4

Indicators of Life: Detection of Life via Remote Sensing

A fundamental goal of NASA's Origins program is to search for life on planets beyond the Earth to further our understanding of how life forms and subsequently evolves. Within the Solar System, we will be able to study samples returned from the surface and sub-surface regions of Mars, as well as probe the oceans that may exist under Europa's ice-sheets. But beyond the planets and satellites of our solar system, our choices are limited. We will have to rely on the information brought to us by the light from distant planets to assess whether life is or might someday be present on those distant planets.

Some of the conclusions of this chapter are that:

- Life on Earth is robust and thrives in a wide variety of environments.

> ***300 years in the making, having recently been wedded to physics and chemistry, biology is now a mature science... Even if complete cells and organisms are still beyond them... [biologists] foresee no need for overarching grand explanations for creating artificial life. An organism is a machine, and the laws of physics and chemistry, most believe, are enough to do the job, given sufficient time and research funding.***
>
> E.O. Wilson (1998) in Consilience

- Given sufficient raw materials, such as cosmically abundant elements, liquid water, and free energy, life similar to what we see on Earth could arise elsewhere in the Universe.
- The environmental impact of life on the surface of a planet is sufficient to make life detectable on another planet located many light years away.

- Trace gasses such as ozone, methane, and nitrous oxide can tell us about the presence of life over billions of years of evolutionary development, particularly for planets within the “habitable zone” where liquid water might be found.
- The competition between biological and non-biological processes in a planetary atmosphere will have to be carefully understood before definitive statements can be made about the presence of life on any particular planet.

DEVELOPMENT OF LIFE

The past few decades have seen a revolution in our understanding of life on Earth, even the kinds and numbers of organisms that dominate our planet. Just a few years ago, the planet was imagined to be dominated by complex, eukaryotic organisms. These eukaryotes comprised the major diversity of the planet, and consisted of four kingdoms: animals, plants, fungi, and protists (single-celled eukaryotes). A fifth kingdom was the single-celled prokaryotes. Using molecular methods (e.g., sequence comparisons of 16S ribosomal RNA or other macromolecules) it has been possible to quantify the genetic relationships between organisms on Earth. Such an approach has yielded phylogenetic trees based on quantitative differences between molecules that all organisms share, such as that shown in Figure 4.1. Here, only three kingdoms are seen, two of which are prokaryotic (Bacteria and Archaea). The major genetic diversity resides in the two prokaryotic domains with the four eukaryotic kingdoms now being combined into one. All of the commonly perceived recognized diversity of life—from mammals, fish, and shellfish to plants and fungi—occupy the lower tip of one branch of the tree of life.

While the last common ancestor cannot be inferred from such data, it is commonly believed that, among the extant organisms, the Archaea are the most primitive, and therefore, may hold important keys to understanding the kinds of organisms and metabolism that may have first arisen. In particular, it is generally believed that the first organisms may well have been heat-loving (thermophilic) and/or hydrogen- or sulfur-metabolizing prokaryotes, either Archaea or Bacteria, such as those found presently associated with deep-sea volcanic vents (Figure 4.2). Vent life flourishes in an environment with no sunlight, little oxygen, high temperatures, and a concentration of hydrogen sulfide so high that it would kill most life on the Earth’s surface. Hyperthermophilic sulfur-reducing archaea consume hydrogen and carbon dioxide for energy, nitrogen and phosphorus to make cell material, and transition metals, such as iron, nickel, manganese and selenium, for cellular functions and proteins. They produce methane as a waste product that could enrich a planet’s atmosphere.

Either life started in this form on the primitive Earth or, alternatively, these might be the only organisms to have survived early collisions by

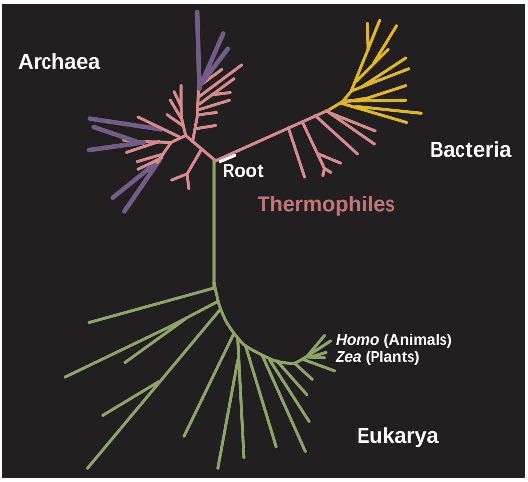


Figure 4.1.
A phylogenetic tree of life suggests that the major genetic diversity on Earth resides in the single-celled prokaryotes, while comparatively little diversity is seen between plants, animals, and fungi.

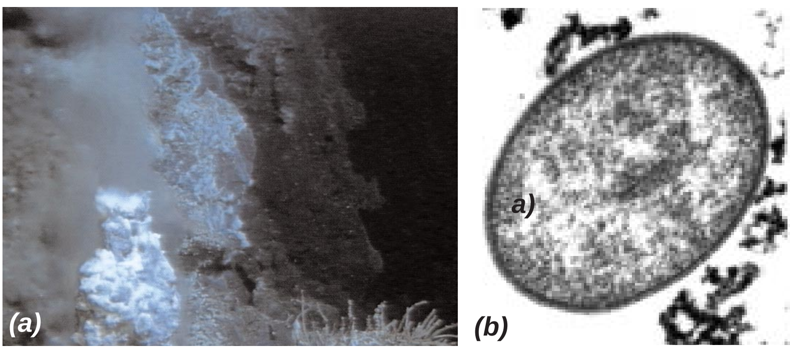


Figure 4.2a.
Underwater volcanic vents (left) are home to some of the most primitive life forms on Earth.

Figure 4.2b.
A micrograph of a thin section through a thermophilic, anaerobic archaeon (courtesy of Melanie Summit, Baross Laboratory, UW Oceanography).

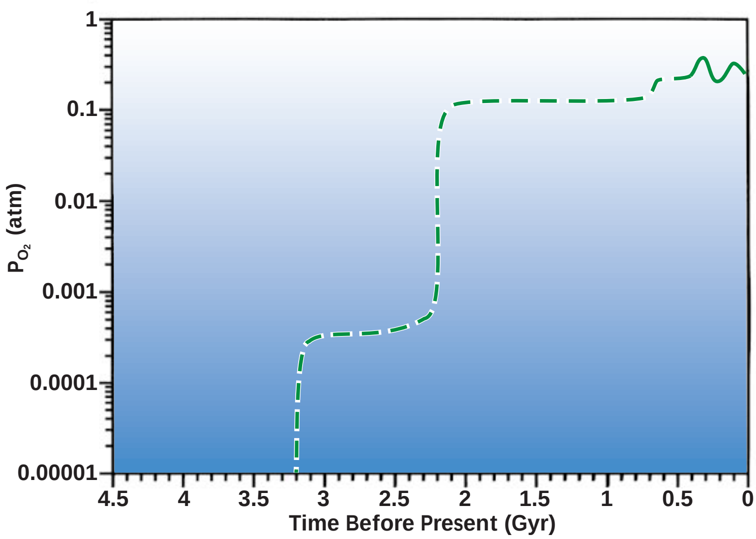


Figure 4.3.
The composition of the Earth's atmosphere appears to have become oxygen-rich due to the presence of life, starting about two billion years ago (Kasting et al. 1983).

comets that heated the oceans and are thus a link to an origin of life under cooler conditions.

The geological record provides evidence for fundamental changes in the Earth's atmosphere about 2 billion years ago when partial pressure of oxygen (P_{O_2}) began to build up (Figure 4.3). This is believed to be due to the process of oxygenic photosynthesis, and due primarily to the activity of the photosynthetic cyanobacteria pictured in Figure 4.4.

REMOTE SENSING AND THE SEARCH FOR LIFE

Table 4.1 describes a hierarchy of information that can be learned about a planet, ordered roughly in terms of increasing difficulty, and the implications of that information for the search for life. The promise of TPF is that its measurements (highlighted in purple in Table 4.1) will not only inform us about physical conditions, but about whether a planet is habitable or even inhabited by life capable of changing the planet's atmospheric composition. The remainder of this chapter addresses those signatures of life that might be prominent in the atmospheres of other planets and detectable using TPF. As Figure 4.5 shows, broad spectral lines detectable in the mid-infrared could demonstrate the presence of: 1) any atmosphere at all via detection of carbon dioxide (Mars and Venus); 2) a warm, wet atmosphere via detection of carbon dioxide and water (Earth); 3) and ultimately a planet bearing life via detection of ozone as a proxy for oxygen (Earth). Weaker spectral lines (Figure 4.6) can provide still more information on the physical processes occurring on a planet.

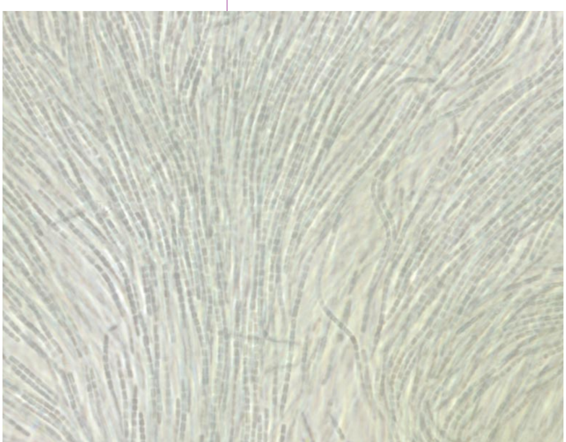


Figure 4.4. A microphotograph of cyanobacteria (blue-green algae) that photosynthesize carbon dioxide to produce oxygen.

ATMOSPHERIC COMPOSITION AS AN INDICATOR OF LIFE

It has long been realized that the presence of life on a planet's surface can, in principle, be detected by its effect on the planet's atmosphere. Planetary scientist Carl Sagan (Sagan *et al.* 1993) credits the original proposal to a 1965 *Nature* paper by Joshua Lederberg, a Nobel Laureate in Medicine (Lederberg 1965). Lederberg pointed out that an atmosphere that has been modified by biogenic gaseous emissions will exhibit a marked departure from thermodynamic equilibrium (Figure 4.5). This condition is not by itself a sufficient condition for establishing the presence of life. In reality, all planetary atmospheres are in a perpetual state of thermodynamic disequilibrium because they are being driven simultaneously by thermally induced reactions at temperatures commonly exceeding 250°C and by photochemically induced reactions resulting from interactions with the parent star's photosphere (5000 K). Nevertheless, atmospheres that contain biogenic trace gases ought to

Table 4.1. Properties of Planets and the Search for Life Using Remote Sensing

Property	Implication for Life	Technique
Orbit characteristics (radius, eccentricity, etc.)*	Existence of planet in habitable zone	Astrometry, radial velocity, direct detection
Mass	Ability to retain atmosphere	Astrometry, radial velocity
Radius	Density and surface gravity	Transit photometry, direct detection
Combination of (temperature, radius, albedo)	Ability to support liquid water, Presence of runaway greenhouse effect	Direct detection in infrared
Atmospheric composition (major gases)	Existence of atmosphere (CO_2) Presence of water (H_2O) Suggestions of life (O_3, CH_4)	Direct detection with low resolution infrared spectroscopy (R~20)
Combination of (radius, albedo)	Density, surface/cloud properties	Direct detection in the visible
Atmospheric gases (minor gases)	Confirmation of life (CH_4, N_2O, oxygen via A-band) Atmospheric structure from line profiles	Direct detection with high resolution spectroscopy in visible/IR (R~1000)
Presence of moons	Presence of tides	Direct detection with 100 μarcsec imaging
Surface features and composition	Existence of oceans and continents	Direct detection with 1 μarcsec imaging

*TPF will address problems highlighted in purple.

be further from equilibrium than those that do not. Biological activities should also show temporal and spatial variations as a function of planetary seasons.

James Lovelock, a British scientist who has championed the Gaia hypothesis that life directs the evolution of its own environment, elaborated on the concept of the spectroscopic detection of life in a second *Nature* paper published later that same year (Lovelock 1965). His idea was more specific. He pointed out that the presence of life in the Earth's atmosphere was indicated by the simultaneous presence of a highly oxidized gas, molecular oxygen (O_2), along with highly reduced gases, such as methane (CH_4) and nitrous oxide (N_2O). All three of these gases are generated predominantly by biological activity. Oxygen is produced by photosynthesis; methane is generated by methanogenic bacteria living in anaerobic environments such as rice paddies and cow guts; and nitrous oxide is generated by bacterial denitrification in soils and in the ocean. Lovelock's paper was written at the time when the Viking missions to Mars were being planned. He pointed out (correctly it seems) that the absence of methane in Mars' atmosphere is an indication that the surface of Mars is not currently inhabited. The Martian atmosphere does contain 0.1% oxygen by volume, but this oxygen is thought to be generated entirely by an abiotic process, namely, the photodisso-

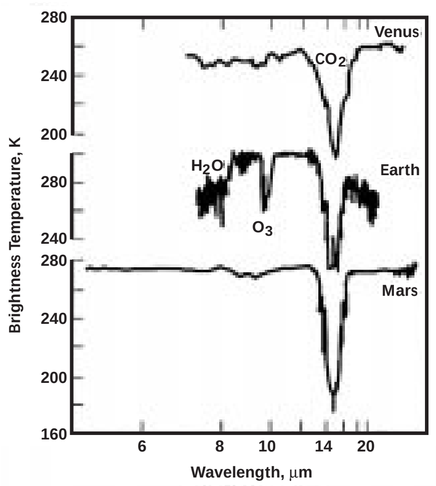


Figure 4.5. Spectral lines in the mid-infrared could characterize the atmosphere of a planet.

ciation of water vapor (H_2O) in the atmosphere, followed by escape of hydrogen to space.

The absence of methane from Mars' atmosphere does not, of course, prove that life is absent there. Martian organisms could conceivably exist underground, out of contact with the atmosphere, or in numbers too small to produce a measurable atmospheric signature. Alternatively, methanogenic metabolism might never have evolved on Mars for some reason. It is difficult to prove that life is absent from another planet by analyzing its atmosphere, because we cannot be sure that life elsewhere resembles, in form or abundance, life here on Earth. The best we can do is to make inferences, the degree of certainty of which depends on the generality of what we know about biological metabolism and the extent to which we understand the processes that control planetary atmosphere composition.

Lovelock's idea of using the simultaneous presence of oxygen and methane (or nitrous oxide) to test for life is useful for some cases, but not in others. Sagan *et al*. (1993) were able to detect these indicators of life on our own planet using data from the Near-Infrared Mapping Spectrometer (NIMS) instrument on the Galileo spacecraft as it swung by Earth on its way to Jupiter. However, since distant planets will be very faint in the visible/near-infrared (IR) and more than a billion times fainter than their parent stars, it is *very* difficult to build a telescope to observe the same bands as those seen by NIMS, or using a visible-light signature to identify molecular oxygen (the oxygen A-band at 0.76 µm). While Angel and Woolf (1997) suggest that a suitably optimized, 6 m space telescope, corrected with ultra-high resolution active optics and a coronagraph could detect the oxygen A-band in Earth-like planets of the very nearest stars, a more robust search technique is needed for an initial reconnaissance. If, however, TPF finds that terrestrial planets are common, then a third generation space telescope with optimized optics could make valuable follow-up observations at the more difficult visible wavelengths.

SIGNIFICANCE OF OZONE

Fortunately, we may be able to infer the presence of life on extrasolar planets without being able to observe oxygen, methane, or nitrous oxide. The key is to look for the 9.6 µm absorption band of ozone (Angel, Cheng, and Woolf 1986; Leger *et al*. 1993). This band is in the middle of the infrared spectral region and is the second strongest absorption feature in Earth's atmosphere after the 15 µm band of carbon dioxide (Figures 4.5 and 4.6). Ozone is readily observable for two reasons: 1) it lies within the 8-12 µm "window" region where water does not absorb, and 2) ozone is located within the Earth's stratosphere, above most of the other absorbing gases. Ozone is formed photochemically from oxygen and is not expected to be present in appreciable abundance in atmospheres from which oxygen is absent (e.g., Levine *et al*. 1979; Leger *et al*. 1993). Furthermore, ozone is a nonlinear indicator of atmospheric oxygen. For example, even at an oxygen level only 1% of the present, the expected ozone column depth is almost 40% of the present global average value (Kasting *et al*. 1985). Thus, while a poor probe of the exact abundance of oxygen, ozone is an extremely sensitive indicator of the presence of oxygen in a planet's atmosphere. Its presence in the Earth's atmosphere could have been detected by astronomers on a distant planet over the past 2 billion years of the Earth's history.

Suppose that one observed ozone in a planet's atmosphere, but could not detect any reduced gas, such as methane or nitrous oxide, because of poor spectral resolution or inadequate photon statistics. (This would likely be the case if one were to aim the proposed TPF instrument at the Earth from a distance of 10 pc.) Is the presence of ozone (or oxygen) *by itself* an indication that life is present on a planet? This question is a tricky one because, as noted previously, oxygen is not only produced by photosynthesis but can also be generated by photodisso-

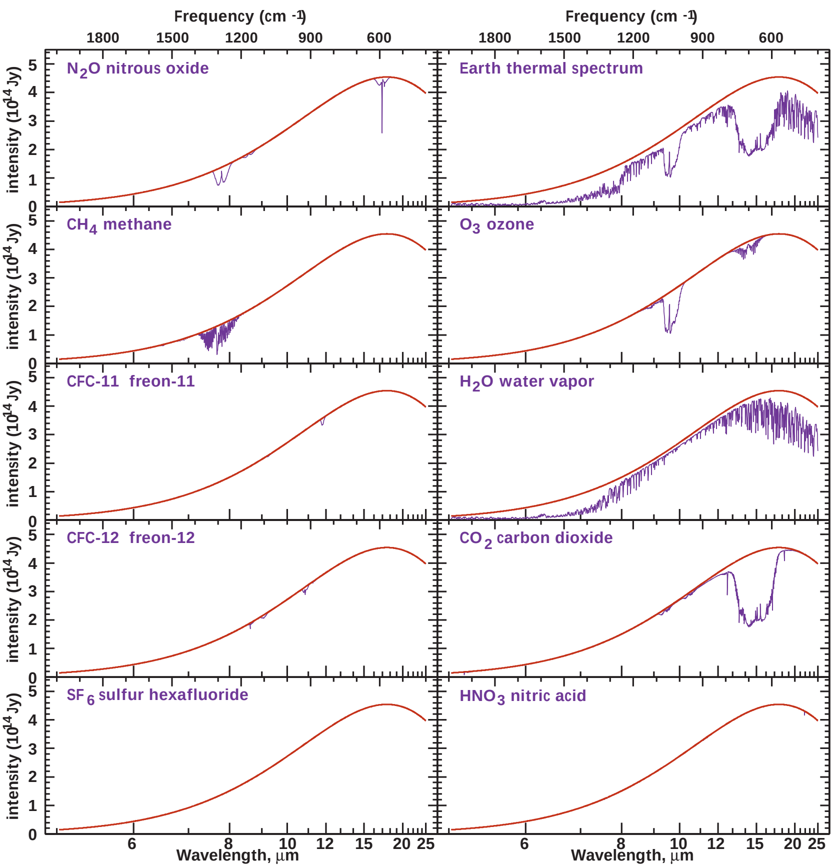


Figure 4.6. Model calculations show the effect of various trace gasses on the Earth's thermal spectrum. The spectrum in the upper right shows the composite effect (calculations courtesy of W. Traub, Center for Astrophysics).

ciation of water, followed by escape of hydrogen to space. Are there any conditions under which this abiotic process could lead to appreciable atmospheric oxygen levels?

The answer to this question is 'yes', but the circumstances under which high abiotic oxygen concentrations could be generated appear to be rather unusual, and it should be possible to ascertain whether a given planet might fall into this category. Our own planet does not–predicted oxygen concentrations for an abiotic earth are of the order of 10^{-12} times the present atmospheric level (PAL) (Kasting 1993 and references therein). The reason is twofold. First, the abiotic source for oxygen is small because the stratosphere is very dry. The rate of hydrogen escape from Earth is governed by the so-called "diffusion limit" (Hunten 1973; Walker 1977), in which the escape rate is proportional to the total hydrogen mixing ratio in the stratosphere, i.e. the fractional abundance of hydrogen in all of its chemical forms. The rate at which oxygen is generated is proportional to the H_2O mixing ratio, which is of the order of 3 to 5 ppmv. The stratospheric H_2O mixing ratio is very low because the Earth's atmosphere has an effective "cold trap" at the tropopause (10-17 km), which limits the abundance of H_2O above that level.

The second reason that abiotic oxygen levels would be low on a planet like Earth is that Earth has appreciable oxygen sinks, including oxidation of reduced volcanic gases (primarily H_2, CO, and SO_2) and weathering of reduced minerals at the surface. The rate of volcanic outgassing alone is sufficient to overwhelm the abiotic oxygen source by a factor of more than 100 (Holland 1978; Kasting 1997). Thus, models of Earth's prebiotic atmosphere (Kasting 1993) predict that little oxygen should have been present. In these models, the oxygen concentration rises to 10^{-4}-10^{-3} PAL in the stratosphere as a consequence of carbon dioxide photolysis, followed by recombination of O atoms with each other; however, the amount of oxygen formed is far too small to produce appreciable amounts of ozone. Hence, it should be easy for TPF to distinguish between an oxygen-rich and an oxygen-poor planet.

One can, however, imagine planets on which the amount of abiotically generated oxygen could be much larger. Indeed, one does not need to go further than our own solar system to find examples. Venus has less than 1 ppm of oxygen in its atmosphere today, but it could conceivably have contained much more oxygen early in its history as a consequence of rapid water loss. Because it is closer to the Sun than the Earth, Venus is thought to have experienced either a "runaway" or "moist" greenhouse, in which the stratosphere became very wet and the rate of hydrogen loss became correspondingly higher (Kasting 1988). Thus, the abiotic production rate of oxygen on early Venus could have been many orders of magnitude larger than on Earth. Conversely, Mars has about 0.1 percent oxygen in its atmosphere, not because the oxygen production rate is large, but because the oxygen sinks are small. Mars is small enough so that it has lost most of its internal heat and is volcanically inactive. Furthermore, the surface is perpetually frozen, making it difficult to erode rocks and expose fresh material for weathering. Indeed, Mars might possess even more oxygen in its atmosphere if it were just a little bigger. Mars currently loses oxygen to space as a consequence of mechanisms like the dissociative recombination of CO_2^+ in the upper atmosphere (McElroy *et al.* 1972). A slightly larger planet with a strong enough gravitational field to shut down these processes could conceivably build up much higher atmospheric oxygen concentrations (provided it was not big enough to be volcanically active like Earth).

We conclude that the presence of ozone and oxygen in a planet's atmosphere should usually be an indication of life, but only for Earth-sized planets that are within the liquid water "habitable zone" (Kasting 1997). A Venus- or a Mars-like planet could prove to be an exception to this rule. Fortunately, we should be able to identify such a planet from its spectrum, which provides information about atmospheric H_2O abundance and surface temperature, and from its location with respect to the theoretically calculated habitable zone around its parent star.

PLANETS RESEMBLING THE EARLY EARTH

So far, we have established that the presence of ozone (and oxygen) in a planet's atmosphere is *usually* an indication of the presence of life, but what about the converse of this statement: Is the absence of oxygen evidence for the absence of life? Here, the answer is clearly "no," based on what we know about Earth's history. Most geologists believe that atmospheric oxygen first rose to appreciable levels sometime around 2.0 to 2.2 billion years ago (e.g., Cloud 1972; Walker *et al.* 1983; Holland 1994). Life, on the other hand, has clearly been around for much longer than this. The microfossil record extends back to at least 3.5 Gigayear (Gyr) ago (Schopf 1993), and indirect, isotopic evidence for life goes back to 3.9 Gyr ago (Mojzsis *et al*. 1996). So, Earth was probably inhabited for over a billion and a half years before any sign of oxygen or ozone appeared in its atmosphere. For TPF, the question then arises: Suppose we observed an extrasolar planet that was an analogue for early Earth. What would we expect its spectral signature to look like, and would we be able to determine if it was inhabited?

This question is more difficult than that of detecting life on planets resembling present Earth because we do not really know what the early biota were like and what biogenic gases were being released. We can make educated guesses, however, based on inferences gleaned from molecular phylogeny. (Molecular phylogeny is the classification of organisms based on the observed sequences of their nucleic acids or proteins.) One inference is that methanogenic bacteria, or methanogens, are very ancient. Methanogens derive energy from reactions such as:

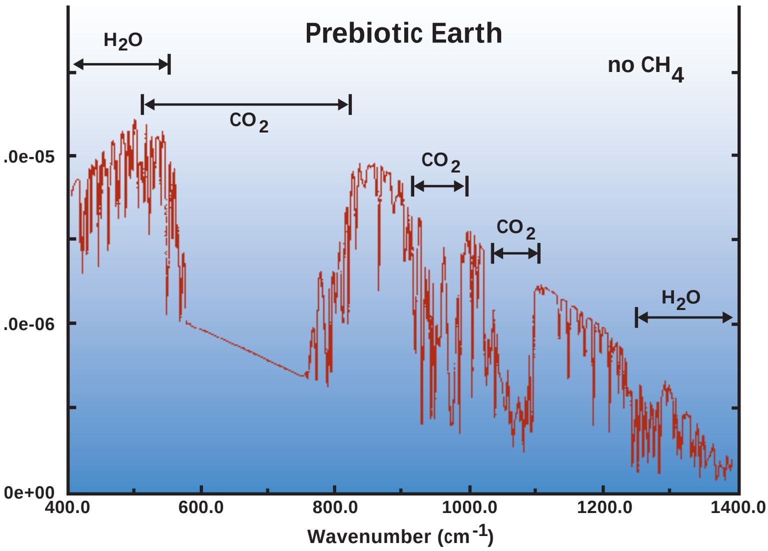
$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O.$$

Both carbon dioxide and H_2 are thought to have been relatively abundant on the primitive Earth, and methanogens probably evolved early on to take advantage of this (Walker 1977). Therefore, methane would likely have been an important biogenic trace gas in the early atmosphere, just as it is today. A major difference is that methane would have had a much longer photochemical lifetime in an anoxic atmosphere. Today, methane is oxidized by OH radicals on a time scale of ~12 years. In an anoxic atmosphere its expected lifetime is 10^3-10^4 years (Kasting *et al.* 1983; Zahnle 1986). Hence, a biological source of the same magnitude as today could result in atmospheric methane concentrations that were orders of magnitude higher than the present methane level of 1.7 ppmv. Methane should also have been well mixed up to heights of 80 km or more (Zahnle 1986), whereas today its concentration declines rapidly above the tropopause. Thus, the spectral signature of methane on an early-Earth analogue planet could be much stronger than in the present atmosphere.

To determine whether TPF might be able to detect methane in an early-Earth analogue atmosphere, synthetic spectra were computed (Figure 4.7). The background atmosphere was assumed to consist of 0.8 bar of nitrogen and 0.2 bar of carbon dioxide, which is considered to be a plausible composition for Earth's early atmosphere (Kasting 1993). The planet's surface temperature was assumed to be the same as for modern Earth, 288 K, and the stratosphere was assumed to be isothermal at 217 K. This is approximately what would happen in Earth's stratosphere if one were to remove the heating resulting from absorption of solar UV radiation by ozone.

The top of Figure 4.7 shows the emitted spectrum of such an atmosphere if no methane were present. The major absorption features that are seen are the 15 µm (667 cm^{-1}) band of carbon dioxide, two "hot" bands of carbon dioxide centered at 9.4 µm (1064 cm^{-1}) and 10.4 µm (962 cm^{-1}), the pure rotation band of water longward of ~18 µm (550 cm^{-1}), and vibration-rotation bands of water shortward of ~8 µm (1250 cm^{-1}). The lower panel shows the emitted spectrum from an atmosphere containing 1% methane by volume (i.e. 10,000 ppmv). This abundance of methane is consistent with the present day biological production of methane (Watson *et al.* 1990) taking place in a pre-photosynthetic world. The stratosphere is almost completely opaque between 1200 cm^{-1} and 1400 cm^{-1} in this case. Such an absorption feature could be seen by even a low-resolution version of TPF.

Would the observation of a strong 7.6 µm methane absorption feature in an extrasolar planet atmosphere imply that life was present? To answer this question, we would have to understand how much methane might be present on an uninhabited planet. The complex atmospheric chemistry of methane discussed in Kasting and Brown (1998) makes it clear that more research is needed to determine what a plausible prebiotic and postbiotic value of the methane concentration might have been for early Earth. Such calculations could then be used to predict what the presence of methane in an extrasolar planet atmosphere might imply about the presence of life. It is clear, however, that any inferences drawn about the presence of life from methane would be much less secure than those based on the observation of ozone in a modern-Earth analogue atmosphere.



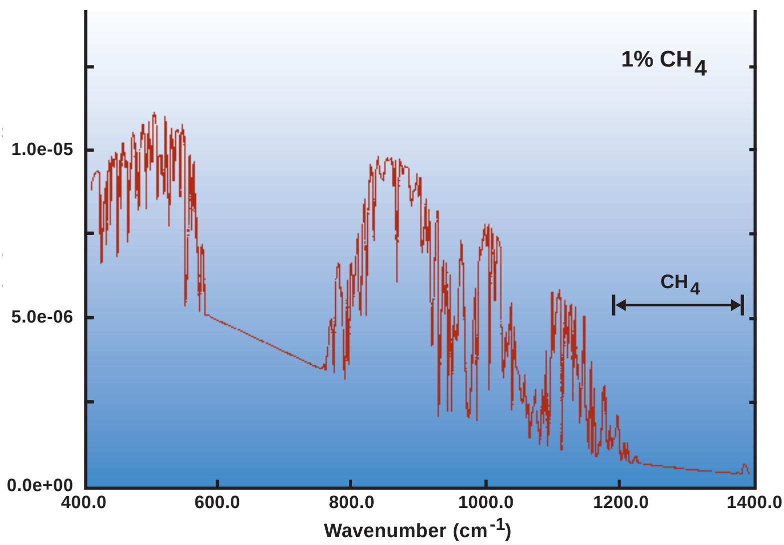


Figure 4.7. Model calculations show plausible thermal spectra for the prebiotic Earth without (top) and with (bottom) the presence of significant amounts of methane (Kasting and Brown, private communication). The strong absorption centered at 7.6 µm (1200-1400 cm^{-1}) would be detectable with TPF.

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