Science Fact

Possible Signs of Life on Venus

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Venus was once thought to have abundant life on its surface, with a humid tropical climate perpetually shrouded in clouds. This was the view of the planet among science fiction writers in the early twentieth century, with such stories appearing right up to the 1960s. By that point, however, space probes and ground based observations had shown that Venus was in fact a hellish place, with a surface temperature high enough to melt lead, an atmosphere so thick that surface pressure is nearly a hundred times that of Earth, and clouds made up of concentrated sulphuric acid. A place more hostile to life is hard to imagine.

And yet a team of scientists, of which I am one, has recently claimed to have found possible signs of life in the Venusian atmosphere.

In this article I will explain what we have found, what it might imply about the nature and history of life on Venus, and what the next steps might be to confirm our results and investigate any Venusian ecosystem more thoroughly.

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Looking for Life

One of the key difficulties in looking for life elsewhere is the problem of what to look for. We already know there are no obvious signs of life on the surface of Mars, Venus, or Titan, for example, since landers on these objects have failed to find the equivalents of plants or animals. This problem is far greater when looking for signs of life on planets around other stars, or in the liquid water oceans that lie deep beneath the icy surfaces of gas giant moons like Europa and Enceladus. We must thus look for more subtle clues to the presence of life.

Liquid water is considered a necessary ingredient for life, though on its own it is not sufficient to indicate life's presence. This is why there is so much excitement about signs of past or present liquid water on the surface of Mars, or beneath the icy surface of Enceladus. For the presence of life to be inferred, in addition to water there must be an indicator of active metabolic processes taking place. It is also helpful if these signs of metabolism are easy to detect and unambiguous, in the sense that they can be produced by life but not by other, nonbiological processes. These chemical signatures for the presence of life are termed *biomarkers*.

The standard example of a biomarker is oxygen (O_2) and its close relative ozone (O_3). There is plentiful free oxygen in the Earth's atmosphere as a result of photosynthesis by plants. It is thus a product of life. In the absence of life, all the free oxygen in Earth's atmosphere would react with other elements (carbon, iron, aluminum, and more) until there was none left. This is because oxygen is highly chemically reactive, and energy is released when it combines with just about anything. The result would be an oxidized atmosphere where there is no free oxygen at all. This is the nature of the atmospheres of Mars, Venus, and, in fact, the early Earth, before photosynthesizing organisms evolved. An oxidized atmosphere, without free oxygen, appears to be the equilibrium state for the atmosphere of a terrestrial planet. A planet found to have an atmosphere rich in oxygen is out of equilibrium, and something has to actively maintain this state. In the case of the Earth, this is photosynthesizing life. Any planets found to have abundant free oxygen in their atmosphere would thus be strong candidates for the presence of life. The next generation of observatories, whether on the ground or in space, that will study terrestrial exoplanet atmospheres, such as the European Space Agency mission concept Darwin, or the NASA mission concept HabEx, aim to search for oxygen and ozone as a biomarker.

However, there is a problem with relying solely on detectable levels of oxygen and ozone as our main test for the presence of life on a planet. If we look at the history of life on Earth we find that while life has been present for at least 3.5 billion years (and maybe as long as four billion years), there has only been enough oxygen in the atmosphere to produce an ozone layer and to be clearly detectable for the last five hundred million years. Thus, if we were to point one of the proposed space telescopes at a distant equivalent of Earth in search of life, it would only be detectable through oxygen and ozone for 1/7th to 1/8th of the time life has been present. For most of its history, life on Earth has been dominated by anaerobic forms, which do not produce or rely on oxygen. Such life is still present on Earth, but since oxygen is highly toxic to it, it hides in pond slime, in the ooze at the bottom of oceans, and in cracks in rocks deep below the surface.

If oxygen and ozone have problems as biomarkers, what else is available? The other classic biomarker is methane. This is produced by many anaerobic lifeforms on Earth as a byproduct of their metabolic processes. In some respects, it can be regarded as the anaerobic equivalent to the oxygen produced by photosynthesis. This would make it an ideal biomarker for earthly anaerobic life on other worlds but for one complicating fact: methane is also produced by geological activity without the need for life. The discovery of methane in the atmosphere of another world, such as Mars where it may have been found, is thus ambiguous. It might indicate the presence of life, but it is just as likely that it is evidence for ongoing geological activity. This is one of the reasons why there is so much controversy around the presence of methane on Mars.

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Other Biomarkers

If methane, oxygen, and ozone are problematic as biomarkers, what else could be used?

The basic requirement for a biomarker is that it is something that would not be present without the action of life. This means looking for chemical compounds that normal equilibrium chemistry will not produce in the typical environments found on terrestrial planets. This is not a small job, but a team of scientists at MIT, led by Professor Sara Seager and Dr. Clara Sousa-Silva, have been sifting through a list of thousands of chemical compounds to come up with good candidate biomarkers for anaerobic life.

One of the top candidates identified as an anaerobic biomarker is phosphine—one phosphorous atom bound to three hydrogen atoms (PH_3). It is a toxic gas that is highly flammable in our oxygen-rich atmosphere. Oxygen-breathing life will have nothing to do with it because it is toxic to them—it is perhaps most famous thanks to its appearance in the pilot episode of the TV series *Breaking Bad* where it is used against a drug gang. (It should be noted that the way it is produced on the show would not work—you have been warned!)

However, while aerobic life has nothing to do with phosphine, it is produced in significant amounts by some forms of anaerobic life. Notable sources of this gas on Earth are piles of penguin dung, putrid ooze in swamps and bogs, and the bowels of some species of badger and fish.

In fact, there is phosphine pretty much everywhere on Earth where oxygen is absent. This makes it a potentially powerful biomarker for anaerobic life on other planets. It can be detected and identified by looking for absorption at wavelengths characteristic of this molecule. This is possible because every molecule has specific modes of oscillation such as bending and stretching of its structure. Thanks to quantum mechanics, each of these oscillations occurs at a specific wavelength. A few of the photons emitted by the thermal radiation of the planet will encounter phosphine molecules as they pass through the atmosphere. Those at wavelengths that can excite the molecule's oscillations will be absorbed, resulting in a drop in brightness at this specific wavelength. This produces an absorption line, and the wavelength of this line allows us to identify the molecule producing it. Calculations show that if phosphine is produced by an alien biosphere in similar quantities to the amount of methane produced by anaerobic life on Earth, then its absorption lines could be detectable by future observatories looking at terrestrial planets up to 16 light-years away.

Phosphine has in fact already been found in our own Solar System, in the atmospheres of the gas giants Jupiter and Saturn. However, it is not a sign of life in these cases. Instead, phosphine is produced in the very hot, ultra-high pressure interiors of these gas giants where there is sufficient energy to shove its constituent atoms together with sufficient force to form the compound. It is then dredged up by convection currents from the interior to the upper levels of Jupiter and Saturn's atmosphere where it can be detected by astronomers. The amount of energy needed to produce phosphine through normal chemical processes is so high that it should not happen at all on a terrestrial planet. This makes it an ideal biomarker—if it is found in the atmosphere of a terrestrial planet there is no known way for it to be produced other than the presence of life.

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A Shot in the Dark

The work on phosphine as a potential biomarker was motivated by the search for life in other solar systems, but why not try to look for it in our own Solar System?

This was the suggestion that Professor Jane Greaves made when I challenged her to suggest some innovative observations that SPICA (the Space Infrared telescope for Cosmology and Astrophysics, a proposed European Space Agency far-IR space telescope and successor to the highly successful Herschel Space Observatory), might make in our own Solar System. The obvious target for such observations was the planet Venus, which, while it has a hellish surface, has layers in its atmosphere at an altitude of 50–60 km, where the temperature, around 0–50° Celsius, is compatible with the existence of liquid water, and the atmospheric pressure is comparable to that on the Earth's surface. This environment has no free oxygen, so anything living there would have to be anaerobic, and is highly acidic, far more than anywhere on Earth. Suggestions that life might be possible in Venus' clouds date back to the early 1960s and Carl Sagan. These suggestions have been bolstered in recent years by observations that show unexplained absorption at ultraviolet wavelengths in the upper atmosphere of Venus.

While SPICA will not fly before the 2030s, Professor Greaves realized that ground-based telescopes operating at millimeter wavelengths could also detect phosphine absorption in Venus, if any existed. We thus proposed to use the James Clerk Maxwell Telescope (JCMT) in Hawaii to conduct some initial test observations to see what kind of limits we could set on the presence of phosphine in our nearest neighbor.

We were granted about eight hours of telescope time in morning twilight when Venus was visible and, in 2017, we got our first observations. Analyzing the data proved to be rather difficult since we were looking for a weak absorption line against the very bright emission of the planet, but, after a lot of heroic work by Professor Greaves and her postdoc Dr. Emily Drabek-Maunder, the spectra came out.

To our great surprise there was what appeared to be a clear detection of phosphine.

Such a surprising result required independent confirmation. We thus applied for time on the giant Atacama Large Millimeter/Submillimeter Array (ALMA) in Chile and, in 2019 we got a few hours of observations. Again, the brightness of Venus proved to be a problem, but again, after a lot of work, this time led by ALMA expert Dr. Anita Richards, the phosphine absorption line we had seen at the JCMT was confirmed.

We had found phosphine, a potential biomarker, in the upper atmosphere of Venus. The amount of phosphine isn't great—about twenty parts per billion—but when none is expected at all, that small fraction was a huge surprise.

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Alternative Explanations

With a detection, rather than the limit we expected to achieve, it became necessary to look much harder into potential explanations that do not involve life. Detailed chemical modeling of all the reactions that could produce phosphine on Venus were examined by Professor Sara Seager's team. This used data from the Russian Venus landers to examine the amount of phosphorous that might be available, and models of the atmosphere down to the surface. None of the thousands of potential reactions examined were able to produce phosphine since they were all endothermic—there was not enough energy available to make phosphine in the amount we had found. This may at first seem surprising given the temperatures and pressures at the bottom of the Venusian atmosphere, but one of the key issues is that phosphine is a phosphorous atom bound to three hydrogens, and Venus is an oxidized environment, where essentially everything is bound to oxygen rather than hydrogen. To make phosphine you have to not only strip away the oxygen that is likely to have bound to the phosphorous, you must also find some hydrogen to bind to it. This presents huge difficulties and even the most optimistic models can only produce one ten-thousandth of the amount of phosphine that we had found.

What about more exotic sources of the chemical? We looked at what could be produced by volcanoes, but Venus would need to have two hundred times as much volcanic activity as it does to produce the level of phosphine seen. We looked at lightning, which may occur in Venus' atmosphere but at much lower levels than on Earth. It turns out that lightning would fail to produce the amount of phosphine seen by a factor of ten million. We even looked at the possibility that phosphorous might be injected into the upper atmosphere of Venus by meteors, but this adds at most a few tons per year, completely inadequate for producing the level of phosphine we see.

To make matters worse, phosphine has a very short lifetime in the atmosphere of Venus. Above an altitude of about 80 km, it is rapidly destroyed by highly reactive radicals, leading to a lifetime of much less than an hour. At lower altitudes, near the base of the atmosphere, the high temperatures and pressures lead to thermal decomposition, as the molecule is broken apart by collisions with other atoms and molecules. This leads to the lifetime of a molecule of phosphine being about three years. At intermediate altitudes things are less clear, with lifetimes likely longer, but depending strongly on the presence, or absence, of various reactive chemicals such as chlorine. However, while phosphine at intermediate altitudes might have a longer lifetime, circulation patterns in the atmosphere mean that it is drawn into a destructive zone on timescales of a thousand years or less. This means that whatever process is producing the phosphine we have found must be operating continuously.

Despite an exhaustive search and examination of exotic production methods including volcanoes, lightning, and meteors, we have been unable to find a clear, nonbiological explanation for its origin.

It may be that there is some strange, unexpected, nonbiological route to producing phosphine in an atmosphere that is otherwise hostile to this compound, but we haven't been able to find it. This leaves us with the possibility that the phosphine we have found is in fact a biomarker, and that there is life in the cloud decks of Venus, at an altitude of about 55 km above the hostile surface.

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A Life in the Clouds

Before we look at the properties of the environment that our putative Venusian microbes call home, let's take a moment to think about whether an aerial biosphere is actually a reasonable thing in an environment we know rather better—Earth's atmosphere.

At first sight, the idea that organisms are living in the clouds seems a little far-fetched. After all, there are no floating aerial plants or algae on Earth. And yet, in spite of low temperatures, the sterilizing effect of ultraviolet light, and the possibility of extreme dryness, there is mounting evidence that microbes can operate quite effectively in Earth's skies, especially inside the liquid water droplets that make up clouds. Gene sequencing techniques have shown that a diverse population of metabolically active microbes live in these liquid droplets. They may even play a role in the formation of clouds.

The one part of the bacterial life cycle that has not been found in liquid droplets in Earth's atmosphere is reproduction. There are likely two reasons for this: the cloud droplets that bacteria live in only survive for three to seven days on Earth; and, secondly, the surface of the Earth is an even more hospitable environment than liquid droplets in clouds. Thus, while bacteria can survive in clouds to be transported over long distances, there is no incentive for them to evolve the processes needed to reproduce in cloud droplets. They just wait until it rains and they land back on the ground.

On Venus, things are very different. Firstly, the surface of the planet is extremely hostile to life, and secondly, cloud droplets can survive for a considerable length of time at the altitude where we have found phosphine—months to years depending on the processes by which cloud layers mix, and the rate at which droplets collide to form larger droplets that are heavy enough to fall to the lower, more hostile parts of the atmosphere.

This gives us a hint as to the possible life cycle of our putative Venusian life. These organisms will likely live inside droplets in the upper cloud decks, at an altitude of 50–60 km, where the temperature is around 40° Celsius and the atmospheric pressure is equivalent to that of the Earth at sea level. The droplets are ferociously acidic—made up of about 85% sulphuric acid and about 15% water—but they are more hospitable than the environment outside the droplets. The organisms live by photosynthesis of some kind, leading to the anomalous absorption seen in the ultraviolet by the Akatsuki space mission, and will reproduce inside the droplet. As time passes, droplets collide and aggregate, getting gradually heavier and less able to remain suspended in the clouds. They begin to fall, entering higher temperature and pressure regions. This means that the organisms have to enter a dormant state, similar to the desiccated spores used by various earthly organisms to survive harsh conditions. Some of these spores will fall out of the atmospheric circulation completely, heading to their doom in the hell that is the surface of Venus. Many, though, will encounter updrafts that bring them back into the more habitable cloud decks, where the desiccated spores act as droplet nucleation sites. Once the droplets have formed around them, the organisms wake up from their spore-like state, and the cycle begins again.

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A Possible History of Life on Venus

How did life come to be in the cloud decks of Venus in the first place? It isn't the kind of environment where we would expect life to emerge, so where did it come from?

On Earth there are a number of places where life might have originated. These include hydrothermal vents deep beneath the surface of the oceans, and tide pools at the edge of shallow seas. While we are unlikely to ever have a definitive answer to the question of where life started on Earth, one factor is common among all the suggestions—the presence of significant quantities of liquid water, which acts as a solvent for the chemicals that form the basis of the first biological systems.

Venus today is very dry, with what little liquid water there is confined to the highly acidic droplets in the cloud decks where we have detected phosphine. But was Venus once very different, and more hospitable to the emergence of life?

Recent NASA models of the early history of Venus suggest that it might have been. These have found that liquid water oceans, compatible with the emergence and development of life, might have persisted on Venus until as recently as a billion years ago. Since life emerged on Earth as much as four billion years ago, this would seem to be ample time for a similar emergence on Venus.

However, something went very wrong for life on Venus about a billion years ago. This is thought to have been triggered by widespread volcanic activity that filled the atmosphere with carbon dioxide so quickly that the usual processes that lead to its removal were saturated, and a runaway greenhouse effect became established. This led to the Venus we see today, whose surface is a veritable hellscape. This disaster was not instantaneous, so there would have been time for life to evolve to come to terms with the developing ecological catastrophe, and to find niches where it might survive in the marginally habitable cloud decks where its traces have now been found.

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The Next Steps

Our result is tentative. It might be that some unusual process that we have not considered can produce phosphine in the atmosphere of Venus without the need for life, so much further work is needed. More observations with ground-based telescopes are underway to monitor the presence of phosphine and to look for other traces of life. Missions to Venus to study the cloud decks in more detail from orbit and to send balloons to float through the acidic clouds will also be necessary. These will hopefully confirm the presence of life and allow us to study it in greater detail.

However, the only way to fully understand how any Venusian biology might work is for a mission to bring back samples that can be studied with the full capabilities of terrestrial biology labs. If there is indeed life in the clouds of Venus, one of the deepest questions we need to ask is how similar it is to terrestrial life. Does it, for example, use similar molecules for heredity, like RNA and DNA, or does it use something different? If we find that its biochemistry is similar to that of earthly life, then the possibility of panspermia, that life evolved once in the Solar System but then spread through meteor impacts to other planets, must be considered. If, conversely, we find it to be very different, then we would have two completely independent instances of the emergence of life, with profound implications for our search for life outside the Solar System.

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Conclusions

Our discovery of phosphine, a biomarker gas, in the upper atmosphere of Venus may fundamentally change our view of life in the Universe, though there is much more work to be done to confirm this result, and to work out its full implications. As a scientist who also writes science fiction, I have at times felt like a character in a story, sworn to secrecy, but bursting to tell people about this amazing result. Now that our paper has been published and press conferences have been given, I can talk about it, but the story is far from over.

References:

Greaves et al., 2020, Nature Astronomy; Seager et al., 2020, Astrobiology; Sousa-Silva et al., 2020, Astrobiology, 20, 235;