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Looking for Life in the IR and Neighboring Spectral Regions

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Abstract. The paper focuses on the issues for detection of life by remote observations. The problem is divided into the detection of terrestrial planets and the detection of life on them. The problem of detection of planets is compared with the observations of the Hubble Deep Field. The difficulty of detection will likely result in many interesting discoveries before detection techniques are adequate. It is proposed that life is the activity of mutually assisting persistence processes. A persistence process is one that uses the Gibbs Free Energy of the environment for repair and development. It is pointed out that because life produces approximations to equilibrium it is intrinsically difficult to detect by remote observations. Chemical signs of life will be distinctive if the abiotic processes that might produce them are implausible, and preferably absent. The ease of remote detection of terrestrial life is contrasted with problems likely to arise for other planets. It is recommended that initial searches be focused on giant planets. The spectral region of the discovery observations will be set by technical issues which are not yet resolved for any technique. For determining whether life is present, as many spectral regions as possible should be observed.

Keywords. astrobiology.

1. Introduction

The first conference on detecting planets around stars that I attended was at NASA Ames research center in 1976. It was initiated by a plan from SETI to build a giant radio telescope "Cyclops" to search for extraterrestrial communications. I remember Jesse Greenstein organizing the meeting, helped by a young David Black, and Phil Morrison played the role of elder statesman. Now, almost 30 years after that meeting, I am asking some fundamental questions about remote detection of life. What makes life sometimes visible, sometimes not? What does it take to prove that life is present? Are Earth-like planets our best planets for remote detection of life? How rare are Earth-like planets likely to be? Which spectral regions are needed for remote evidence of life, and how convincing can that detection be? How should we best start the planet and life detection process, and how can such a difficult and expensive process proceed? The observer issues involved in the search for extrasolar microbial life are two-fold. There is an astronomical problem of being able to observe earth-like planets around other stars, and there is a bio-geo-chemical problem of trying to interpret evidence about the possible presence of life.

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2. The Astronomical problem

If we are fortunate, we will find an earth-like planet fairly close, say at a distance of 10 pc. In that case the planet will be comparable in brightness with the faintest stars seen in the Hubble deep field pictures (William *et al.* 1996). The star will be separated from the planet by the width of that faint image, and it will be about 25 magnitudes brighter. Further, the planet image will be confused with other participants in its planetary system. Not only may there be other planets, often with projected separations as low as 0.01 arc seconds, but there is likely to be a strong zodiacal glow, that can only be made less competitive with the Earth signal by increasing the angular resolution.

If we are less fortunate, Earth-like planets may be cosmically abundant (one per galaxy would give 10^{11} planets), but locally rare. The solar system, with its planet orbits having typical eccentricities of 0.06 stands out against the radial velocity planets, the non-roasters with their typical eccentricities of 0.35. Indeed, if the eccentricities of our planet orbits are independent, the probability of the solar system having arisen from the same process as the radial velocity planets is about 10^{-8}. More likely, the eccentricities of planets in a system are interdependent. Or equally there may be a suite of planetary systems like ours, perhaps 30-100 times less common than the currently found radial velocity planets. Sorting out the frequency of systems like ours is a first priority, and perhaps the observations by the Kepler mission will answer this need.

Even though Earths are difficult to observe, and may be modestly rare there are a suite of astronomical problems to be studied on the way to seeing them. Put our goals in perspective. The first stellar parallax observations were made just 1.7 centuries ago. Our conference room at Villefranche-sur-mer is about 4.4 centuries old. *De Revolutionibus* is 4.6 centuries old, and Aristarchus who first looked for stellar parallax lived 23 centuries ago. While astronomy waited for stellar parallax, there were many discoveries along the way, including proper motion, double stars, the velocity of light etc.

Along our way towards other Earths, astronomy can start to ask some fascinating questions. What are the varieties of planetary systems, and the frequency of the various types? How do planetary systems change with time? How can the masses of small planets be estimated, and even better measured? Can giant planets be used to measure the age of systems? How do the abundance and masses of comets change with system characteristics? Can we start to learn about planetary satellites. And there will be all those questions I have not yet thought of because I do not know the varieties of systems that will be found. If we are seeking one specific goal, we are almost guaranteed disappointment. If we are interested in the progress of science, we are almost guaranteed success.

3. Life and terrestrial layered structures

It is not trivial to decide whether some terrestrial structures are produced by life. One kind of layered structure associated with microbial mats is the stromatolite. These heaped up structures arise because microbes grow towards the light by 0.5mm per day, and with some of the sticky substances they produce, they trap sediments. Then variation of growing conditions, day to night, summer to winter etc produce a vertically stratified deposit. In general there is agreement that the younger stromatolites were produced by living organisms, but as they get older, and traces of the organisms are harder to find, there gets to be less and less agreement as to whether they were produced by microbial activity, or are stromatoliths - objects that did not necessarily result from living processes.

One layered structure formerly believed to be fossiliferous was once named the Canadian Dawn Animal *Eozoon canadense* (Hofmann 1971). It was only when a structure like this was found amid igneous material that the idea that it had been some kind of living organism was put to rest.

The Banded Iron Formations (BIFs) that mostly formed from 3-1.8 Gy ago are seen as relics of life processes. Iron, in solution, is green and divalent (ferrous) whereas trivalent ferric iron is red and insoluble. The activity of photosynthetic bacteria either in production of oxygen, or directly by using the iron in solution converted it to insoluble ferric iron or black magnetite (ferri-ferro iron). This settled to the ocean floor. Again, variable production resulted in layered structures, red/black, with milky white chert (SiO_2) layers between, and with the iron layers containing carbon believed to be a residue from the microbes. Such a layered structure could only be produced before the oceans were oxidized and iron ceased to be dissolved. After the Great Oxidation Event (2.2-1.8Gy ago), the iron shows up as redbeds, as in e.g. old red sandstone. There is mostly agreement that BIFs dating back to 3.5 Gy ago were the result of bacterial activity, But 3.7-3.8 Gy layered structures in Greenland are somewhat different, and it is highly disputed as to whether life was involved in their production.

Greenland's Isua BIFs are thinly layered alternations of black magnetite with carbon and a white hydrated magnesium calcium silicate. Here, some suggest that the carbon found with the magnetite is not biological but was produced by the effect of heat and pressure on ferrous carbonate (siderite). This process preferentially leaves ^{12}C rich carbon behind, with the ^{13}C carbon escaping as CO_2.

$$6FeCO_3 = 2Fe_3O_4 + C + 5CO_2$$

On Akilia Island, the layers are different again, with magnetite and carbon found between a highly transparent quartzite. There is a rather small amount of Akilia iron quartzite material, some in smooth uniform layers, but another part has been messed up by a pyroxene dyke passing through, and its study has produced correspondingly odd discussions. But most of the fuss seems to be about whether one can prove that the carbon is an organic residue. The fact that the iron was deposited layered at all in both regions, presents a problem that is more easily resolved by the intervention of living organisms seems to have been lost in the battles. But the point of discussing this here is that if it is so hard to prove that life processes were active on early earth, we are due to have severe problems dealing with the much lower level of evidence we can expect from extrasolar planets.

4. What are we looking for?

Life is characterized by survival (Darwin 1859). The various definitions offered for it do not seem to take this into account, see e.g. (Cleland & Chyba 2002). Indeed, a key need for a definition of life is that it explains the difference between life and death. Biologists seem to want to include evolution in the definition, though it is too slow to be a present observable for most life forms. Chemists want to include the idea that life is a chemical process. It is certainly true that terrestrial life is chemical. But there is no a priori reason why life should be restricted by the absence of chemical interactions, and we will later consider physical life. Likewise, life is not the same as complexity. Indeed if we merely needed complexity to persist, we would never die because our state after a crucial process or organ fails is not appreciably different than before. Besides, complexity is a subjective phenomenon - one person's complexity is another person's mess (high entropy state). Also, life is more than linked cycles (though it is likely to include them), because

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a number of key life processes, membrane formation, reproduction and evolution for example are not cyclic. Here we will use a hypothesis (to be published) that life is the activity of mutually assisting persistence processes. A persistence process is one that uses the Gibbs Free Energy of the environment for repair and/or development. Key persistence processes include reproduction, metabolism, cellularity and evolution, but the definition of life needs to recognize the similarity that holds these processes together rather than focusing on differences among persistence processes. In this hypothesis death is readily explained as the failure of one process that causes collapse by the domino effect.

Life processes are distinct from those of a stone that merely holds together rather well. And life is different from single persistence process such as fire or crystallization in that linked processes can have benefits of enhancing each other's survival. So reasonably compatible survival processes are likely to stay together after they come together, and to fit their workings together. On the other hand, since environmental resources are limited, there will be competition for them, and associated selection (Malthus 1798, Darwin 1859). Thus cooperation and competition are both inherent in life processes.

The obvious resources of non-equilibrium conditions are in chemical gradients that result from a variation in the oxidation state of material from the inner part of a planet to its surface. Also, the thermal gradient from a hot interior could either drive heat engines in convective fluids, or help maintain an oxidation/reduction gradient. The most distinctive non-equilibrium process on Earth is the thermalization of sunlight. Departure from equilibrium is shown by the presence of the reflection spectrum.

It is also plausible that the influx of complex organic molecules from comets, meteorites, interplanetary dust particles and interstellar dust has played a role in initiation of key prebiotic processes (Deamer *et al.* 2002). These natural products are organized molecules, and so are potentially contributors to the initial organization of living organisms.

The fact that life uses the departures from local thermodynamic equilibrium of the environment implies that life is an equilibrator. And since natural process also tend to produce equilibration, though usually on a slower timescale, life will often be intrinsically difficult to detect.

5. Where and how to look for life

Because life feeds on departure from LTE, the most distinctive features produced by life are likely to be produced in transition regions, where mixing produces departures from LTE. Transitions between liquid solid and gaseous surfaces are likely to acquire the greatest abundance of life activities.

For planets where the atmospheres is not transparent or has a strong haze layer above the surface, leaving it unseen from outside, it will be hard to get evidence about the presence or absence of life, because evidence about physical conditions at the surface will be hard to obtain. On the other hand, for some other planets the absence of an atmospheric shield against strongly ionizing electromagnetic radiation may mean that life needs to hide beneath the surface, and that could make it hard to detect too.

Chemical signs of life will be distinctive if the abiotic processes that might produce them are implausible, and preferably absent. If abiotic processes are potentially present but weakly active, then unless life produces a very strong signal the evidence will be ambiguous. This then shows that the presence of life is unlikely to be determined by the mere presence or absence of some material, but rather by the determination of the quantity of the material coupled to an analysis of potential source and sink rates. Such an analysis will require a suite of good measures that characterize the planet and its environment.

Chemical life like that on Earth has a possibility of revealing itself because it uses reduction/oxidation gradients to manufacture the materials it uses. Earth's interior has materials produced in the reducing environment characteristic of the proto-planetary solar system. As a result, a strongly reducing atmosphere is unlikely of itself to be a useful indicator - it will seem to show that the internal environment of the planet is dominating its exterior. Even if this is untrue, and in the absence of life the exterior would be mildly oxidizing or neutral, that will be extremely hard to prove.

A strongly oxidizing atmosphere on the other hand is less likely. Any volcanic activity will continuously bring up reducing material, which will combine with the oxidizer and remove it. Oxidation is the natural result of photolysis of water and hydrogen escape from the surface of a small planet, so it will be up to the observer to prove that the rate of hydrogen escape is insufficient to cause the observed condition. On Earth at present, water photolysis is about 10^6 times less effective than is oxygenic photosynthesis.

The best chemical evidence for life will be the simultaneous observation of oxidizers and reducers, e.g. oxygen and methane. Then since each destroys the other, there is evidence of simultaneous sources of each, and the prediction of production rates may be possible.

From these comments it can be seen that for very cool planets or large planets which retain hydrogen, proof of the presence of life will require some extraordinary material or process to be present. For most planets and satellites, life may well be present but the evidence of it will rarely be accessible to the remote observer, at least with the minimal telescopes that will make early direct detection of planets. Advanced telescopes either ones that image the planet as a single point, but produce detailed high signal-to-noise ratio spectra or ones that eventually image the surface, or probes that visit the planetary system could have a substantially greater ability to detect life.

Meanwhile, there is a different activity, currently in just a few biochemical laboratories, but likely to become more widespread in the future. Biochemists are exploring the processes of the origin and development of terrestrial life. If the astronomical observations come too slowly, they may be bypassed by our understanding so well how Earth life formed that we can project the likelihood of life developing elsewhere. This will be particularly true if we find that no rare processes occurred in the origin of terrestrial life.

6. Why is life on Earth so readily detectable?

Sagan *et al.* (Sagan *et al.* (1993)) studied Earth from the Galileo spacecraft while it was en route to Jupiter. They noticed three potential signs of life. The first was the suite of strong modulated monochromatic radio signals emitted from our planet, from TV, radar stations etc. The second was the red vegetation edge, especially prominent in Amazonia. The third was the abundant oxygen and weak methane signatures of our Atmosphere.

As we consider the possibility of observing radio waves as with the SETI research, we have to realize how recent is our radio and radar technology. Other technologies such as the steam engine have nearly vanished after only a 200 year reign 10^{-7} of our planet's history. We are at a stage of rapid development in technology, and it would seem that our radio technology using powerful transmissions may well be replaced e.g. by laser transmission over large distances, or by processes we have not yet considered. It may be that there will be signs of advanced technology, but we are liable to confuse the signs of advanced technology with natural noise sources. Shannon has indeed pointed out that an optimum communication will look like noise.

The vegetation red edge is a sign of an internal photoelectric effect, but our experience of such effects have shown some photoelectric effect with a sharp wavelength of cut on,

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and others where there is a near asymptotic rise below the critical wavelength. The chlorophyll edge that we see could appear at some other wavelength, and the energy requirements for oxygenic photosynthesis operated by coupled processes could permit the photoelectric edge to be at a wavelength of as long as 1 micron - it all depends on the energy loss of electrons as they cascade down a biochemical pathway. Even though for some places on Earth there is a remarkably strong edge, the integrated signal is quite small Arnold *et al.* (2002), Woolf *et al.* (2002), Seager *et al.* (2005). The problem is perhaps that land vegetation requires abundant water, and this is mainly present in regions with frequent cloud cover. The vegetation red edge mainly seems to be a signal to be explored when there is good spatial resolution over a planet such as Sagan *et al.* used.

Finally, we come to the various signatures of oxygen, methane, nitrous oxide etc. To us this is compelling evidence of the presence of life. But it is compelling because we have good evidence of the surface conditions on Earth. It will be hard to know nearly as much about a remote planet. Atmospheric oxygen has a turn over time of about 10,000 years because 99.9% of the oxygen is used up in oxidizing the organic material produced, and so production and destruction rates are close to equilibrium. The high oxygen abundance in Earth's atmosphere occurs because destruction processes are relatively inefficient. In the Carboniferous Era, before white rot fungi had developed as a way of demolishing dead trees, oxygen destruction was even less efficient and the oxygen abundance was as high as 35%. At the extinction event at the Permian Triassic boundary (of uncertain cause) the abundance was for extended periods near 10%. In the Proterozoic Era, when oxygen production was likely within a factor of a few of that today, the oxygen abundance was much lower, perhaps because the small structures of bacteria were more easily oxidized. Even more disturbing is the evidence suggesting that oxygenic photosynthesis could plausibly have been around for 1.5 Gy before the atmospheric oxygen content became appreciable. The transition to a weak oxygen atmosphere is currently an unexplained event, somehow coupled to the great snowball earth events near 2.3 Gy ago, and the late Proterozoic rise to near present levels seems associated with a second set of snowball earth events. Since we plan to use an oxygen atmosphere as an indicator of an inhabited planet, we need to understand why our atmospheric oxygen abundance has responded so strangely to both glaciations and to biological production.

We have Earth as a planet that at present has easily visible effects produced by life. Perhaps this is connected to the presence of oceans. Some of this is because surface life is protected by our atmospheric ozone layer, but our atmosphere is still substantially transparent. Some of the visibility is an effect of recent human technology, part of a rapid transition and therefore of doubtful duration. It is interesting and curious. It is worth looking for such easily observable effects elsewhere (e.g. SETI). The terrestrial signatures phenomena as a group also deserve more study. If a not-Earthlike planet is beyond the solar system, the prospects of being able to identify the activity of biological processes appears to be substantially reduced.

7. Determining the characteristics of a planet from its spectrum

The distinction in the title of this section, which was supposed for the title of this talk is not a very helpful one. The first issue is to detect terrestrial planets rather than to characterize them. En route to that major achievement, we will be learning how to take the planet's spectrum, and the first region where we observe will be set by technical capability rather than a strong scientific preference. Because of the difficulty in proving that we have a planet, either habitable or with life, we need all the information from all spectral regions we can get!

The boundaries of infrared and ultraviolet are set by the sensitivity of the eye and do not match the boundaries of present day or likely future detectors. Likewise the boundary between the reflection spectrum of the Earth and its emission spectrum is not at one end of the infrared but rather near the geometric mean of the infrared spectrum, either might be considered and infrared detection! The main vibrational transitions of molecules are in the mid infrared, but electronic transitions such as in chlorophyll A are at one end of it. Rayleigh scattering is one of our better measurers of atmospheric pressure varies as λ^{-4}. But the $\tau = 1$ point moves longward with increasing pressure, and in the plausible range of terrestrial planet pressures it can move from the ultraviolet through the visible into the infrared.

The optimum wavelength for having some unambiguous measures is the mm. wave region. Millimeter waves would show a continuum which measures ground temperature. The 5mm oxygen line measures both amount of oxygen and ground pressure. The 13.5mm line measures amount of water and also gives ground pressure. A radio interferometer could eliminate star radiation 10^5 times the planet signal, a factor 100 better than for the 9.7 micron ozone line, and there would be a minimal signal from zodiacal dust. Unfortunately the measurement needs several square km of collecting area even with system noise temperature of 10K. So, for the foreseeable future we must consider the IR through UV range.

Each of the 7 octaves of spectrum from 25 to 0.2 μm. has some useful spectral feature to offer! Sometimes strong bands will saturated, and weaker bands will be more informative. Sometimes there will be features overlapped, and additional lines will be needed for confirmation. In general, an identification from a single broad feature is not a good identification, especially if the noise is high. This is why we have the concept of a more sensitive device, Life Finder. Also, there are differences between the emission and reflection spectrum of a planet. All the bands in the emission region of the spectrum are not only telling about the molecules present and their amount, but are also telling about the thermal structure of the atmosphere down to whatever layer develops a high optical depth. Likewise the reflection spectrum is good for telling about the quantities of material in the atmosphere above some reflecting layer, perhaps ground, perhaps cloud, but the temperature of the various layers is not determined, and the size of the planet and hence its mass are ill known. For these reasons examining both spectral regions is desirable.

All bands that we could see in early studies will be in the square root portion of the curve of growth, where the band strength is more determined by the atmospheric pressure than by the amount of the molecule. Though angular resolution is good in the visible region of the spectrum, the near infrared just longward offers a much better view of some key features related to habitability. Each of the 7 octaves of spectrum from 25 to 0.2 μm. has some useful spectral feature to offer! Sometimes strong bands will saturated, and weaker bands will be more informative. Sometimes there will be features overlapped, and additional lines will be needed for confirmation. In general, an identification from a single broad feature is not a good identification, especially if the noise is high. This is why we have the concept of a more sensitive device, Life Finder. Also, there are differences between the emission and reflection spectrum of a planet. All the bands in the emission region of the spectrum are not only telling about the molecules present and their amount, but are also telling about the thermal structure of the atmosphere down to whatever layer develops a high optical depth. Likewise the reflection spectrum is good for telling about the quantities of material in the atmosphere above some reflecting layer, perhaps ground, perhaps cloud, but the temperature of the various layers is not determined, and the size

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8. Physical life

Chemical life may not be the only life in the universe. We already have mobile Mars Rovers with sensors, communication power and a little intelligence at the device end. We could imagine devices with more tactile and actuating ability, more intelligence, sensors to observe their internal states, a capability of making mines and factories to reproduce themselves, and a core program that drives them to "survive". This would be one possible example of physical life. We have not seen self-initiated or non-human initiated physical life elsewhere, but there is always a first observation.

Our chemical complexity tends to produce emotional rather than rational responses. In contrast, electronic life with its logic circuits is inherently rational. It will recognize that diversification of habitat is a better survival technique than developing a large population in one place. Indeed too large a population in one place makes it vulnerable and potentially self-destructive. An astronomically wide diversification of habitat is preferred. For an organism with reliance on electricity, places like Earth with chemically active atmospheres and oceans are to be avoided (do not follow the water!). Low surface gravitational potential is helpful, so moons and asteroids are likely habitats. But since stellar radiant energy will be used for most activity, the inner parts of planetary systems are the most likely places. The organisms would be physical autotrophs, and there would likely be minimal chemical signature.

9. Looking Under the Lamp Post

The illustration above is one of many that could be made to show that our universe may have much life that is not spectroscopically detectable. Indeed as has been shown, Earth is likely an unusual place where we think we could observe it from a distance and be fairly sure that life is there. So if Earth-like planets are sufficiently common to be observable, they are obvious candidates to examine for signs of life, and non-Earth like planets will be harder to interpret for signs of life. If Earth-like planets are not common, our next best option will be to observe planetary systems to understand why Earths are rare, and what causes the rarity. We are looking for life, not where it is, but where we can hope to observe it - if it is present. This is analogous to the man looking for his front door key under the lamp post, because that is the only chance he has for finding it.

The study of Earths will be expensive. Looking for Earths will be the hardest task ever attempted in astronomy, requiring telescopes and auxiliary equipment that is large and very precise. How will we persuade our fellow humans to pursue this task, and if we cannot, is there any alternative?

10. The strategy

We already have a short-term strategy! Every astronomer interested in planets, having access to a large ground telescope, and having a suitable discovery strategy is trying to observe extrasolar planets. Those who have a creative understanding of optics are trying to improve the techniques. The next phase will be to make steadily more difficult observations progressing towards a 25 magnitude differential between the planet and its star for the shorter wavelengths of the reflection spectrum, and differentials of 18 magnitudes at mid-IR wavelengths, all at a separation of a fraction of an arc second. New larger telescopes are being commissioned, built or planned. Some are trying to get large telescopes at unusually appropriate sites such as Antarctica. Space projects are being developed, but the large funds required are keeping the projects mostly about 20 years into the future. And the fate of the Superconducting Supercollider is in all of our consciousnesses. Not only do unlikely processes require excellent verification, but the search for them requires convincing a public that prefers sports and cosmetics, and in at least one country, does not even accept the evidence that evolution is a fact.

Our powers of persuasion are limited, because though the appropriate strategy for long-term survival is to expand a living organism's bases to other worlds, our chemical makeup is ill adapted to novel environments. Indeed our expansion on Earth has been to create our preferred environment on a small scale. But in space, the fall-back strategy has to be to make a doubly protected environment, because the terrestrial fall-back of living in the unprotected environment will not work there, and the protected environment becomes small and cramped. Nobody would want to spend a lifetime in a small cramped environment for the benefit of long-term-future descendants. So we are forced to appeal on the grounds of interest rather than usefulness to humanity.

In the long run we require telescopes so large that current economic processes will not support the work. But fortunately current terrestrial economics do not apply to the distant future. We are in the middle of the second industrial revolution, the automation and artificial intelligence revolution. What physical life forms do on their own, particularly off the surface of the earth is not set by our input. They would create their own energy from the Sun, they could create their own substances by mining and refining. They could create their own labor force by factory reproduction. And they would build their own telescopes. The long term study of life in the universe may well be out of human control.

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Discussion

Vakili: You have not explained your choice of spectral region for first observation

Woolf: The choice of the region for initial observations will be set by technological difficulties not yet fully explored. I have previously stated my reasons for being concerned with issue of vibrations. These issues apply principally to observations at short wavelengths using restricted size space telescopes. Other problems of equal gravity may yet surface.