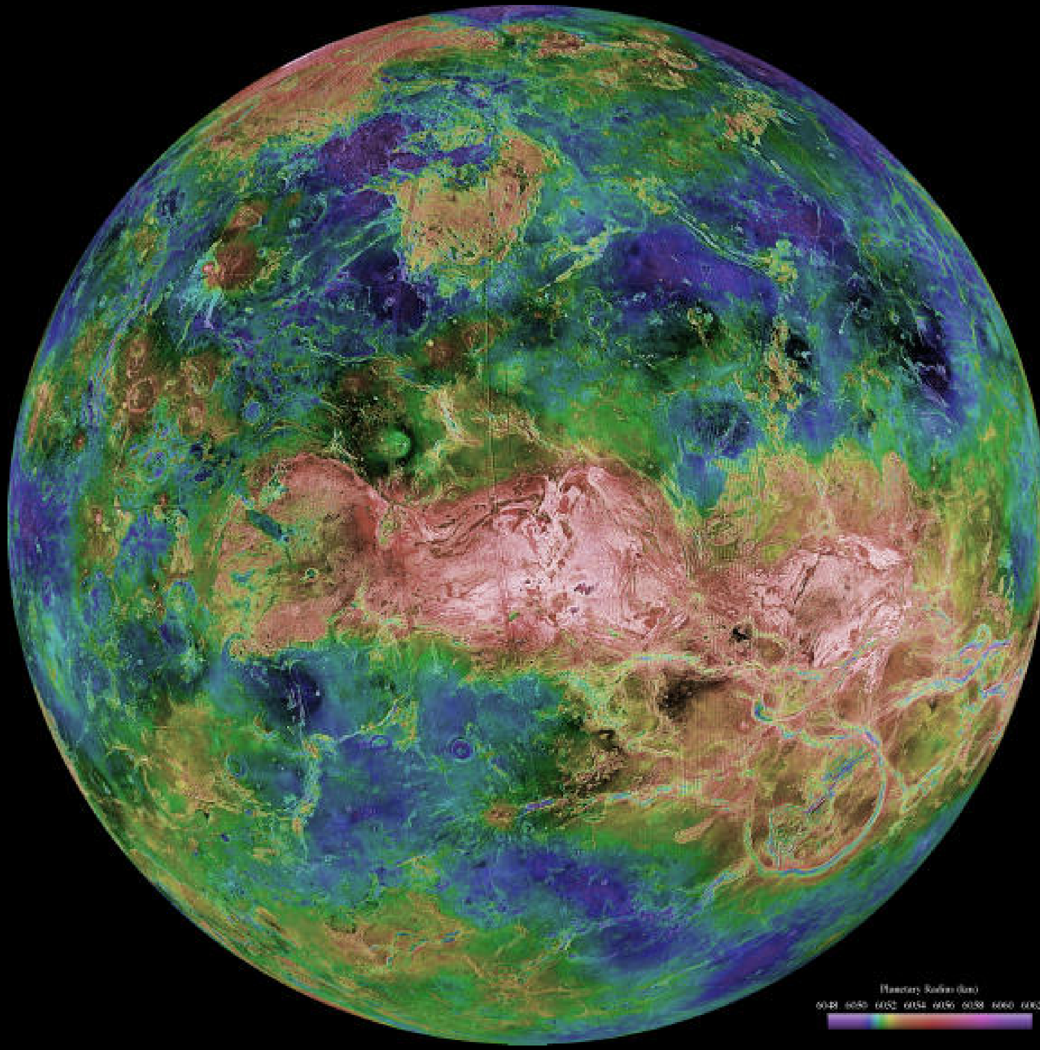
- The problem with Mars is its small *size* compared to Earth
  - Mar's has half Earth's diameter and $1/10^{th}$ its mass
- Volcanism and plate tectonics (?) ended early, and the carbonate-silicate cycle feedback didn't work
- Also, Mars' small size allowed it to lose heavy elements (C, N, and O) to *space*

Why isn't Venus habitable?

- Venus apparently had a lot of water early in its history, but it lost it because of a *runaway greenhouse*
  - Very high D/H ratio (~150 times Earth's value)
- 93-bar, CO_2-rich atmosphere
- Surface temperature: 730 K
- Practically no water



UV image (false color) from the Galileo spacecraft. Courtesy of NASA.



Venus as seen by Magellan

- Does Venus have plate tectonics?

Probably not..

Image made using *synthetic aperture radar* (SAR)

http://www.crystalinks.com/venus703.jpg

Earth topography

- Earth's topography shows tectonic features such as *midocean ridges*

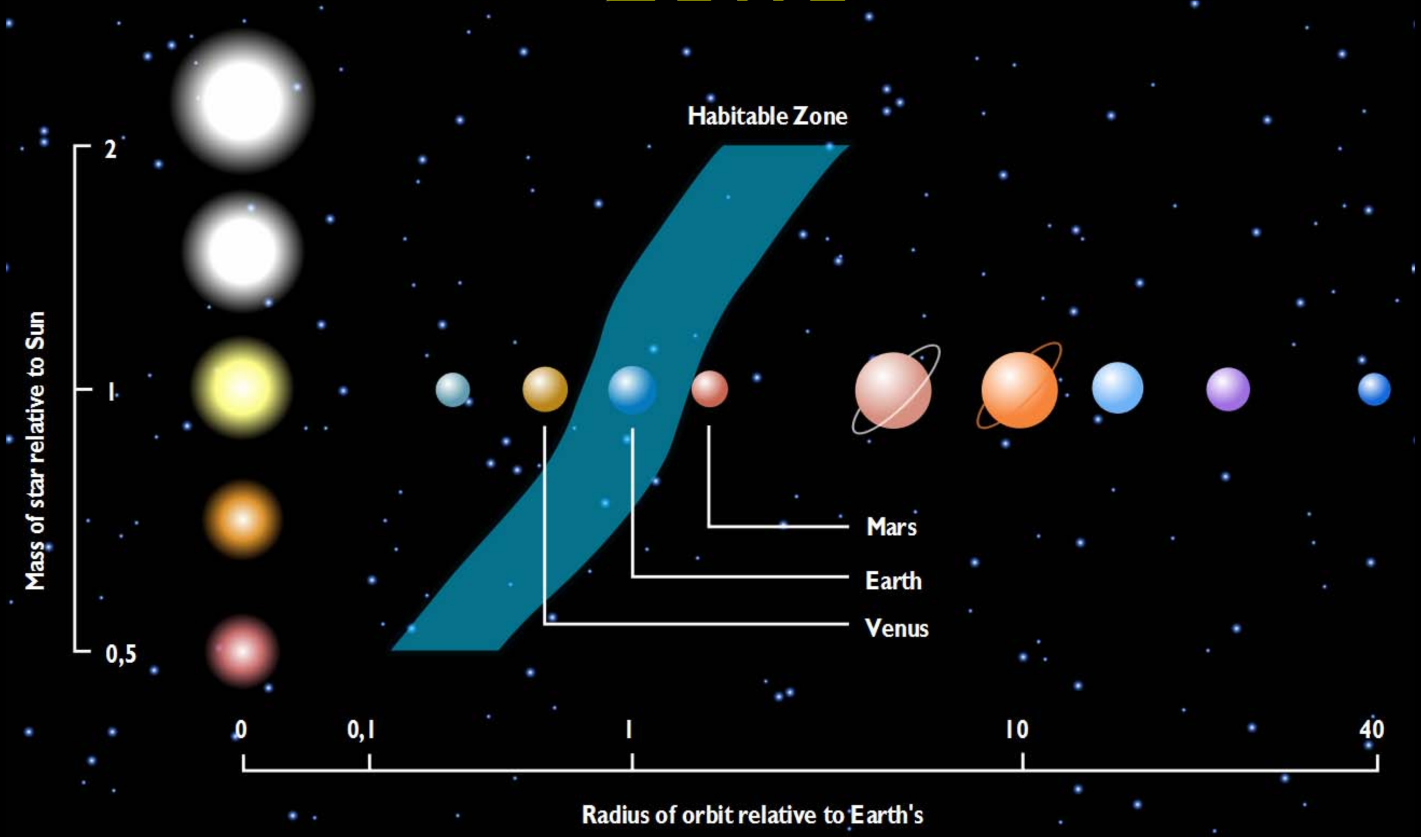
http://www.kidsgeo.com/geography-for-kids/0012-is-the-earth-round.php

Earth topography

- *Linear mountain chains* are also observed

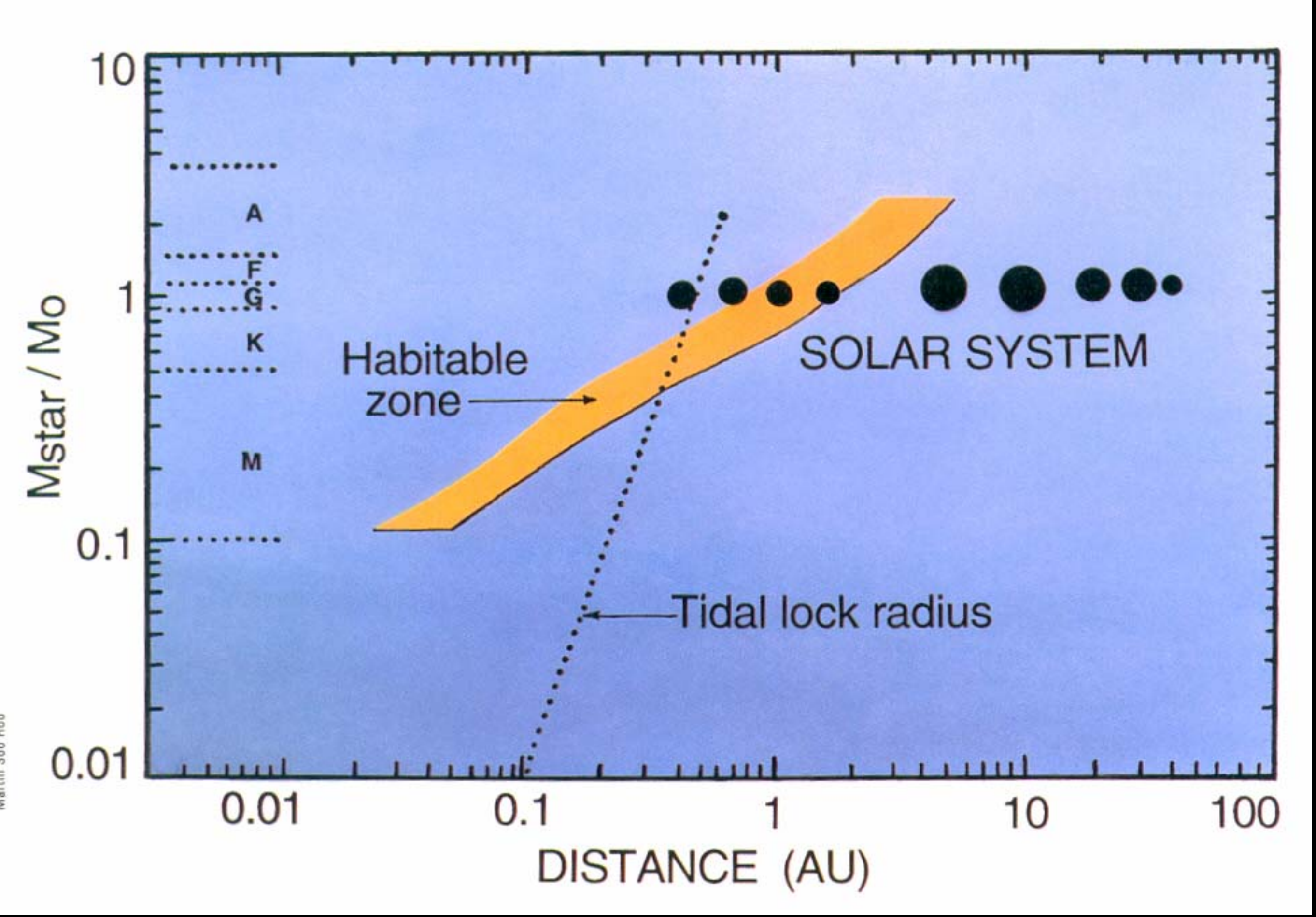
http://sos.noaa.gov/download/dataset_table.html

The (liquid water) habitable zone



- If we put all this together, we can estimate the boundaries of the *habitable zone,* where liquid water can exist on a planet's surface
- The habitable zone is relative *wide* because of the negative feedback provided by the carbonate-silicate cycle

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



ZAMS* habitable zone

*Zero age main sequence

Kasting et al., *Icarus* (1993)

- The habitable zone is considered to be reasonably wide as a consequence of stabilizing feedbacks between atmospheric CO_2 and climate
- Bad things happen, though, to planets around stars much different from the Sun
  - --F and A stars: high stellar UV fluxes, short main sequence lifetimes
  - --Late K and M stars: tidal locking, stellar flares, initial volatile inventories?

- Part 2: Can we find Earth-like planets around other stars?

Indirect detection methods

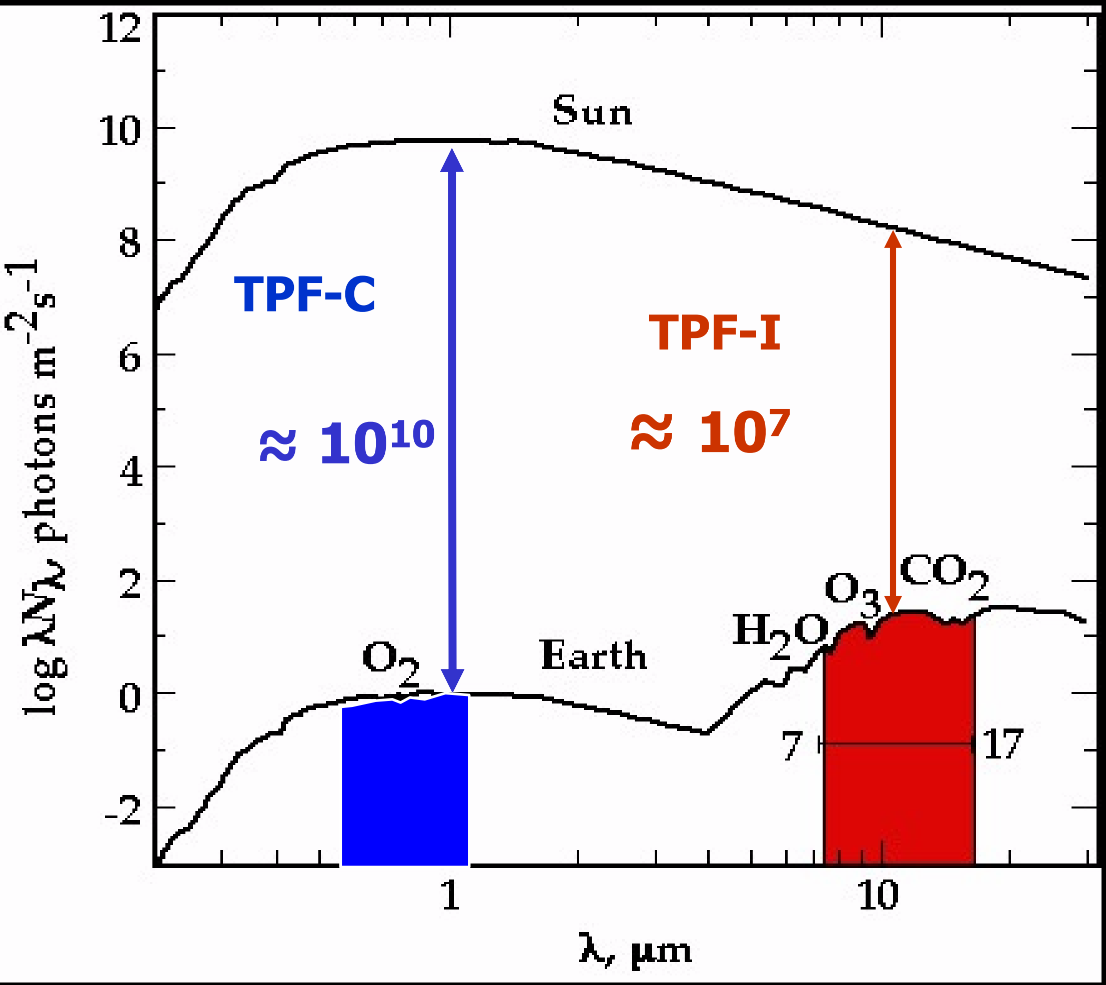
(looking for the effect of the planet on its parent star)

1. Radial velocity
2. Transits
   - Statistics on Earth-like planets from *Kepler*
   - Spectra of hot Jupiters from the *Hubble Space Telescope* and *Spitzer*
3. Gravitational microlensing
4. Astrometry

Direct imaging

- The real payoff will comes from observing Earth-like planets directly, i.e., separating their light from that of the star, and taking spectra of their atmospheres
- This will require large, space-based telescopes

Terrestrial Planet Finder (TPF)



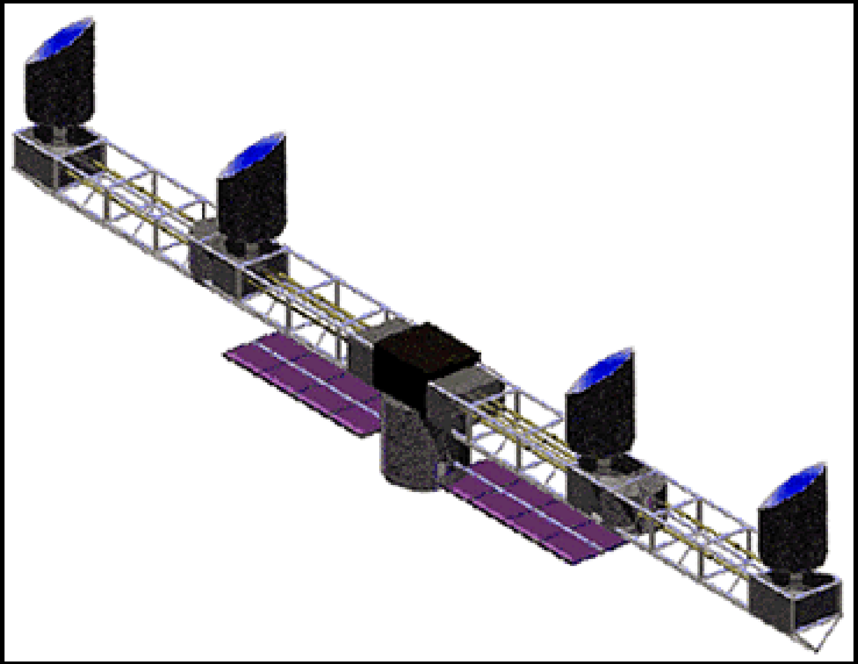
Visible or thermal-IR?

- Contrast ratio:
  10^{10} in the visible
  10^{7} in the thermal-IR
- Resolution: $\theta = \lambda/D$
- Required aperture:
  ~8 m in the visible
  80 m in the IR

Courtesy: Chas Beichman, JPL

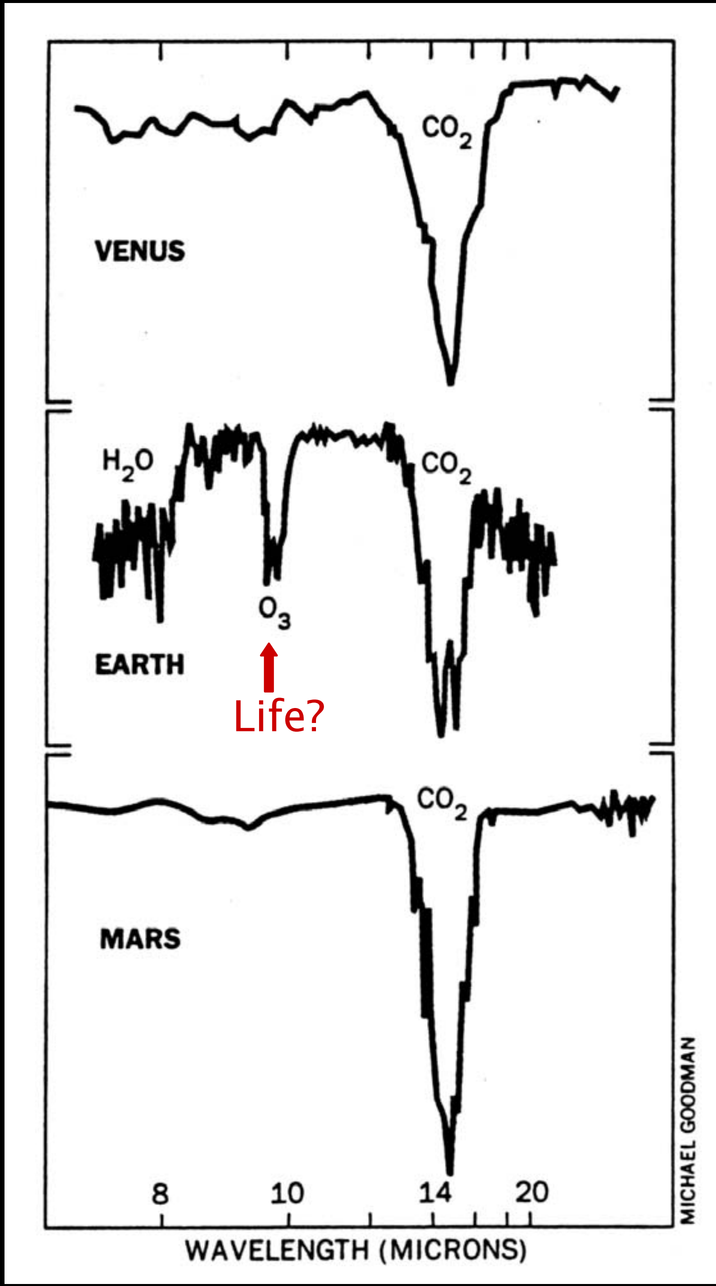
Evolution of TPF flight design concepts

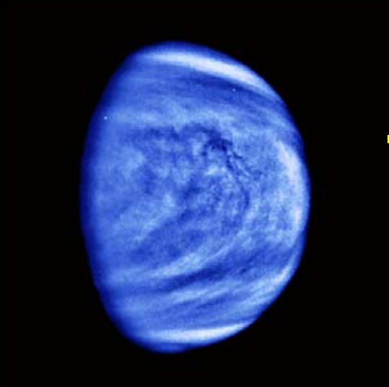
- The original idea was to fly a thermal- infrared *interferometer* on a fixed 80-m boom, similar to SIM, but bigger (and cooled)
- Disadvantages:
  - Vibrations
  - Fixed baseline



TPF-I (or Darwin): Free-flying IR interferometer

- This idea has now evolved into a free-flying interferometer, similar to ESA's proposed (but now postponed) *Darwin* mission
- Advantages: good contrast ratio, excellent spectroscopic biomarkers
- Disadvantages: needs cooled, multiple spacecraft

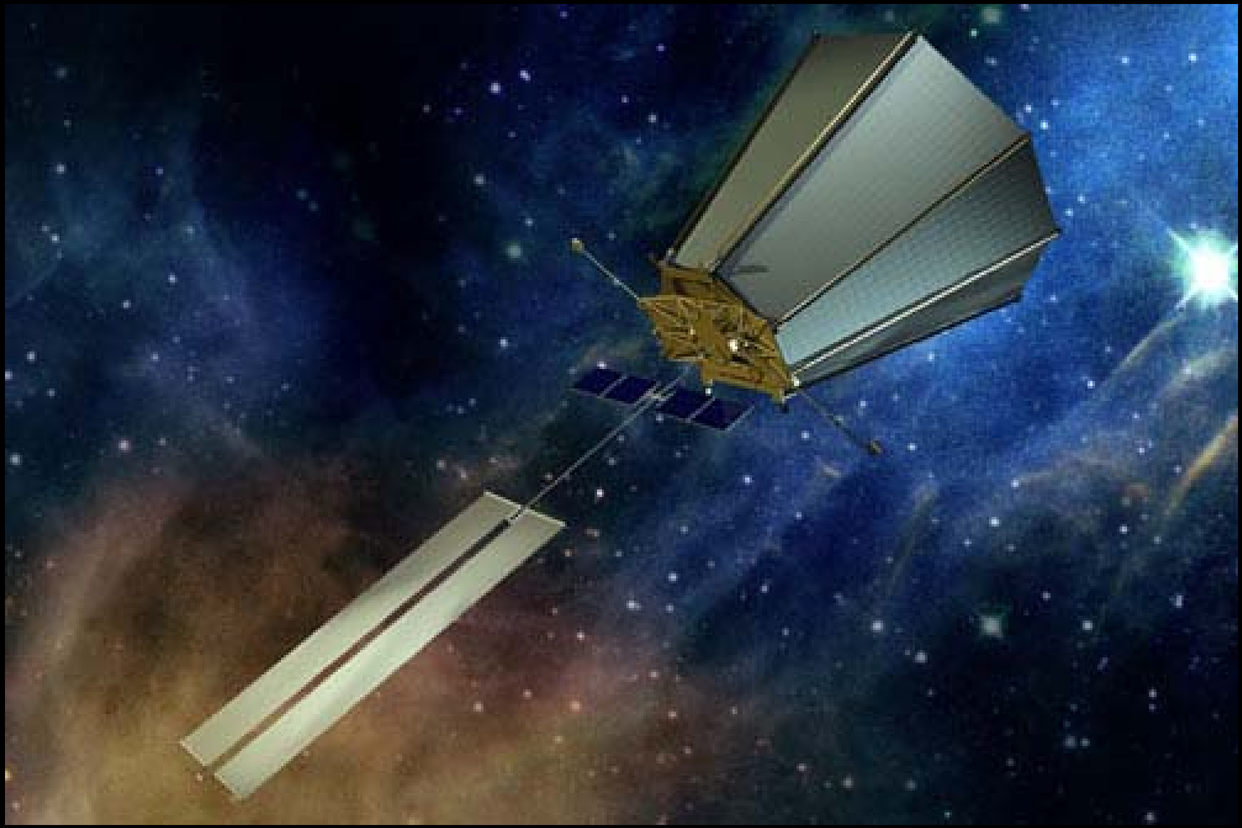




Thermal–IR spectra

Source:
R. Hanel, Goddard Space Flight Center

TPF-C: Visible/near-IR coronagraph



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

New Worlds Observer: a 2-spacecraft visible planet finder

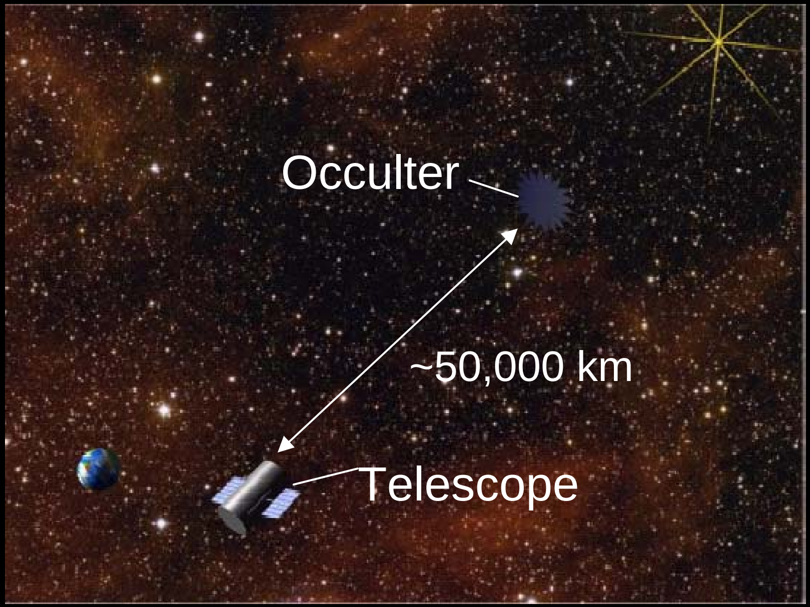
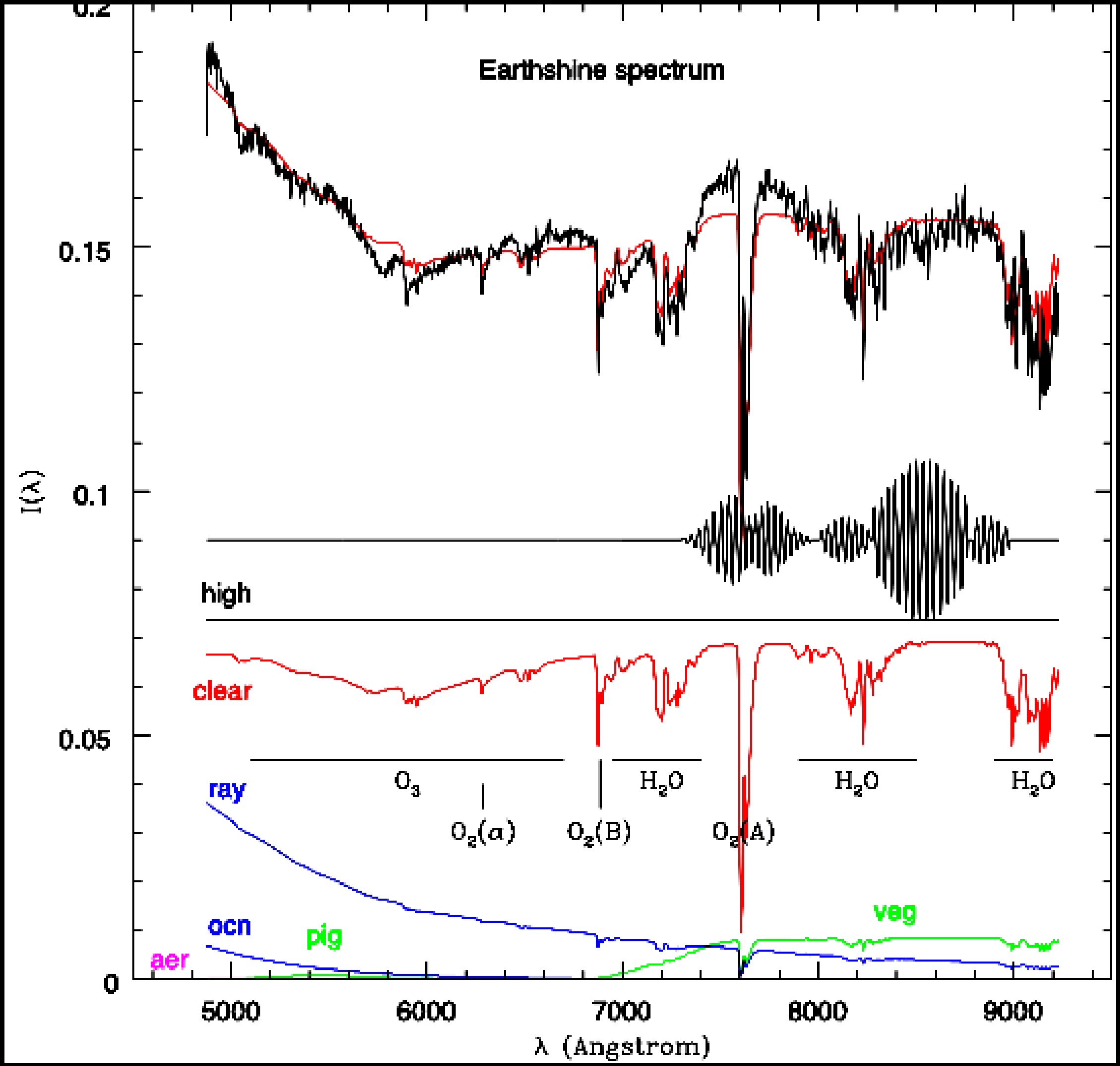
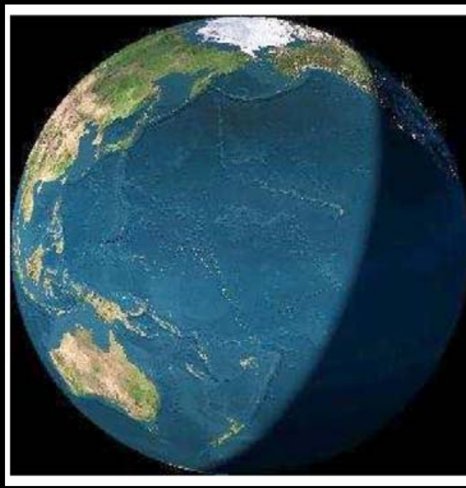


Diagram from homepage of Webster Cash, Univ. of Colorado

- One can also detect terrestrial planets in the visible by placing an *occulting disk* (or flower) between the telescope and the target
- Advantages: Excellent starlight suppression capabilities!
- Disadvantages: Pointing this array at multiple targets and maintaining precise inertial alignment over 50,000 km is time- and fuel- consuming. So, it helps to already know where the planets are located ⇒ may need SIM!

Visible spectrum of Earth



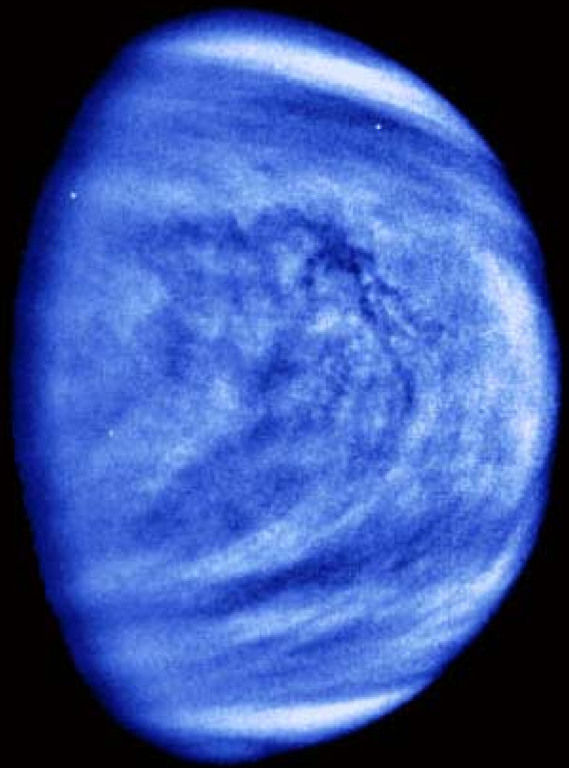


Integrated light of Earth, reflected from dark side of moon: Rayleigh scattering, chlorophyll, O_2, O_3, H_2O

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

"False positives" for life?

- One can imagine possible *"false positives"*, in which the signature of O_2 or O_3 is *not* an indication of life
- The easiest example to understand is a *runaway greenhouse* planet like early Venus. If it loses hydrogen faster than it loses oxygen, then large amounts of free O_2 might accumulate in its atmosphere



Oxygen and methane: a more robust biosignature

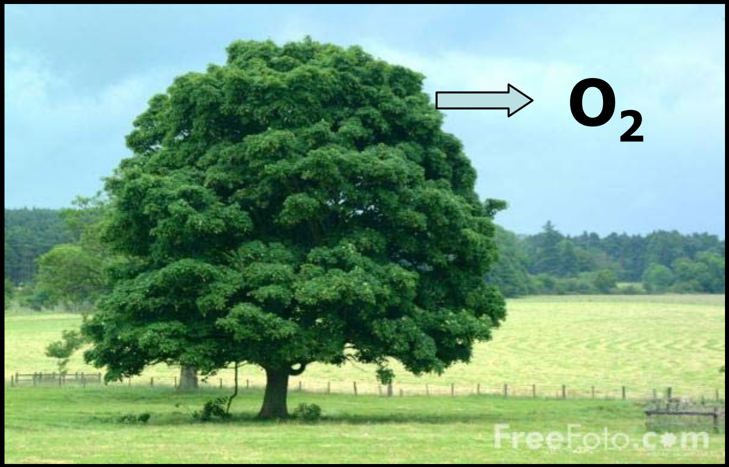
- Green plants and algae (and cyanobacteria) produce oxgyen from photosynthesis:

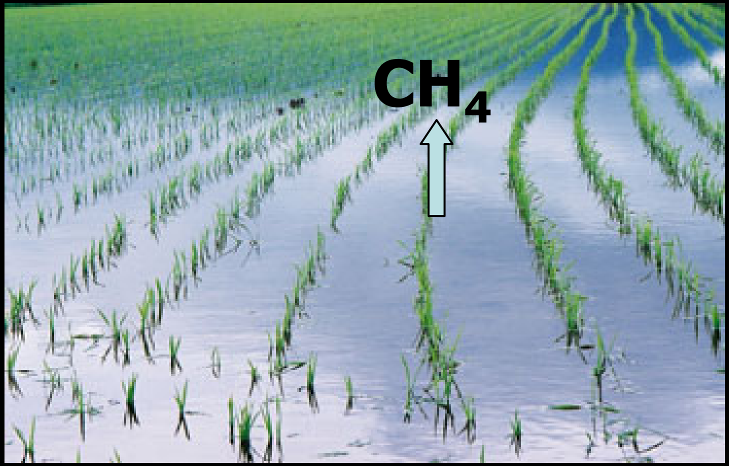
  $CO_2 + H_2O \rightarrow CH_2O + O_2$

- 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*





*As first pointed out by James Lovelock

NATURE · VOL 365 · 21 OCTOBER 1993

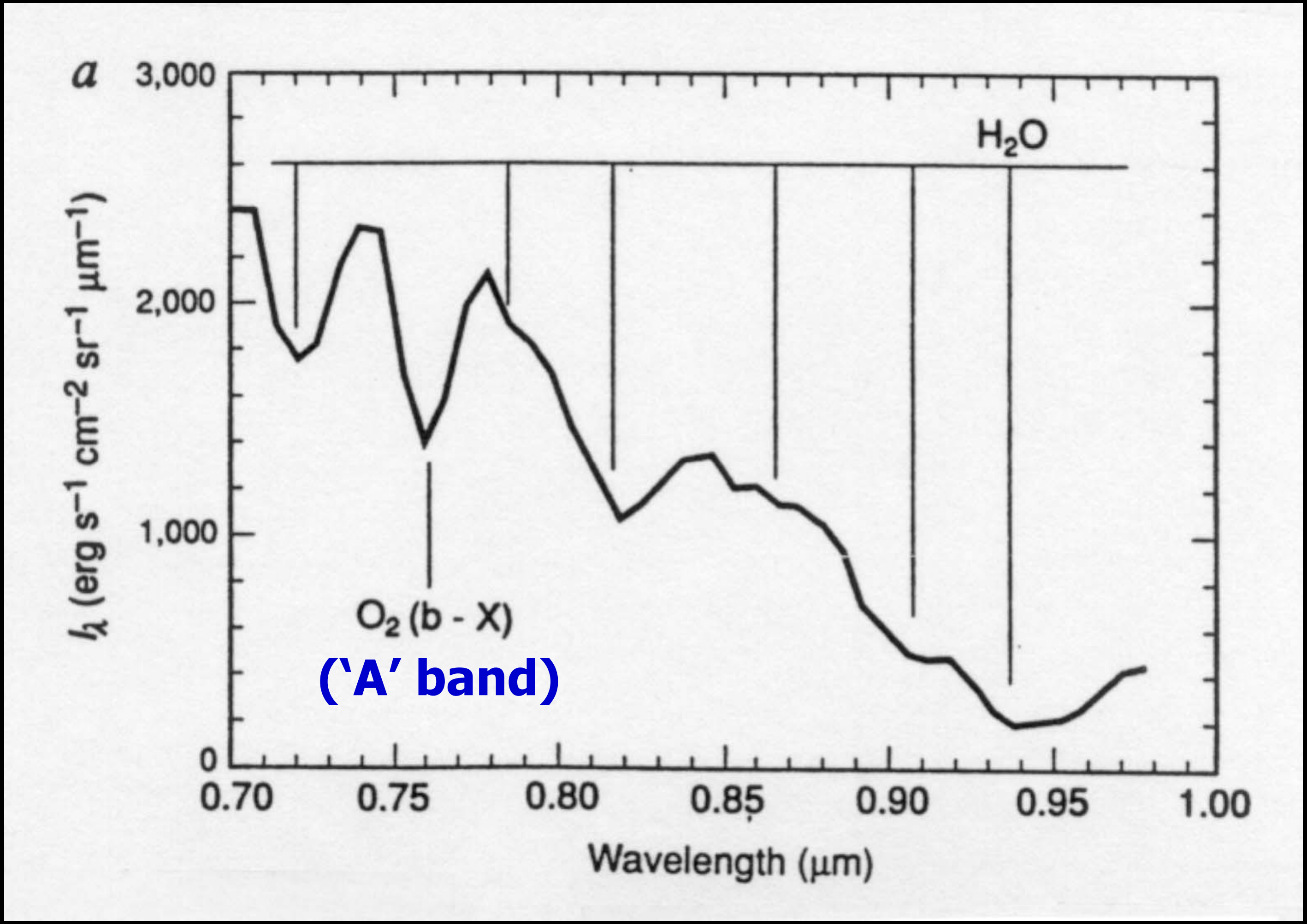
A search for life on Earth from the Galileo spacecraft

Carl Sagan*, W. Reid Thompson*, Robert Carlson†, Donald Gurnett‡ & Charles Hord§

* Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853, USA
† Atmospheric and Cometary Sciences Section, Jet Propulsion Laboratory, Pasadena, California 91109, USA
‡ Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242-1479, USA
§ Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80309, USA

In its December 1990 fly-by of Earth, the Galileo spacecraft found evidence of abundant gaseous oxygen, a widely distributed surface pigment with a sharp absorption edge in the red part of the visible spectrum, and atmospheric methane in extreme thermodynamic disequilibrium; together, these are strongly suggestive of life on Earth. Moreover, the presence of narrow-band, pulsed, amplitude-modulated radio transmission seems uniquely attributable to intelligence. These observations constitute a control experiment for the search for extraterrestrial life by modern interplanetary spacecraft.

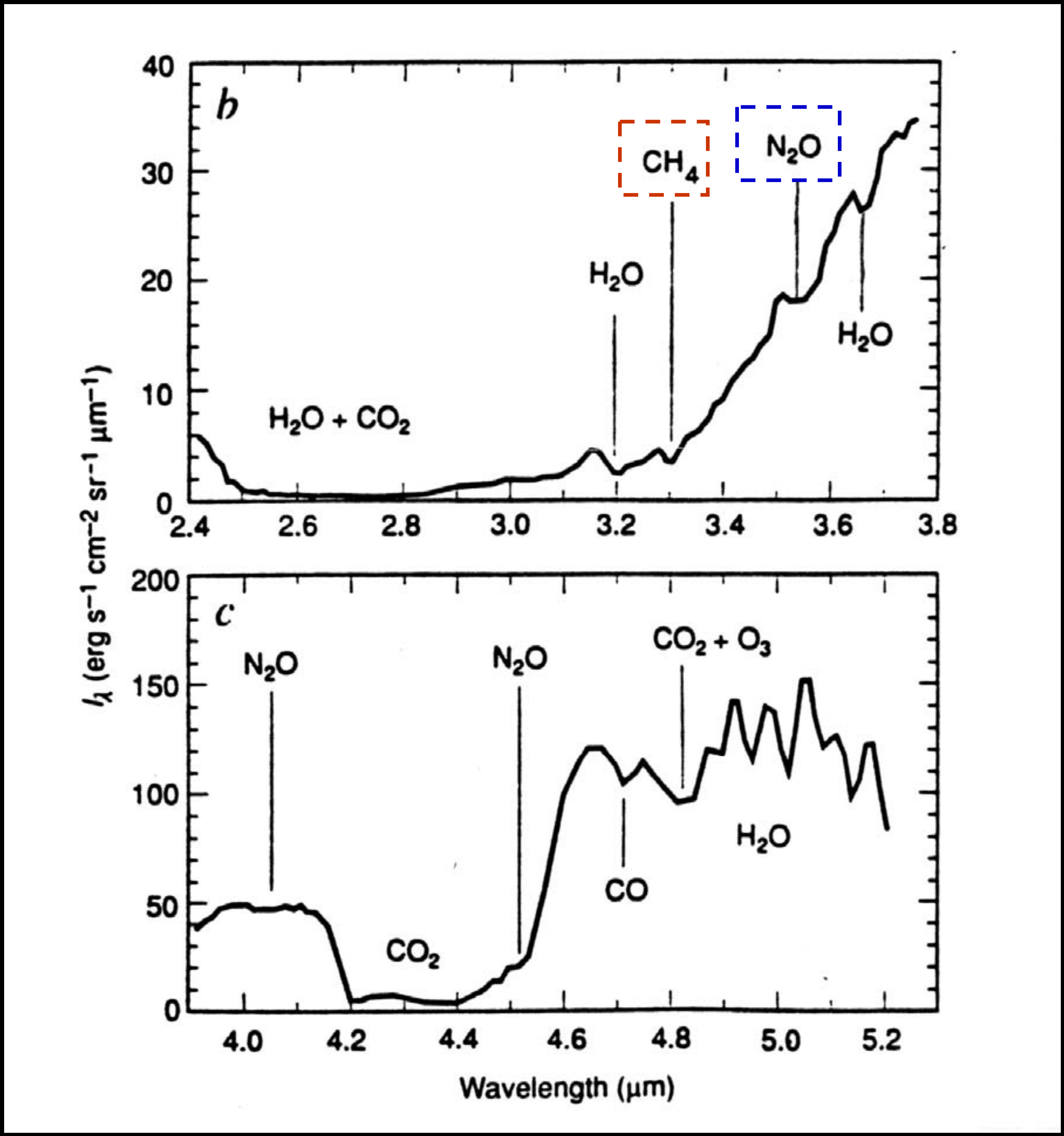
NIMS Data (from Galileo)



Sagan et al. (1993)*

*But credit Toby Owen for pointing this out (1980)

NIMS data in the near-IR



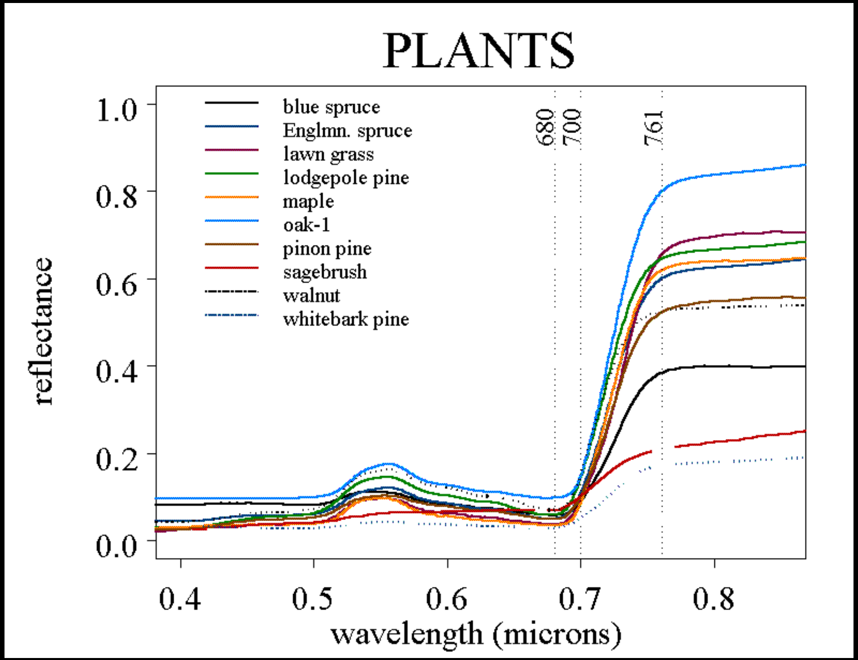
Sagan et al. (1993)*

- Simultaneous presence of O_2 and a reduced gas (CH_4 or N_2O) is the best evidence for life

*Credit Joshua Lederburg and James Lovelock for the idea (1964)

The "red edge" of chlorophyll

- Another potential biosignature is the so-called *"red edge"* of chlorophyll
- Plants (including algae) *absorb* sunlight below 0.7 µm (700 nm) and *reflect* it above that wavelength
- Seeing this in a planet's spectrum is difficult, however, because the signal is muted in the oceans



N. Kiang et al., Astrobiology (2007)

Galileo spectral imaging of Earth

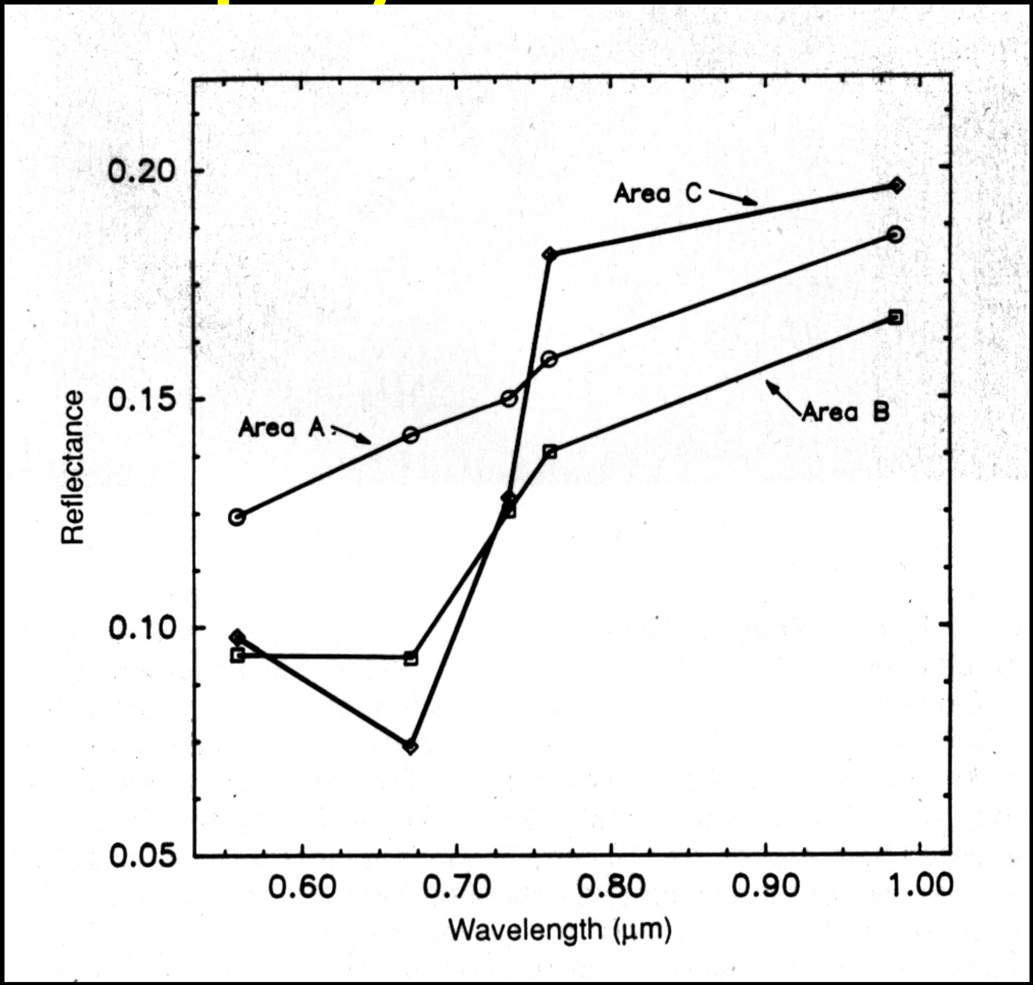
'True' color
(red, green, violet)

Longer wavelengths
(red, green, 1 μm)

Sagan et al. (1993)

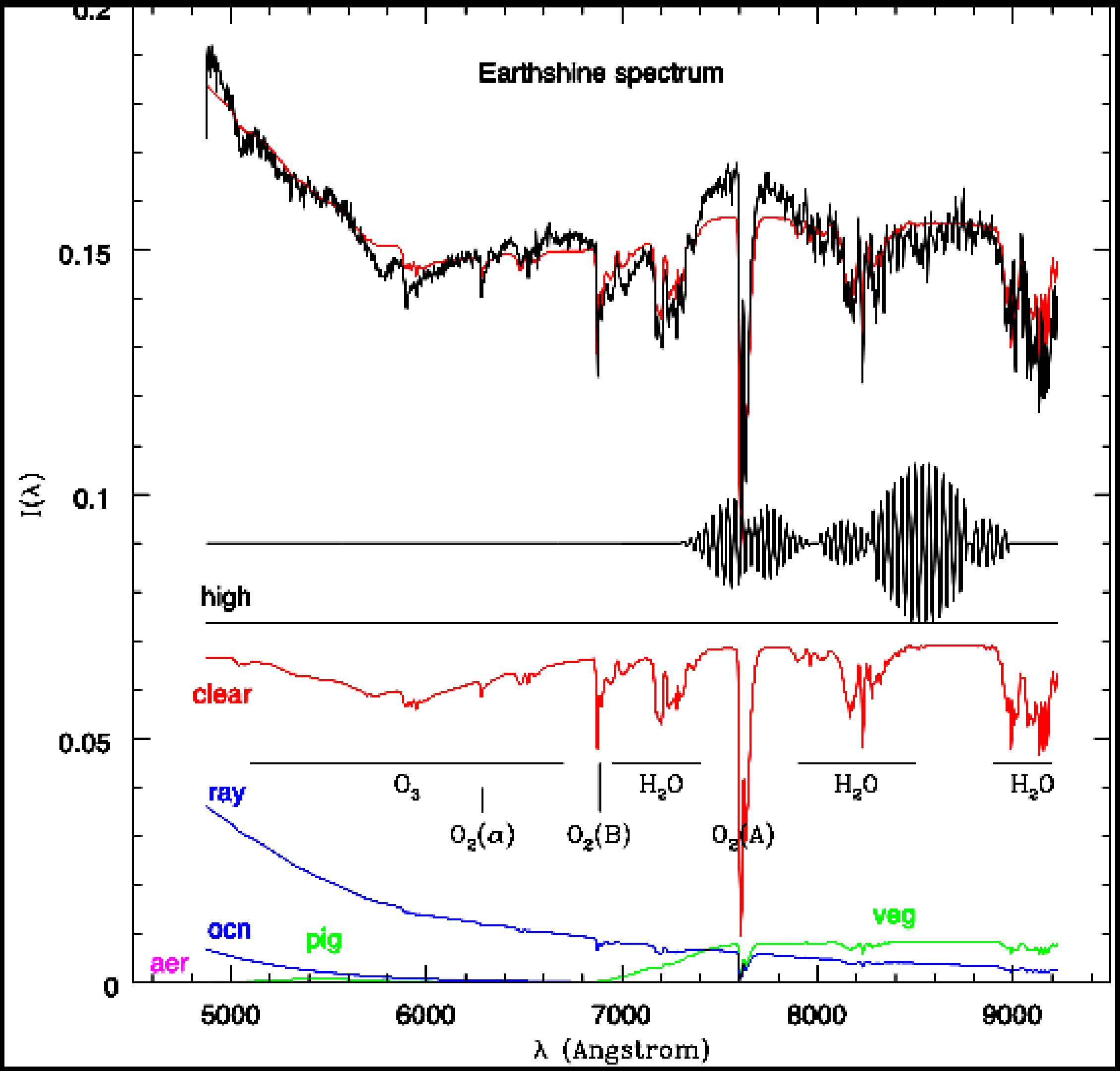
The 'red edge' of chlorophyll

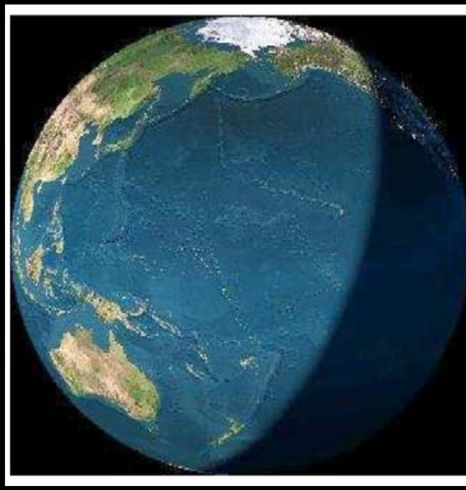
Spectral bands centered on the 'red edge'



Sagan et al. (1993)

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

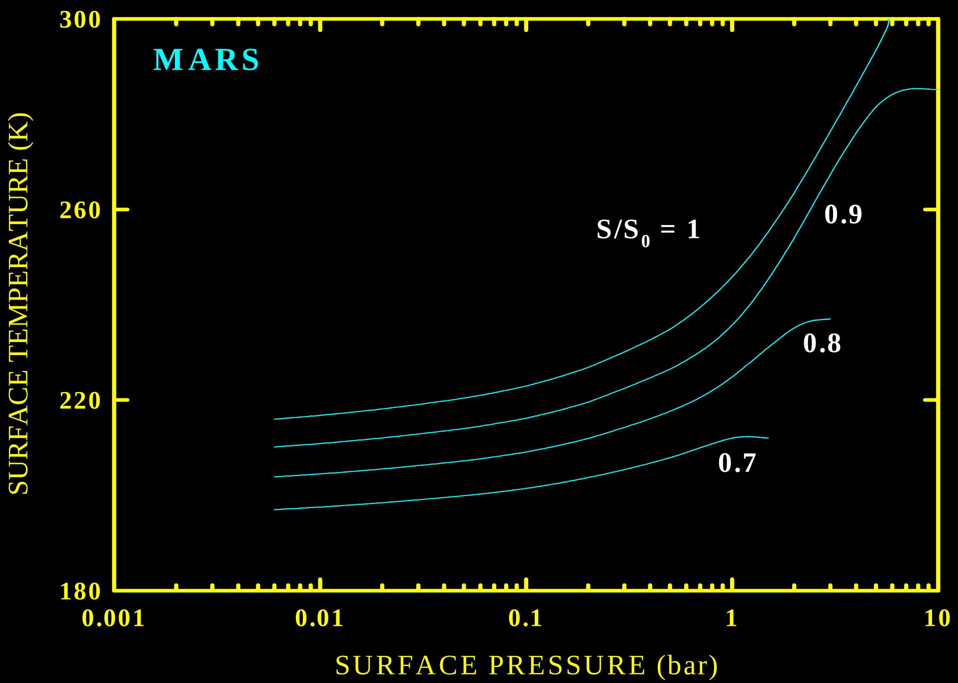
Conclusions

- Earth-like planets *may* be common
  - We'll hopefully find out from Kepler
- Habitable zones around F, G, and early K stars are relatively wide
- Space-based *astrometry* (*e.g.*, SIM) could help us find out where Earth-sized planets are located
- *Direct imaging* of planets in either the visible or thermal-IR could find interesting biomarkers
- NASA should commit to flying *all* of these missions over the next 10–25 years

- Backup slides

Mars' climate evolution

- What about Mars? Why doesn't the same logic apply here?
- Mars could be habitable today if it had enough CO_2 in its atmosphere
- Ancient Mars is difficult to keep warm with just CO_2 and H_2O as greenhouse gases

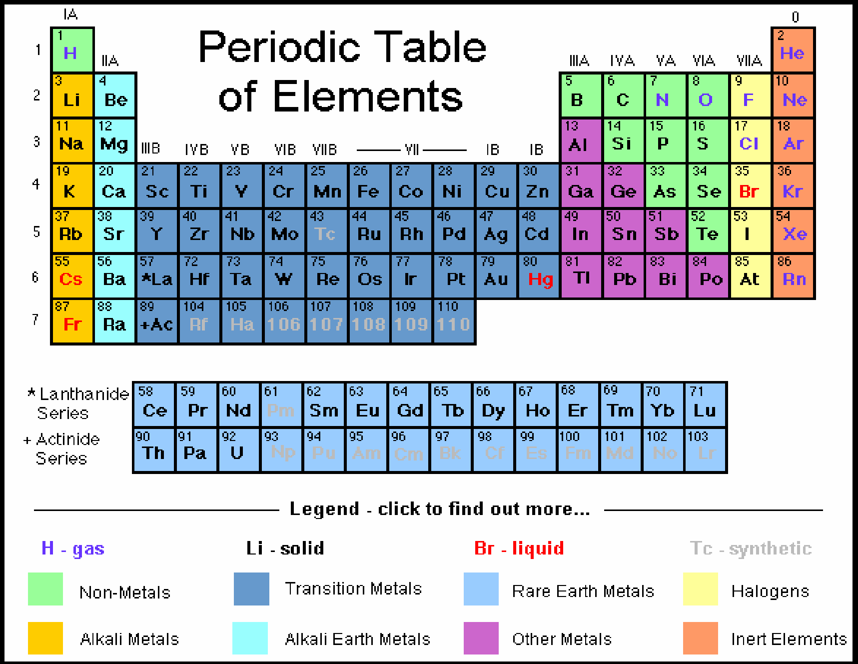


J. F. Kasting, *Icarus* (1991)

Chemistry is the same everywhere

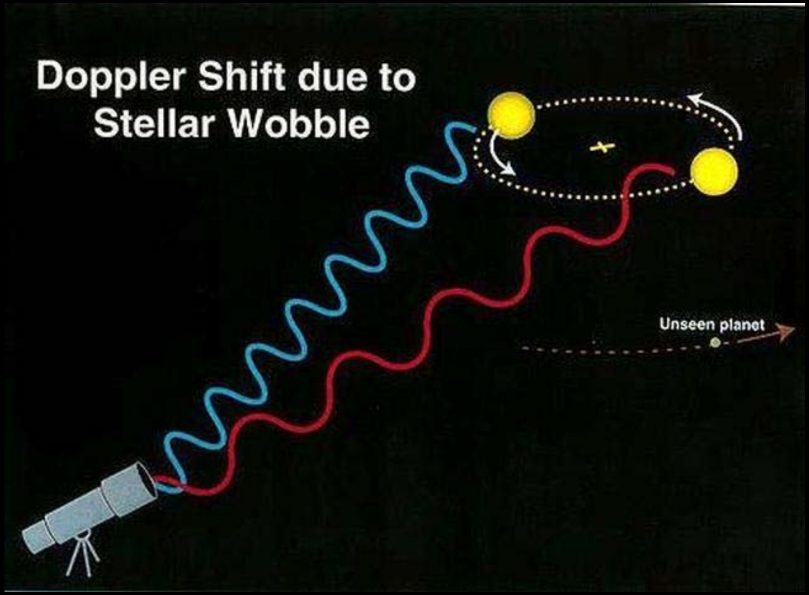
- The same *elements* are observed on Earth, in the Sun, and in stars
- Different chemical reactions can yield energy for metabolism, *e.g.*

  $SO_4^{=} + 4\ H_2 \rightarrow$
  $S^{=} + 4\ H_2O$
  (sulfate reduction)
- These same reactions should yield the same energy *anywhere*, given similar chemical abundances

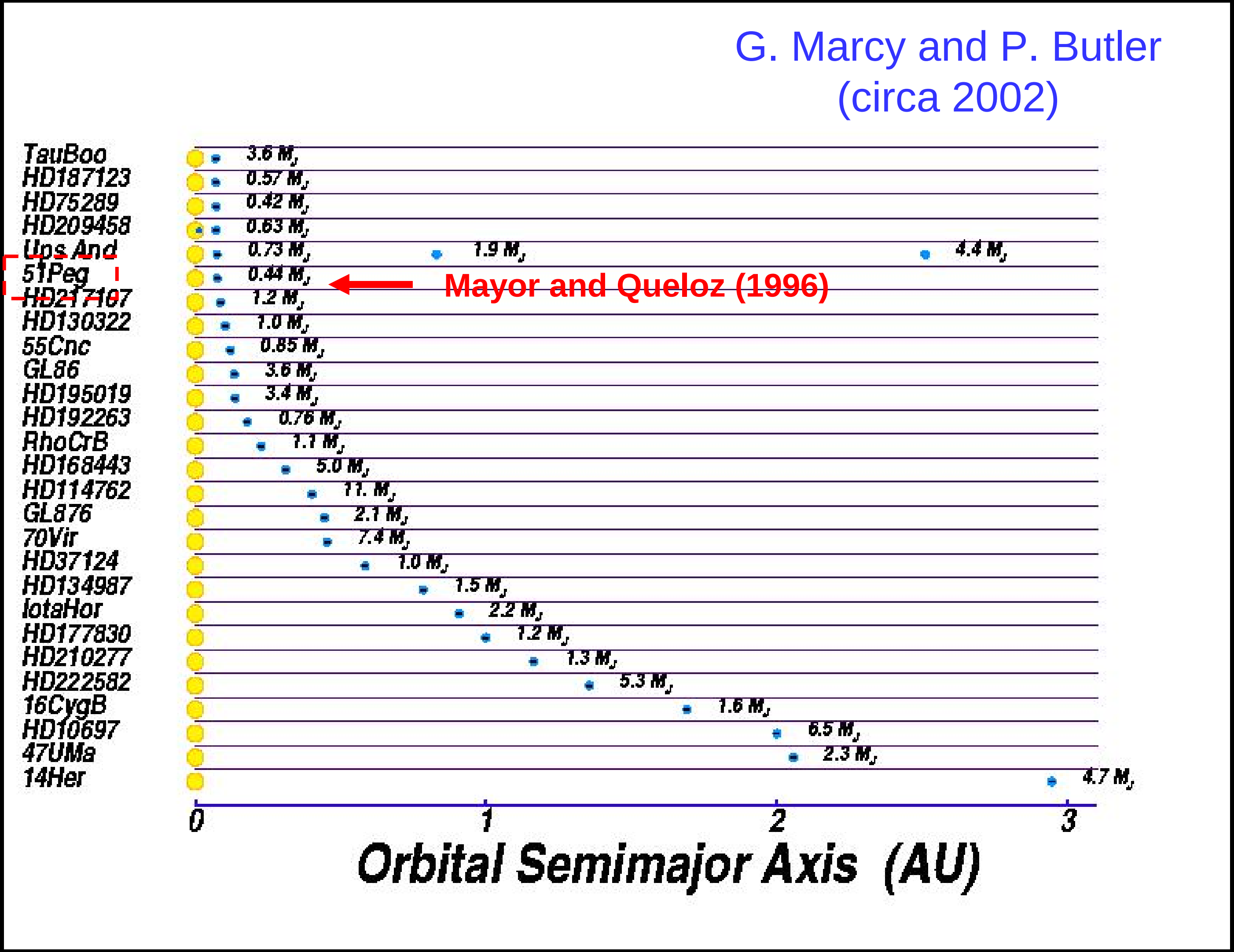


Radial velocity (Doppler) method

- Many extrasolar planets (over 400) have been detected already, most by using the *radial velocity,* or Doppler, method
- None of these planets are as small as Earth, however

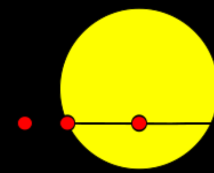


"Hot Jupiters"



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



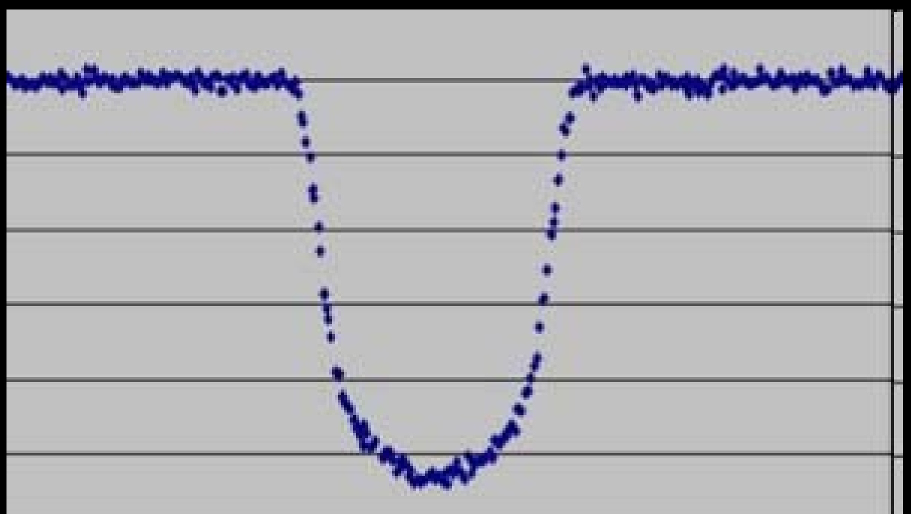
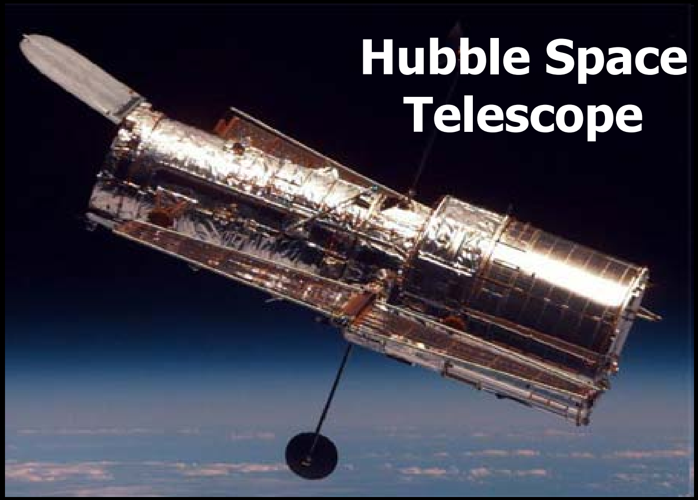
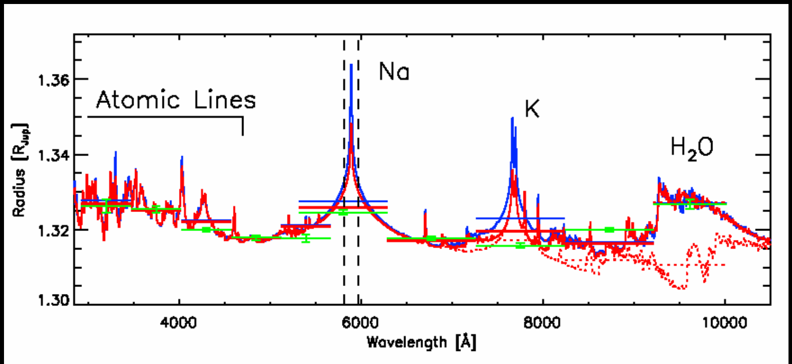


Image from Wikipedia

Transit spectroscopy

- *Visible spectra* of HD209458b taken from the Hubble Space Telescope show the presence of sodium (Na), potassium (K), and water (H_2O) in the planet's atmosphere
- *Infrared spectra* from the Spitzer Space Telescope have also been used for this purpose
- So far, we have been looking strictly at hot Jupiters



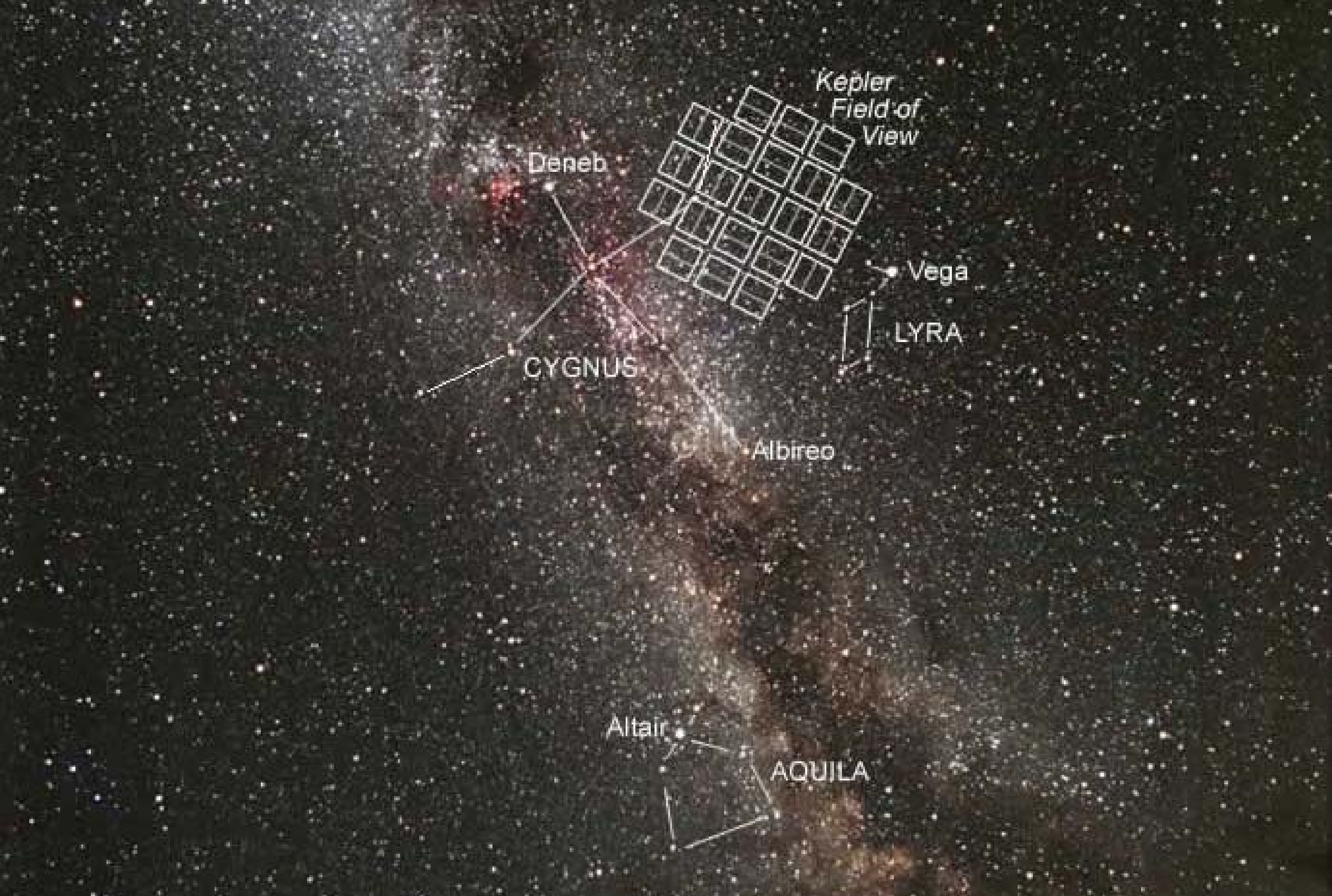


T. Barman, Ap.J. Lett. (2007)

Kepler Mission

- This space-based telescope will point at a patch of the Milky Way and monitor the brightness of ~100,000 stars, looking for transits of Earth-sized (and other) planets
- 10^{-5} precision *photometry*
- 0.95-m aperture ⇒ capable of detecting Earths
- Launch: March 5, 2009

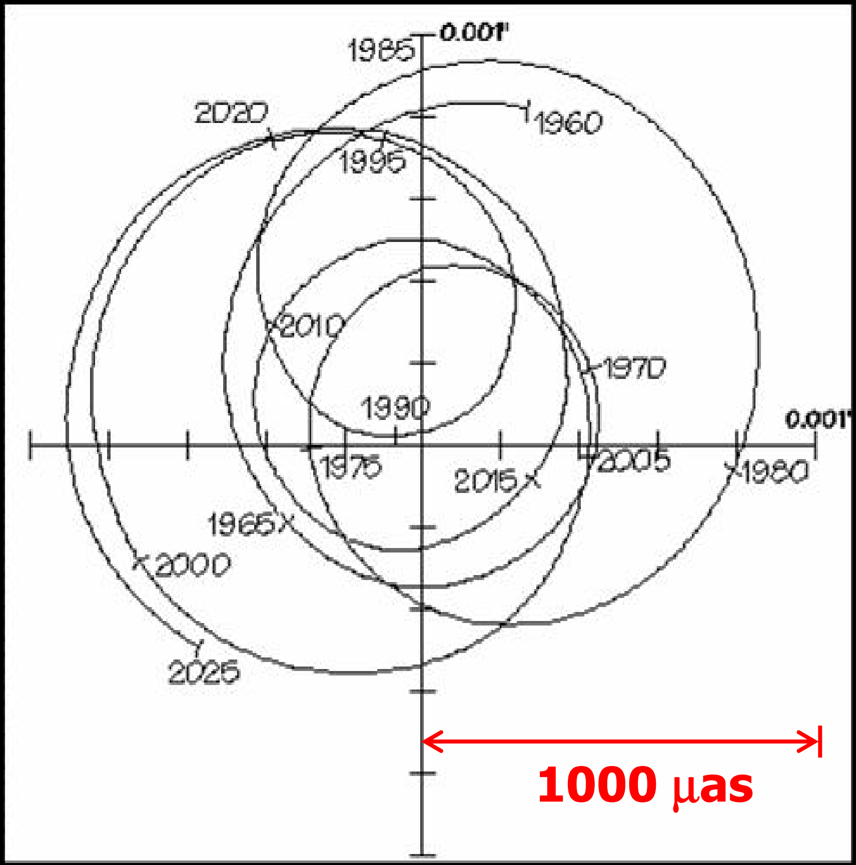
http://www.nmm.ac.uk/uploads/jpg/kepler.jpg



- Even if it works perfectly, Kepler will only find distant Earths
- We'd like to find the ones nearby…

Astrometric method

- Calculated motion of the Sun from 1960 to 2025, as viewed from a distance of 10 pc, or about 32 light years
- Scale is in arcseconds
- You get the *actual mass* of the planet because the plane of the planet's orbit can be determined
- Can do astrometry from the ground, but the best place to do it is in space ⇒



http://planetquest.jpl.nasa.gov/Navigator/material/sim_material.cfm

SIM – Space Interferometry Mission

- Narrow-angle astrometry: 1 μas precision on bright targets*
- Could be used to identify Earth-mass (or slightly larger) planets around a significant number of nearby stars
- Much of the required development work has already been done

http://planetquest.jpl.nasa.gov/SIM/sim_index.cfm

*Ref: Unwin et al., *PASP* (Jan., 2008)