Direct Detection of Exoplanets

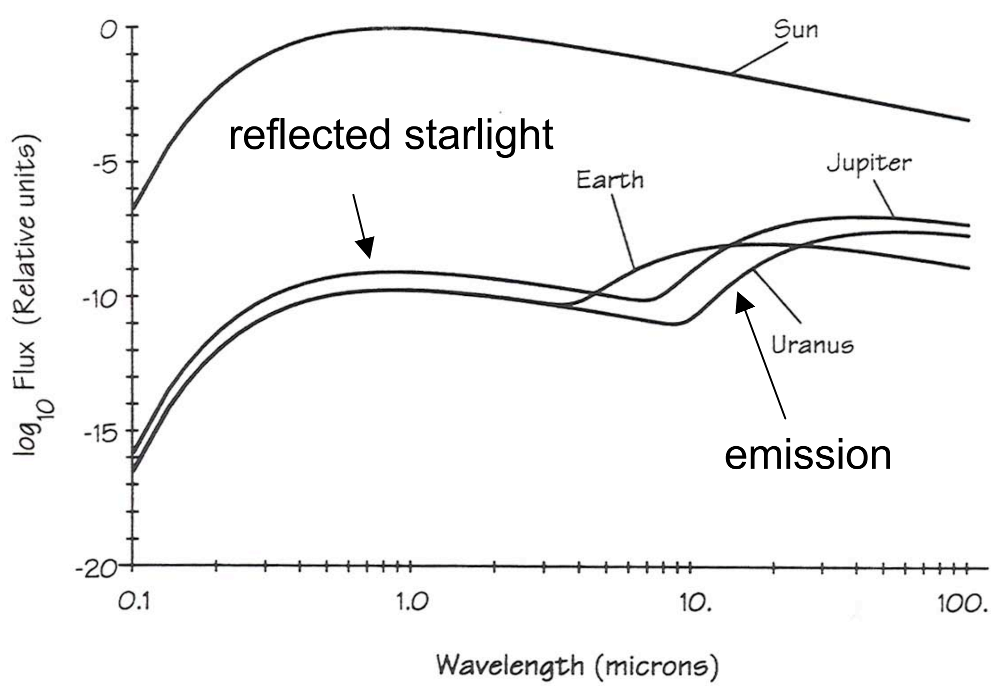
Direct detection = producing an actual image of the object, not indirect detection through its influence on its parent star. The basic problems:

1. Star's light drowns out planet's reflected+ emitted light by many orders of magnitude. How to eliminate the star's contribution?
2. If you are to see the planet, you have to have sufficient *angular resolution* to separate the planet from the star. Otherwise your "image" will be a fuzzy blob. This problem is more severe for detection of habitable zone terrestrial-like planets, because they are close to their parent stars.

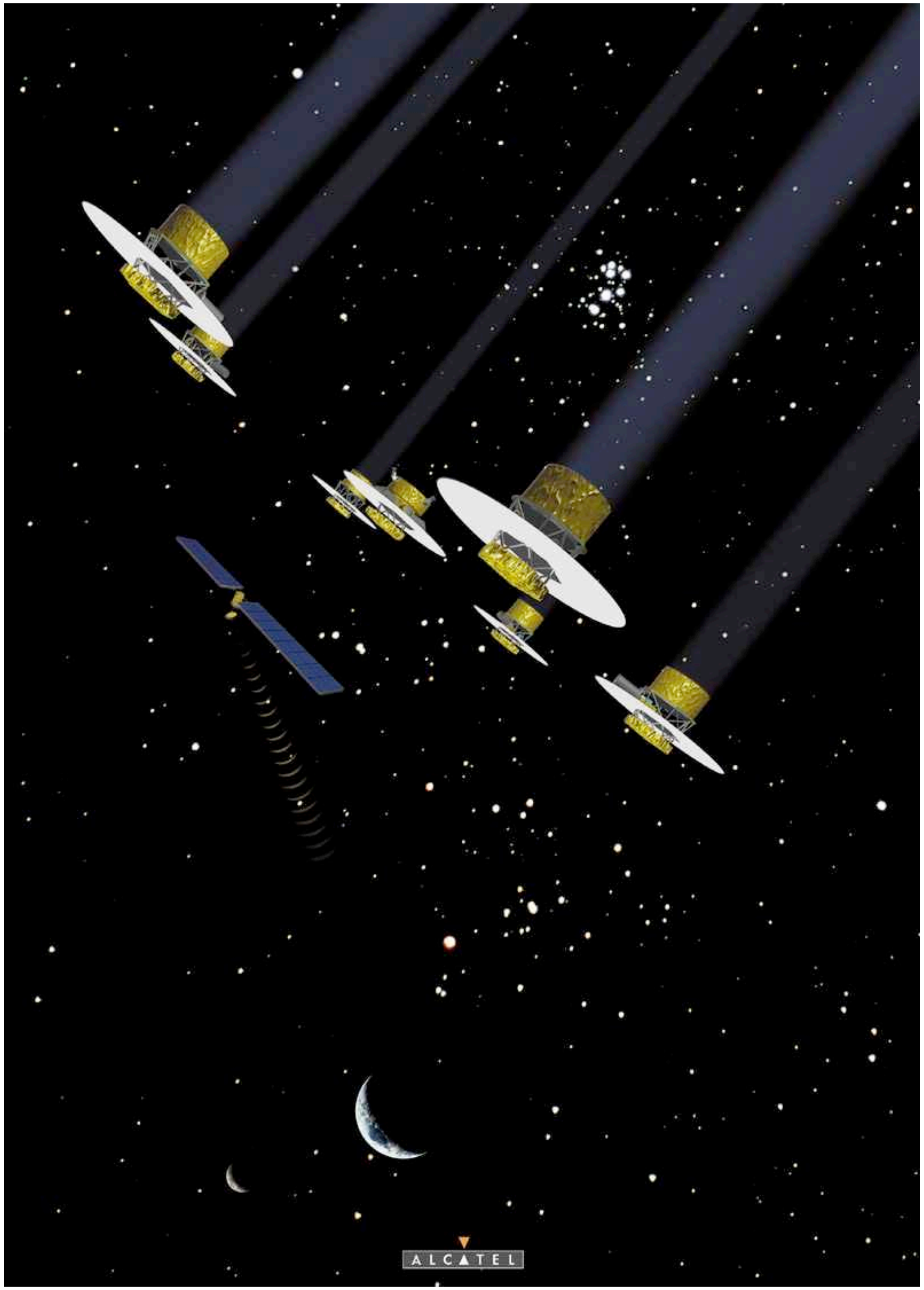
We should not expect to resolve *the planet itself* (e.g. seeing oceans and continents), only the planet and the star. Once we have that, what we want is a *spectrum* of the planet in order to search for potential *spectral biosignatures.*

Direct detection: Overwhelmed by starlight

The illustration below shows the spectrum of the Sun and a few planets as they would appear from several light years away. Notice that the Sun's light completely "drowns out" the light from the planets. This is the major reason why ***direct detection*** (seeing the planet itself) is too difficult for now, except perhaps for giant planets. But direct detection remains the long-term goal.



The spectral energy distributions of the Sun, Jupiter, Earth, and Uranus as they would appear at 5 pc, averaged over a 10% spectral bandpass. Note the decreased ratio of solar to planetary flux in the thermal infrared, compared to visible wavelengths.



Direct detection: TPF/Darwin

Direct detection of terrestrial-like planets.

Recall that major problems are

1. Seeing the reflected light or infrared emission from the planet in the glare of the star, and
2. Resolution: the angular separation of the star-planet will be extremely small (tiny fraction of arcsecond).

So need a very large telescope in space:

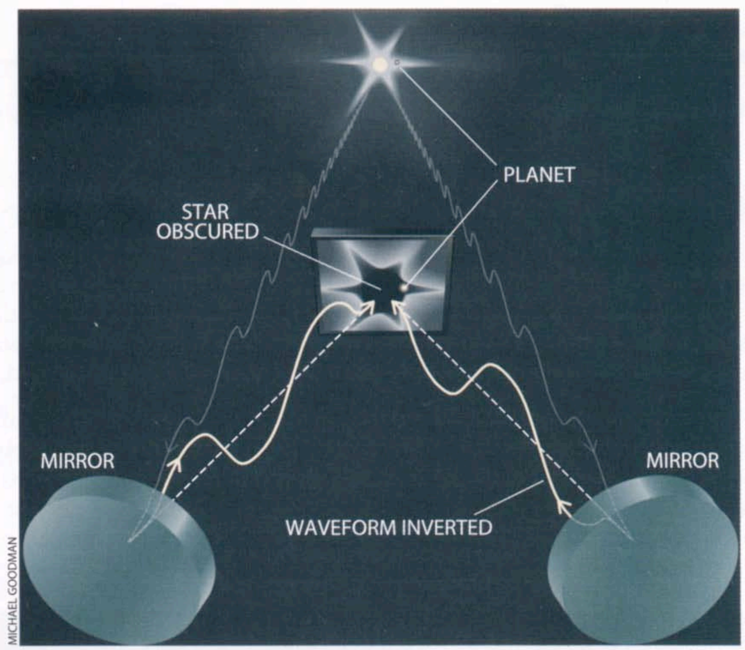
Terrestrial Planet Finder/Darwin (artist conception shown to left)

How will TPF block the starlight?

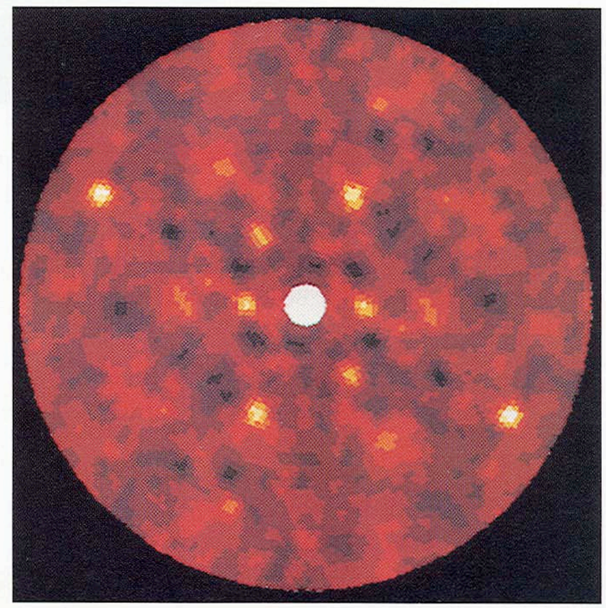
What wavelength region(s) will be used and why?

Blocking or canceling the starlight

Nulling ***interferometer*** (left) and simulated detection of terrestrial-mass planets by TPF (right).
Interferometer makes double images of each planet on opposite sides, canceling the starlight.
There are several other designs for interferometers as well as ***coronagraphs*** *(blocks the star).*
This tells us the planets are there, but what we *really* want is the **spectra** of Earth-like exoplanets.



CANCELING STARLIGHT enables astronomers to see dim planets typically obscured by stellar radiance. Two telescopes focused on the same star (*top*) can cancel out much of its light: one telescope inverts the light—making peaks into troughs and vice versa (*right*). When the inverted light is combined with the noninverted starlight from the second telescope (*left*), the light waves interfere with one another, and the image of the star then vanishes (*center*).



A computer simulation of Earth-like planets around another star, as imaged by a set of telescopes in space. The instrument would work at 10 microns in the infrared, where the contrast of a planet with respect to the nearby star is favorable. Light from the separate telescopes is combined so as to efficiently blank out the central star; this process leads to two image of each planet, on opposite sides of the star. (SOURCE: Courtesy J. R. P. Angel and N. Woolf.)

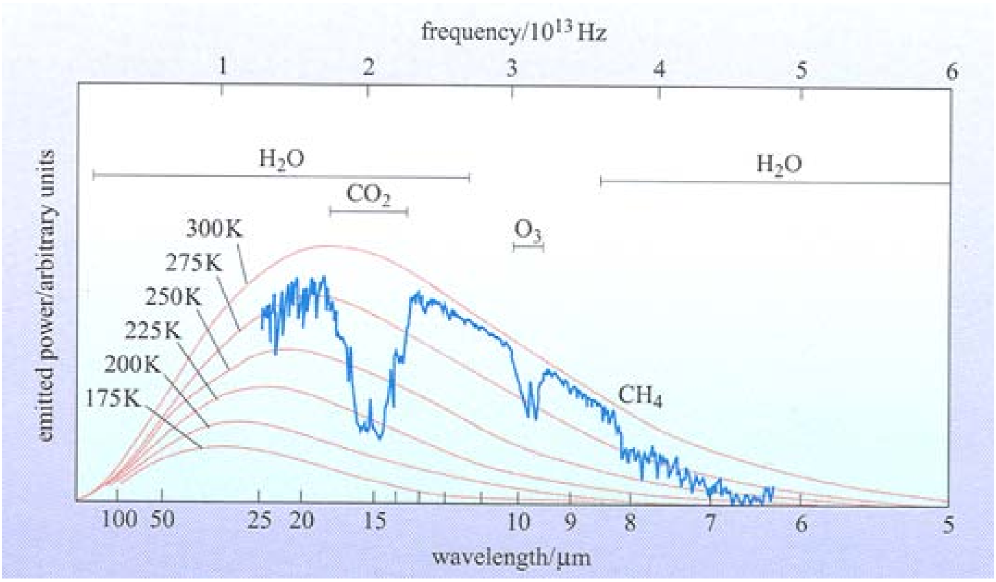
Spectral biomarkers

Even if we can image an Earth-like planet in the habitable zone of some star, we will not be able to resolve its surface features in the foreseeable future. (No "zooming in" to see oceans, forests, city lights… Later we'll see how you *can* detect some of these through *reflected light*.)
Instead, we must infer presence of life from a *spectrum* of the planet's atmosphere.

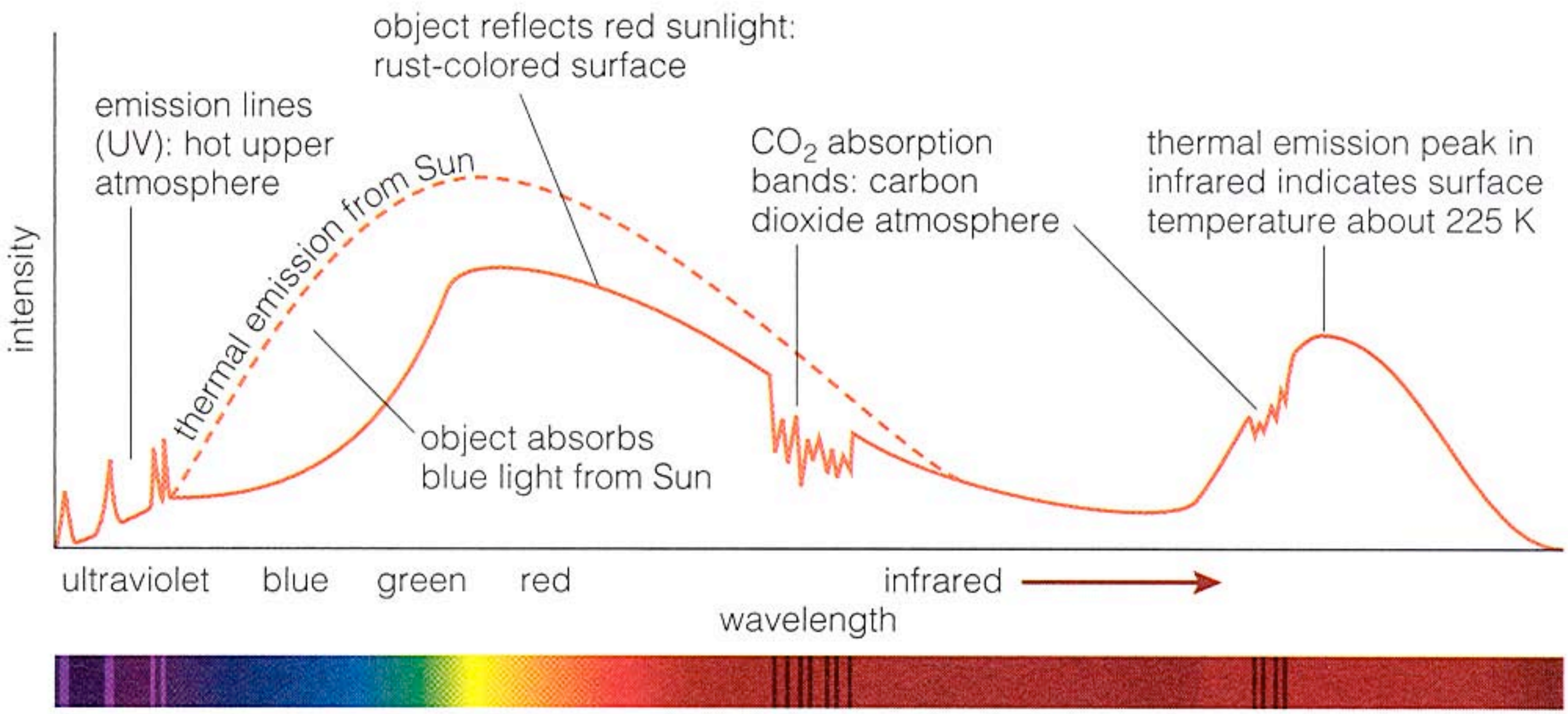
Planet's spectrum?? Planet's surface is emitting continuous radiation peaking in the infrared. This radiation must pass through the atmosphere, where there are molecules that absorb infrared radiation in broad *bands*, the molecular equivalent of spectral lines.

What we see is then the planet's continuous thermal emission (red curves below) with deep absorption bands (blue lines below) that can be identified with particular molecules.

This is the absorption spectrum of the atmosphere, but we can also learn a lot from the *reflection spectrum* of the planet's surface. (Next slide)



How the *reflection* (in visual) and *emission* (in infrared) spectrum tell you about the nature of the planet



(You can probably guess what planet this is…)

Infrared spectra of Venus, Earth, and Mars

(Figure in textbook).

*Notice features of **ozone** and water vapor for Earth*

Why does ozone distinguish Earth from Venus and Mars, and mark Earth as (probably) inhabited?

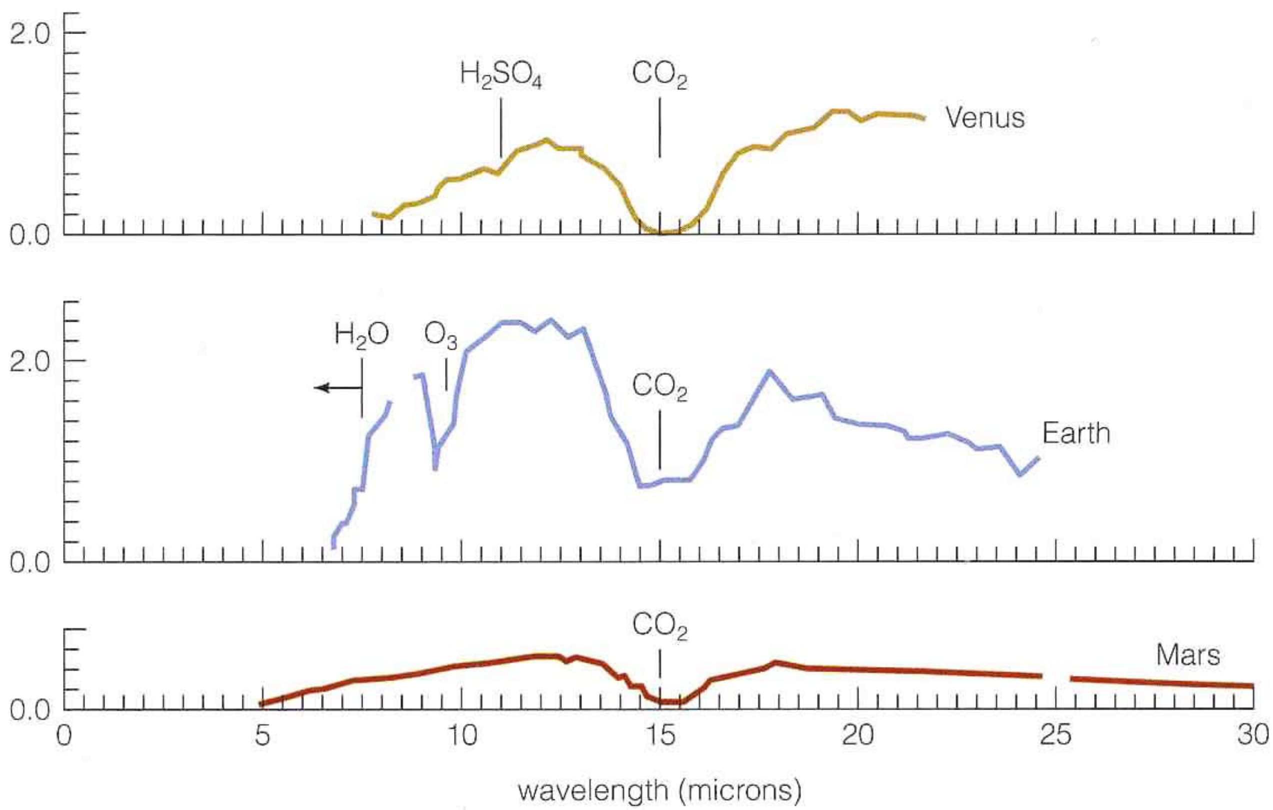


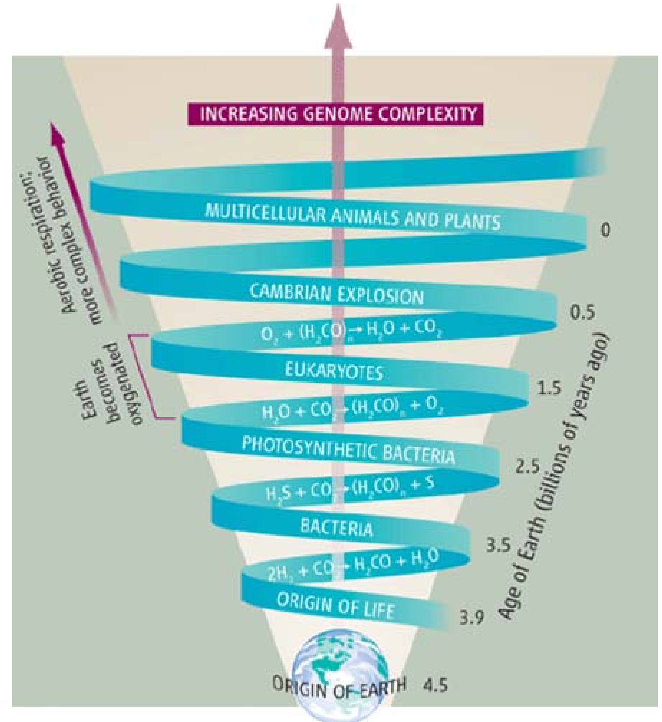
FIGURE 10.16 The infrared spectra of Venus, Earth, and Mars, as they might be seen from afar, showing absorption features that point to the presence of carbon dioxide (CO_2), ozone (O_3), and sulfuric acid (H_2SO_4) in their atmospheres. While carbon dioxide is present in all three spectra, only our own planet has appreciable oxygen (and hence ozone)—a product of photosynthesis. If we could make similar spectral analyses of distant planets, we might possibly detect atmospheric gases that would indicate life.

Briefly: Rise of oxygen and ozone on Earth

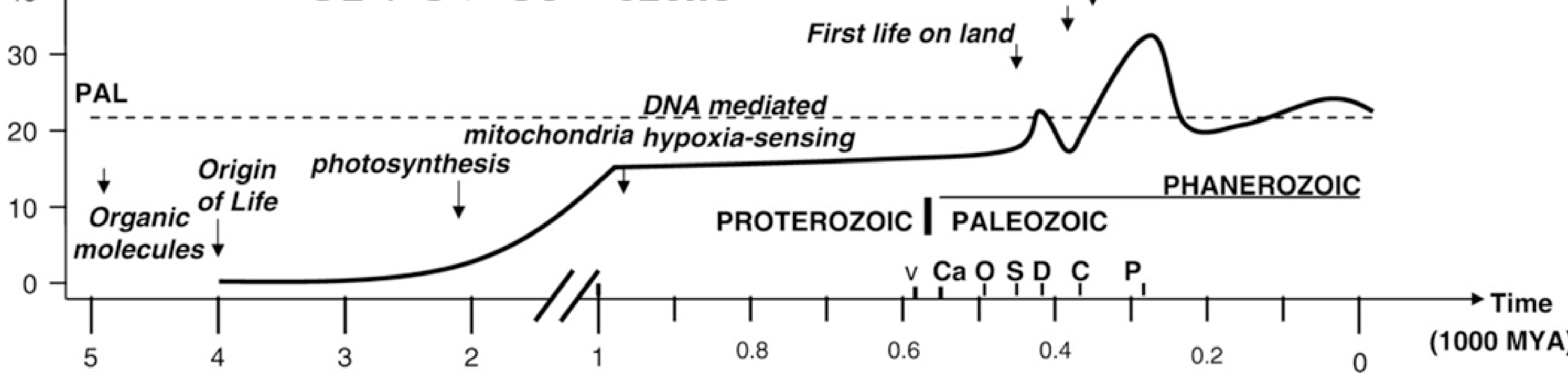
No way to get significant oxygen without photosynthesis. Even a little oxygen produces strong ozone band in the infrared (and ozone shield for protection of organisms).

This apparently began about 2-3 Gyr ago on Earth. The continued increase to present oxygen levels (and larger--see figure) is associated with specific increases in complexity (see "spiral" illustration to right; we'll cover this in detail in Part IV).

For this reason it is believed that ozone is a spectral biomarker for exoplanetary photosynthesis.

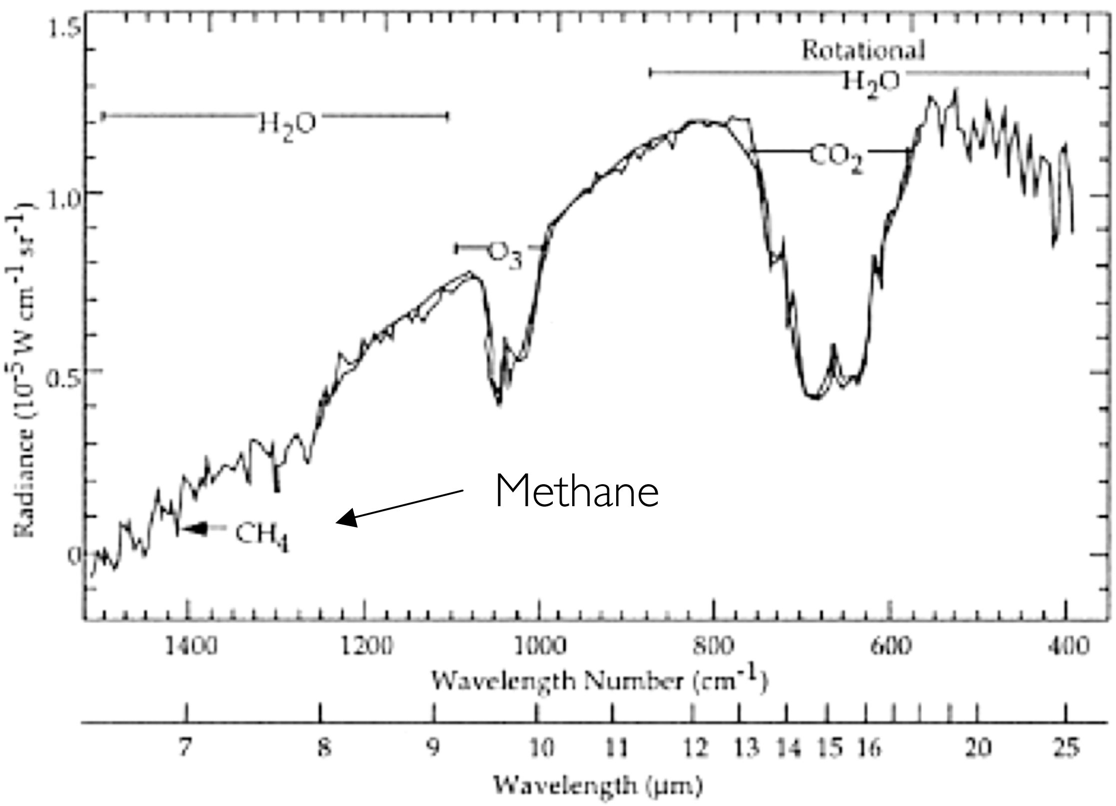


O2 + UV photon > O + O
O2 + O > O3 = ozone



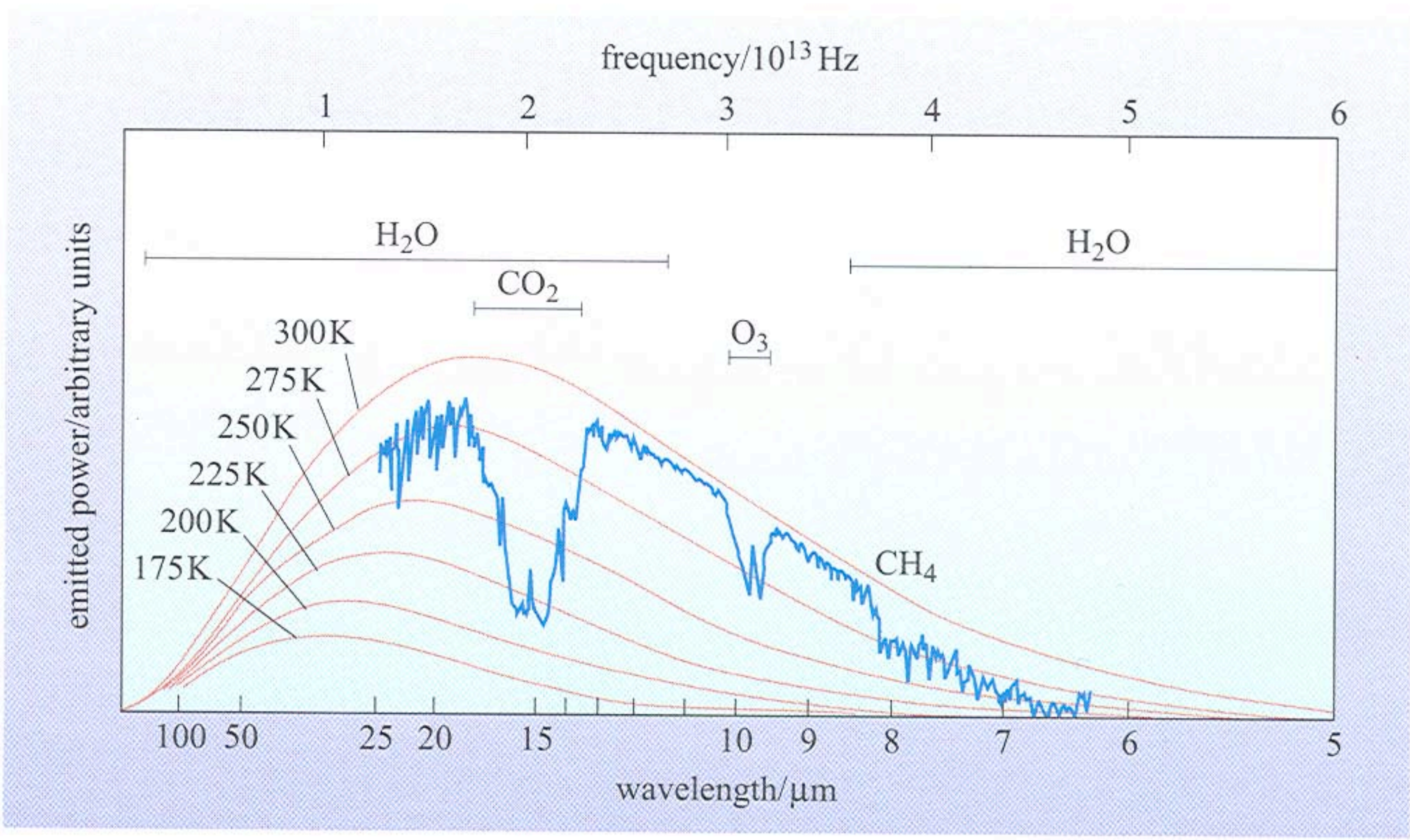
An even bigger giveaway that life is present: Simultaneous ozone and methane detection

How could you have methane in an oxygen-rich atmosphere?
➞ *methanogens* (bacteria that metabolize methane)

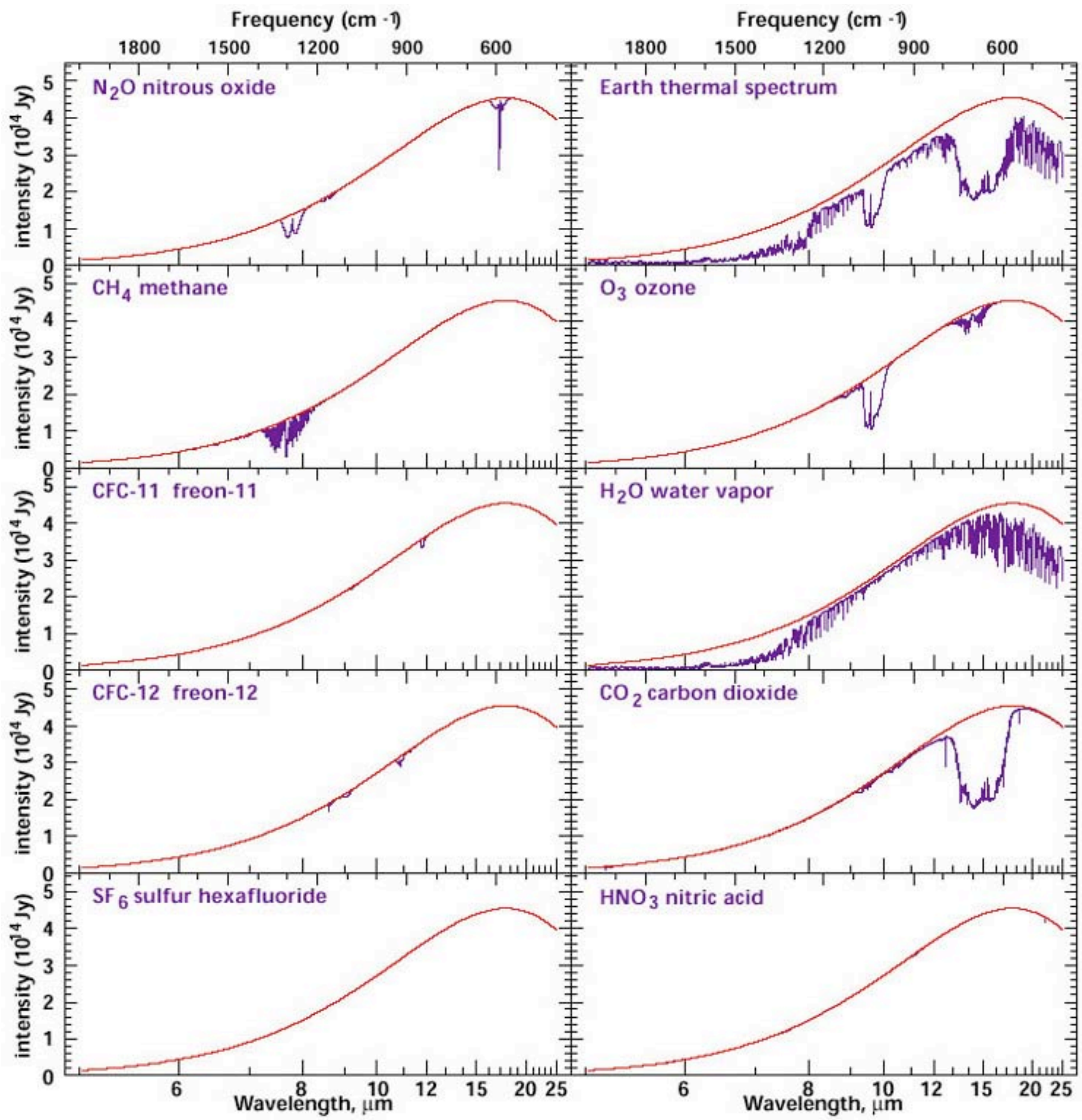


Infrared spectrum of the present Earth

Red curves are blackbodies of various temperatures.
What are the potential signatures of life, or of habitability?
(Note: wavelength increases to the left on this plot)



Trace gases in the Earth's infrared thermal spectrum. Composite is in upper right.

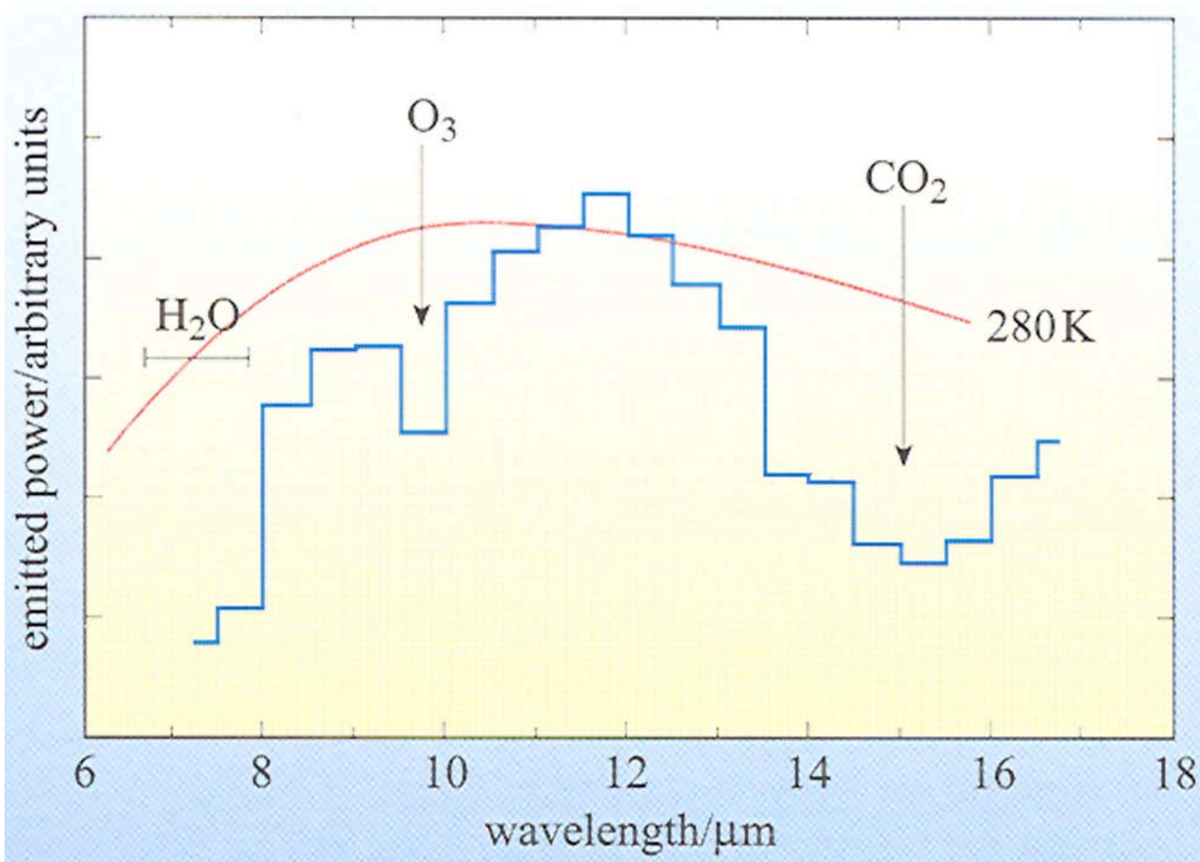


Spectrum of Earth-like planet at realistic spectral resolution

Plausible IR spectrum of Earth-like planet 10 pc away as observed by TPF/Darwin for 40 hour exposure.

Notice that the poor resolution is the major problem for detecting many biomarkers.
(Compare with previous high-resolution spectrum of Earth.

Still, many think that simultaneous detection of H_2O and O_3 (and CH_4) would be strong evidence for life

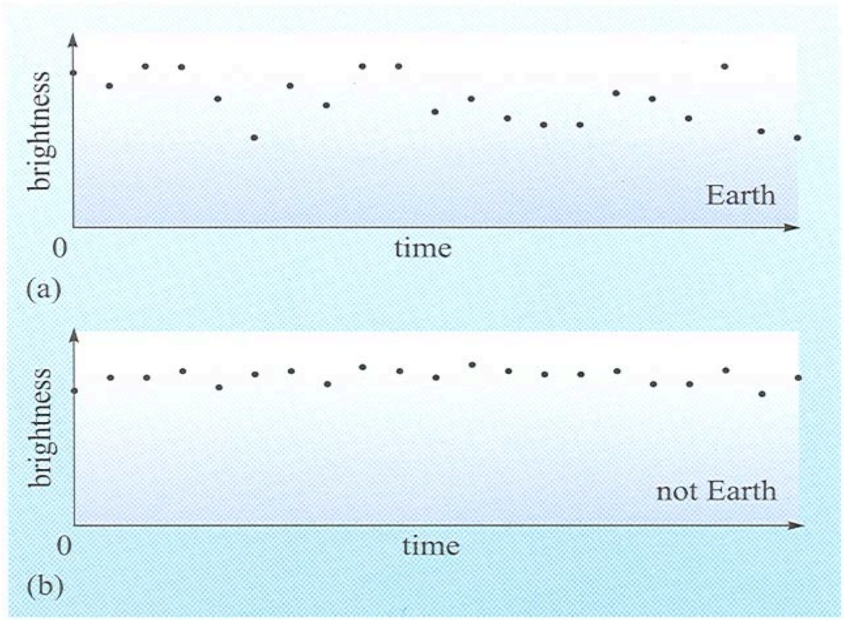


Direct detection: Reflection spectrum (planet not resolved)

Maybe we could learn about a planet without a spectrum (i.e. photometry only). This is possible in the visible because the albedo (fraction of reflected light varies for different materials (left below). Or variation could distinguish continents from oceans (right). So observe light in a few wavelength bands as a function of time (light curves).

Typical Albedos of Terrestrial Materials

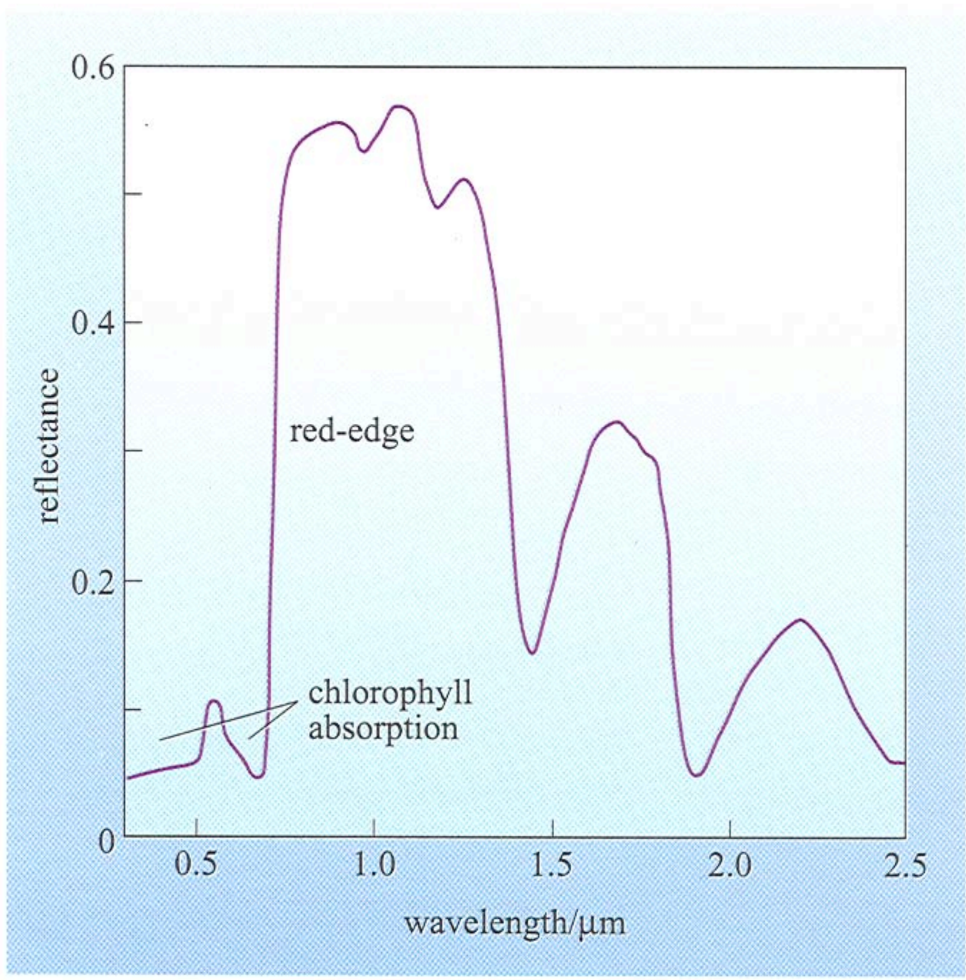
Material	Albedo (Percent)
Earth system as a whole	30
Sand	25
Dense Forest	8
Field crops	25
Water (sun near horizon)	40-75
Water (sun overhead)	6
Fresh snow	85-95
Concrete	20-30



Light curves that typify the sunlit hemisphere of (a) the Earth and (b) a terrestrial body with a more uniform surface.

The Vegetation "Red Edge"

Another suggestion: the **reflection** spectrum in the **visible** part of the spectrum could show the "red edge" exhibited by most vegetation (on Earth!)

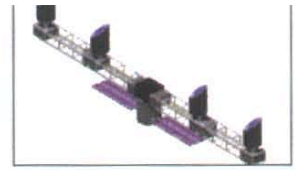
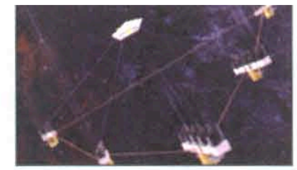


To the land of wishful thinking…

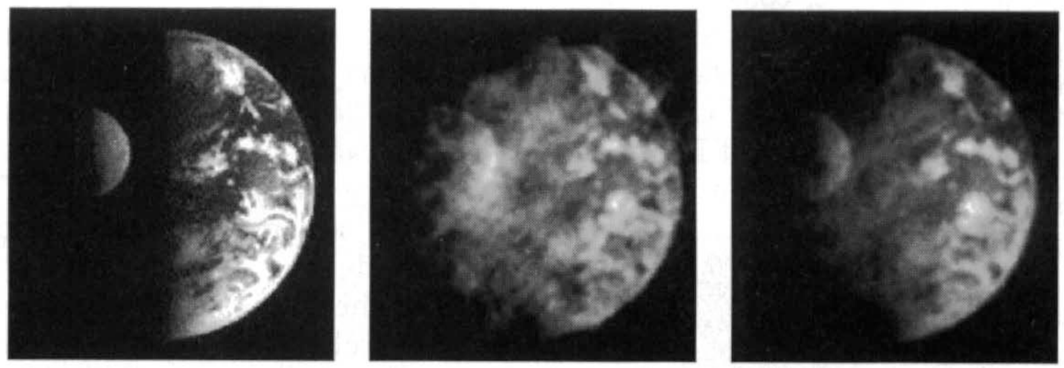
Future space missions for detection of terrestrial-mass planets.

Note: ISI=Darwin, similar to TPF and will probably be combined.

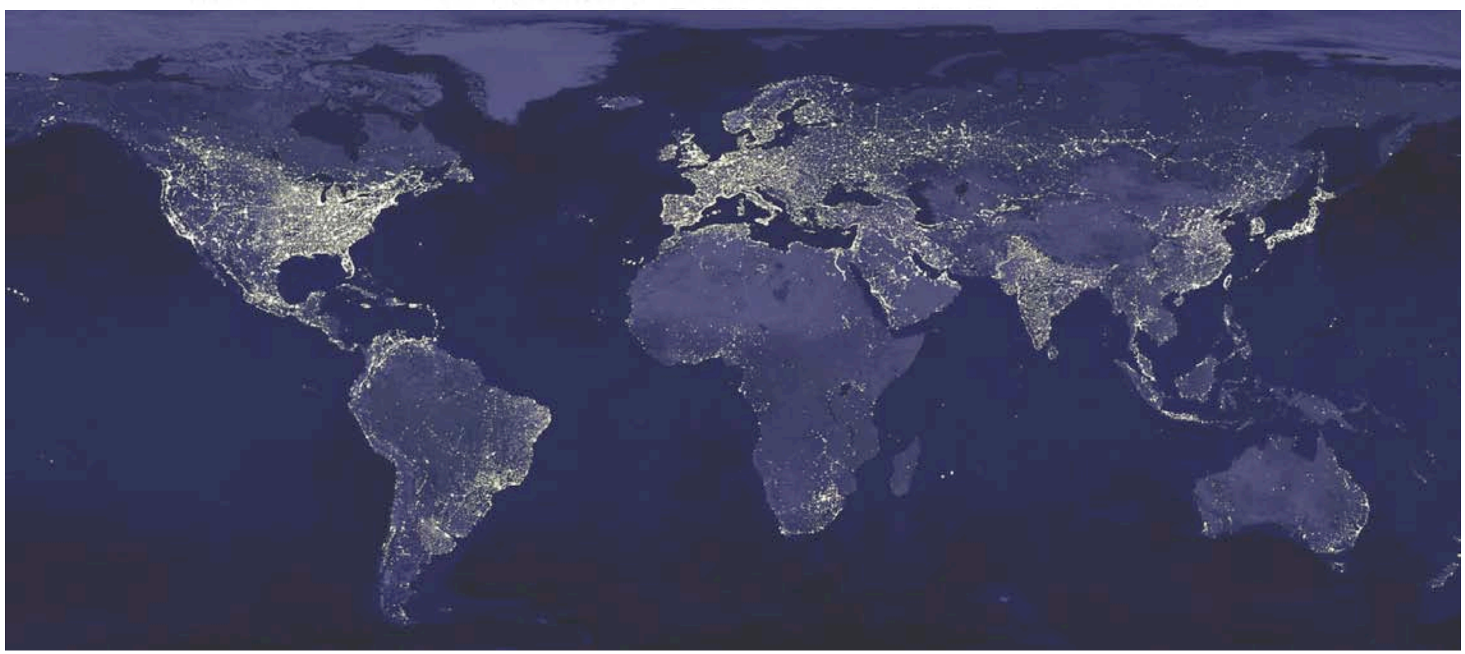
Planet Imager is still on drawing board. TPF replaced by "Lifefinder" (?)

					
Mission name	Deep Space 3	Space Interferometry Mission	Infrared Space Interferometer	Terrestial Planet Finder	Planet Imager
Agency	NASA	NASA	ESA	NASA	NASA
Baseline	1 km	10 m	50 m	100 m	6000 km
Resolution (mas)	0.1	0.001	50	25	0.0003
Waveband (micrometers)	optical	optical	7–17 Infrared	7–17 Infrared	7–17 Infrared
Function	Technology demo	Star wobble	Family portrait	Family portrait	Planet images
Launch Date	2002	2005	2009	2010	2020

Top: Earth as would be seen by instrument somewhat larger than TPF
Bottom: Earth at night

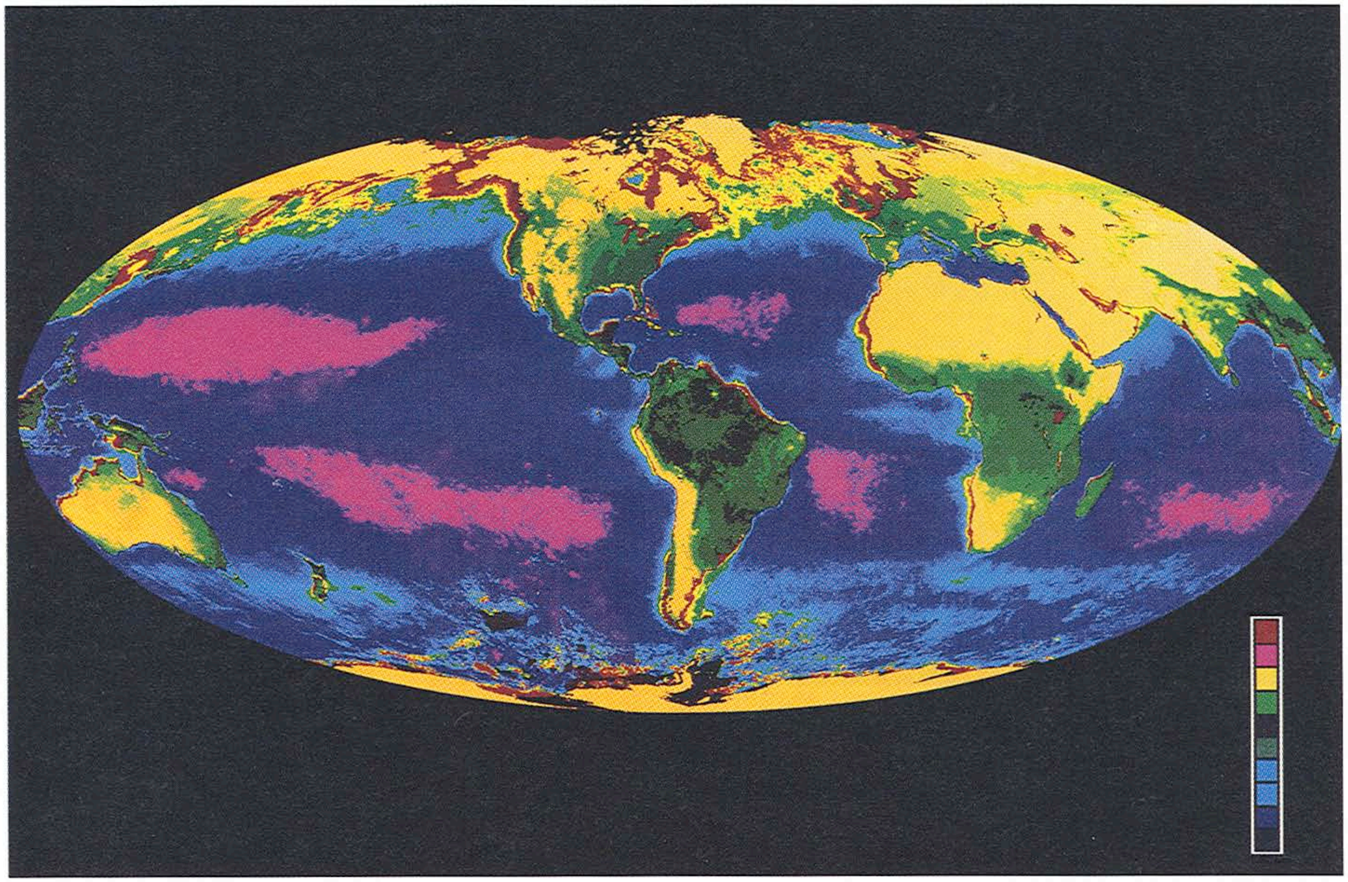


Imaging Earth. Views of home close up *(left)* and from 10 light-years away taken with a hypothetical interferometer with a 150-kilometer baseline and 48 telescopes *(center)* and 150 telescopes *(right)*.



The ultimate direct detection:

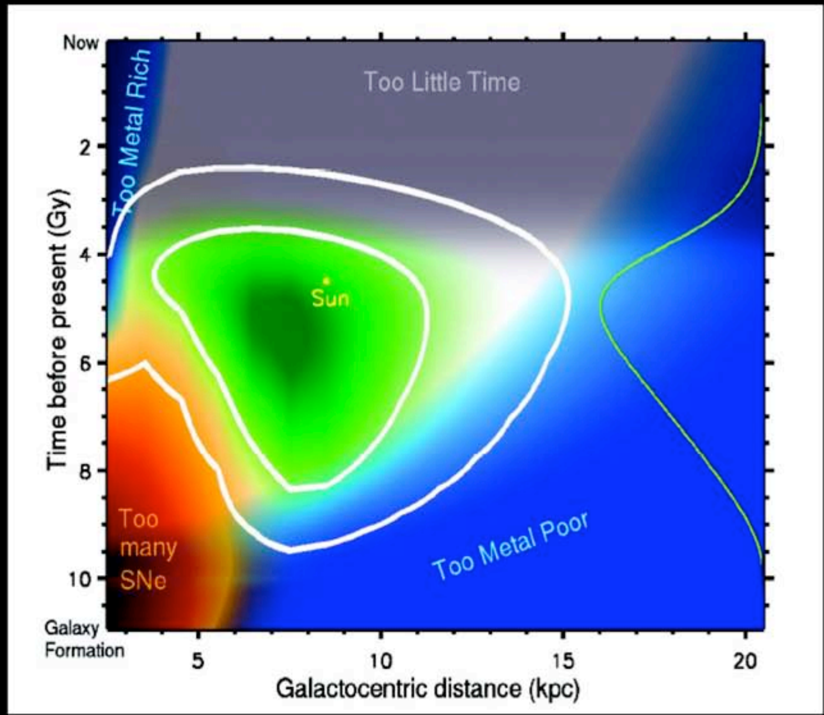
Extremely unlikely in next two decades (see figure caption)



The Earth's Biosphere This computer-generated picture shows the distribution of plants over the Earth's surface. Ocean colors in the order of the rainbow correspond to phytoplankton concentrations, with red and orange for high productivity to blue and purple for low. Land colors designate vegetation: dark green for the rain forests, light green and gold for savannas and farmland, and yellow for the deserts. (NASA)

The galactic habitable zone

- There may also be a preferred time and location within the *galaxy* for habitable planets to exist
- Stars that are too close to the center of the galaxy are subject to frequent near-collisions and more supernovae and gamma ray bursts
- Stars that are too far out in the galaxy (or that evolved too early in its history) may be too metal-poor
- Fortunately, though, the GHZ is probably large compared to the local solar neighborhood



Ref.: Lineweaver et al., *Science* (2004)