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before the

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Chairman Smith, Ranking Member Johnson, and Members of the House Committee on Science, Space, and Technology, thank you for allowing me to testify at this important committee hearing. I was selected for this spot because I chaired the planning committee for a recent National Academies' workshop entitled "Searching for Life Across Space and Time" held on Dec. 5-6, 2016, in Irvine, CA. Henceforth, I will refer to this as the 'Biosignatures Workshop'. As you will recognize, an Academies' workshop is a venue for discussion and debate—an essential effort in allowing the scientific process to unfold. Published proceedings chronicle the presentations and discussions that take place at these types of Academies' activities, and the proceedings from the December event will be published later this Spring. My testimony today will attempt to summarize my personal perspective on key points made by various participants at that workshop. However, I will update this story with four important discoveries, three of which were announced after the workshop was held. And I will attempt to show how the present search for life relates to the ongoing search for intelligent life, which was *not* discussed at the workshop. I should emphasize that I am speaking in my personal capacity as an active researcher and am not speaking on behalf of the National Academies of Sciences, Engineering, and Medicine.

Relation of the search for life to SETI

Interest in the search for life off the Earth has been growing continuously over the last four decades. Many of us are ultimately motivated by the Search for Extraterrestrial Intelligence (SETI), which has been going on for that amount of time, or longer. We would like to know whether there is someone else to talk to out there in the galaxy, or in the larger Universe. The late Carl Sagan helped pioneer this search and inspired millions of people worldwide, including me, to share his aspirations.

In a logical world, however, SETI would have been preceded by a search for less complex forms of life. If life does originate in places other than Earth, then simple life forms are probably more abundant than complex or intelligent life forms, according to the Drake equation that Carl Sagan helped formulate (along with Frank Drake). We started looking for intelligent life first because the technology for building radio telescopes matured well before that needed to look for life itself. Looking for simple life is *difficult*. Within the solar system, we can do this most effectively by sending spacecraft to other planets and observing them either from orbit or from landers/rovers, like the Curiosity rover that is exploring Mars right now. Outside of the solar system, astronomers have identified numerous exoplanets from the ground using the radial velocity, or Doppler, method. More recently, our knowledge of exoplanets has exploded as a result of NASA's successful Kepler Space Telescope mission. Kepler found planets by detecting their transits in front of their parent stars. Thanks to Kepler, we now know the addresses of thousands of exoplanets, and we also know that most stars are accompanied by two or more planets. But we know virtually nothing about whether any of these planets are habitable or inhabited. Figuring this out is our biggest goal for the future.

Subdividing the search for life

At the recent Biosignatures Workshop, we divided the search for extraterrestrial life into four quadrants, as shown in Fig. 1. The two vertical columns represent in-situ life detection (which we can do in the solar system) and remote life detection (which is all that we can hope to do for exoplanets, given present technology). The two horizontal rows represent life 'as we know it' and life 'as we don't know it'. We don't really know how different alien life would be from us, and this affects where we think to look for it, as well as the techniques we might use to identify it.

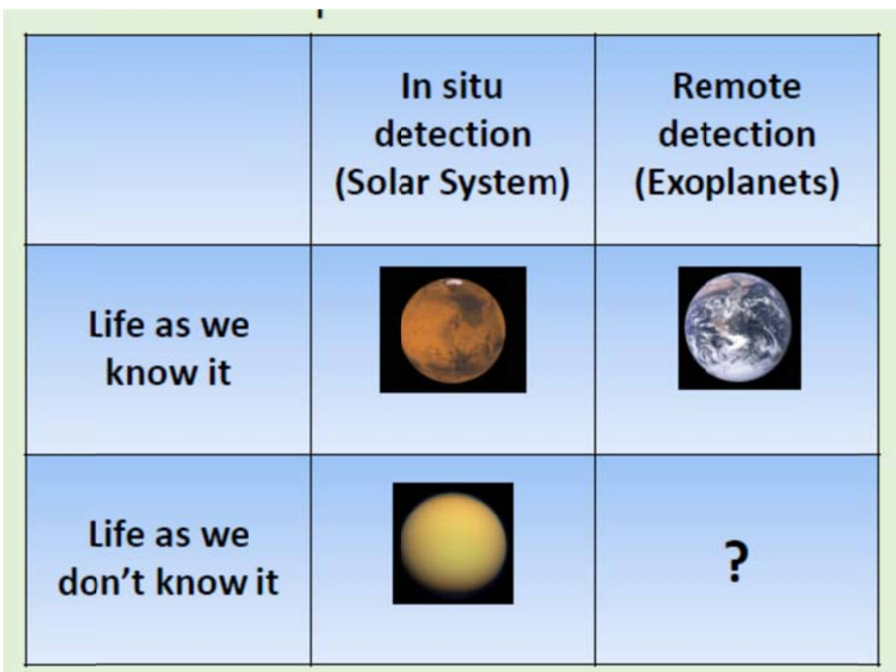

Fig. 1 Schematic diagram showing the four different conceptual areas in the search for life off the Earth. The planetary bodies that are representative of three of these areas are (clockwise from the upper left) Mars, Earth, and Saturn's moon, Titan. The fourth area is undefined for the moment, and likely to remain so.

In situ detection of life as we know it

Mars

Life as we know it here on Earth shares many common characteristics. At its most basic level: 1) Life is carbon-based, 2) it requires the presence of liquid water at least some of the time, and 3) it utilizes the molecules DNA and RNA to store and transfer genetic information. Mars is one planet within the solar system where we might search for this type of life. Indeed, various researchers have proposed that life could have been transferred from Mars to Earth, or vice versa, by meteorites. So, it might not actually be surprising to find DNA-based life on Mars. One workshop participant, Gary Ruvkin from Harvard Medical School, suggested sending a modern, mobile DNA sequencer to Mars. Such machines can detect and analyze extraordinarily small samples of DNA, and would likely be able to find Earth-like life if it was there. But if martian organisms don't rely on DNA, then such a search would be fruitless even if Mars was teeming with life.

Big strides in Mars' exploration have been taken over the last few years by the Mars Exploration Rovers, which began their mission in 2003, and by the Curiosity rover, which has operated since 2014. John Grotzinger from Caltech, who has been involved in both missions, gave an overview of Curiosity results, highlighting the evidence for long-lived lakes. Jennifer Eigenbrode from NASA's Goddard Space Flight Center talked about detection of organic compounds. Organic compounds have indeed been found, but that is to be expected because of continual meteorite bombardment. Bottom line: Curiosity has found additional evidence of habitability—i.e., an environment with conditions appropriate to the support of life at some time in the past—but nothing that would definitely indicate present or past life. Curiosity has also reported seeing methane, in agreement with ground-based observations, but that finding remains controversial. (Some researchers have argued that Curiosity brought the methane with it from Florida.) The ESA-Russian ExoMars Trace Gas Orbiter mission, which is at Mars now and will achieve its science orbit early next year, will hopefully answer this question.

Mars exploration is proceeding at a good rate, with missions launched at nearly every 2-year opportunity. The big debate is whether to concentrate on additional orbiters and rovers, sample return, or human exploration. I will not attempt to weigh in on this question. This will be one of the issues discussed by the 2022 planetary science decadal survey, organized by the National Academies of Sciences, Engineering, and Medicine.

Ocean worlds

Jupiter's moon, Europa, and Saturn's moon, Enceladus, both harbor subsurface oceans and could also conceivably be home to life as we know it. But they differ from Mars in the sense that transfer of life between the outer solar system and Earth is considered unlikely. So, if we were to find life on one of these moons, it would likely indicate that life originated more than once—a point made by JPL's Kevin Hand at the workshop. This in itself would be a discovery of enormous importance, as we still do not know whether the origin of life is a chance event, or whether it happens whenever the circumstances are right. Possible life forms on these moons could still be carbon-based and require liquid water, but whether they would utilize DNA and RNA is an open question that biologists would love to answer.

Update #1: The most exciting news in this field is the recent announcement (made well after the workshop) that molecular hydrogen, H_2, has been identified in the plume emanating from Enceladus' south polar region (J.H. Waite et al., *Science*, 2017). The Cassini spacecraft has flown through the plume multiple times and had previously identified CH_4 (methane) and CO_2 (carbon dioxide), in addition to the major constituent H_2O. Finding H_2, and measuring its concentration relative to H_2O, allowed researchers to estimate the thermodynamic *free energy* available from the reaction: $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$. This is one of the reactions used by methanogenic bacteria here on Earth to power their metabolism. The Cassini researchers calculated that the available free energy in Enceladus' subsurface ocean was an enormous 80±20 kJ/mole. To put this in perspective, methanogens on Earth can typically draw H_2 down until they are only getting about 10-15 kJ/mole. Synthesizing ATP (adenosine tri-phosphate) from ADP (adenosine di-phosphate) requires 35.6 kJ/mole. ATP is the standard unit of energy 'currency' for terrestrial organisms. If the new analysis is correct, there is plenty of free energy available to sustain life in Enceladus' ocean. But we are left to ponder why, if methanogens are there, have they not drawn H_2 down to lower concentrations, as they do here on Earth. Could it perhaps be because they are limited by other factors, e.g., nutrient supply? Given the uncertainties, it would clearly be wrong to conclude at this time that Enceladus is inhabited. But there is lots of incentive to study this object further.

Progress in learning about ocean worlds has been greatly accelerated by the approval of funds for NASA's Europa Clipper mission. Clipper will make multiple passes by Europa and may be able to sample plumes that have been reported based on observations from the Hubble Space Telescope. Clipper should also be able to determine the thickness of Europa's icy crust and take spectra of the brownish material that is thought to ooze up through the cracks. A Europa lander mission, which has been extensively studied but not yet been approved, could take this search even further. It is considered to be technically difficult, though, because of the intense charged particle radiation environment on and around Europa.

In situ detection of life as we don't know it

Titan

Some biologists (and chemists) who like to think 'out of the box' have suggested that life may be a more general phenomenon than what we encounter here on Earth. A formal report issued by the National Academies in 2007, entitled *The Limits of Organic Life in Planetary Systems*, examined this hypothesis in some detail. Informally, this document is sometimes referred to as the 'Weird Life' report. NASA and NSF co-organized a recent 'Ideas Lab' to follow up on this report. Life on Saturn's moon Titan, if it exists, would fall into this category. Titan, which has been explored over the past 15 years by the NASA-ESA Cassini mission and the accompanying Huygens probe, sports lakes of liquid methane. The mean surface temperature is a frigid 93 K, compared to 288 K here on Earth. Whether or not life could originate or survive on Titan is unknown. Earth-like life obviously could not, but perhaps there is some kind of life that could. Finding life on Titan would be even more profound than finding life on Enceladus or Europa because it would suggest that life is an extremely general phenomenon. Some astrobiologists, including me, are skeptical about this idea; however, it is a testable hypothesis that deserves consideration. Indeed, Ellen Stofan proposed a Discovery-class space mission to drop a boat into Titan's methane seas and sample them. Stofan's mission was turned down, not because it lacked scientific merit, but because no one thought it could fit under the Discovery cost cap. It will likely be done someday, not necessarily to find life, but just to see what is there.

Remote detection of life as we know it

Exoplanets

The search for life as we know it extends to exoplanets, as well. None of the other planets in the solar system are truly Earth-like; they differ greatly in their masses, and of course they are all at different distances from the Sun. But rocky exoplanets within the liquid water 'habitable zones' around their parent stars could conceivably be Earth-like. We will not be able to explore them directly, however, at least for the foreseeable future, and so we will have to rely on remote life detection techniques. Life that is present at the surface of a planet can modify the planet's atmosphere in a way that is remotely detectable, using spectroscopy. This falls within my own area of expertise, and so I can report on developments in this area with some degree of confidence.

It was recognized many years ago (Joshua Lederberg, *Nature*, 1964) that Earth's atmosphere is well out of thermodynamic equilibrium and that this is largely due to the presence of life. But thermodynamic disequilibrium, by itself, is not necessarily a sign of life. I have just argued above that the high availability of free energy in Enceladus' ocean—a sign of thermodynamic disequilibrium—could actually indicate that methanogenic life is *not* present. Earth's atmosphere is in extreme disequilibrium for a specific reason: Photosynthetic organisms living on its surface produce O_2 as a byproduct of using H_2O to reduce CO_2 to organic matter. Most of the very large amount of O_2 in Earth's atmosphere, 21 percent by volume, was produced in this way. At the same time, there are anaerobic (O_2-free) regions on Earth where methanogens can produce CH_4. Other anaerobic organisms (denitrifying bacteria) produce nitrous oxide, N_2O, which is also a reduced gas that can react with O_2. Thus, *the simultaneous presence of significant quantities of O_2 and a reduced gas such as CH_4 or N_2O* remains the best remote biosignature that we know of. This realization has not changed substantially for the last 50 years.

Progress has been made, however, in identifying other, somewhat more ambiguous, biosignatures. Some researchers prefer to call these 'biohints'. Our own research group makes computer models of Earth's atmosphere during the Archean Eon, which lasted from 3.8 to 2.5 billion years ago. O_2 was not yet abundant during this period, but life was most certainly present during most or all of this time. Our models suggest that CH_4 should have been abundant during this time period, perhaps accompanied by organic haze. So, early Earth could have looked a little bit like Titan. We would be able to distinguish an 'Earth' from a 'Titan', however, because the 'Earth' would be much warmer and its atmosphere would contain H_2O and CO_2, as well. Both of these gases are completely frozen out of Titan's atmosphere.

Significant attention has also been paid to the question of whether O_2 by itself could be considered a biosignature. This question is motivated by the fact that O_2 would be much easier to spot in Earth's atmosphere than would CH_4 or N_2O, because of its much higher concentration. So, if other Earth-like planets do exist, but not around the very nearest stars, we may well encounter this situation. Consequently, theoreticians like myself have spent considerable time and energy studying the possibility of *false positives* for life, i.e., planets that might accumulate high levels of atmospheric O_2 without life being present. I will mention just one of these false positives here, because it is the easiest to understand: Suppose that you had a planet like early Venus that was initially endowed with lots of water, but that lost that water because it was too close to its star, and so it experienced a *runaway greenhouse*. The H_2O would be photodissociated by stellar ultraviolet radiation, the hydrogen would escape to space, and O_2 would be left behind. Fortunately, this particular false positive would be easy to identify, because the water would be gone. (Unless, of course, we caught the planet right in the act of losing its water. But we would be suspicious of such a planet, anyway, because it would lie within the inner edge of its star's habitable zone.)

I will not bore you with a lengthy discussion of all of the possible false positives, or the ways we might have of ruling them in or out. As I said, there is a growing literature on this topic, which is available on request. I should say that much of this research has been funded by NASA's R&A programs, particularly Exobiology, Habitable Worlds, Emerging Worlds, and the NASA Astrobiology Institute. NASA has been forward-looking in funding these programs, which are helping to lay the groundwork for the interpretation of future exoplanet spectra. As a result, there is now a community of researchers, many of them young (unlike myself), who are poised to take advantage of such data when they become available.

Planets around M stars

Planets orbiting M stars (dim red-dwarf stars) deserve special mention because they are the ones that are most likely to be observed over the next 10-15 years. An Earth-like planet is, by definition, roughly Earth-sized, whereas M stars are significantly smaller than the Sun. Thus, M-star planets create a deeper dip in the star's light when they *transit* (go in front of) the star. The habitable zone of an M star is also much closer to the star (because the star is so dim), and hence the probability of a transit is higher. When the planet transits the star, a small amount of the star's light passes through the planet's atmosphere, and this can be examined spectroscopically. Consequently, M-star planets can be studied with existing and planned space telescopes. Existing telescopes (Hubble and Spitzer) have only been able to characterize gas or ice giant planets (hot Jupiters and warm Neptunes). But the James Webb Space Telescope (JWST), which launches next year, *may* be able to obtain spectra of a few rocky, habitable-zone planets. This, of course, is an extremely exciting prospect.

<u>Update #2</u>: Another major discovery that was announced after the December Biosignatures workshop was the existence of 7 planets orbiting the M star TRAPPIST-1. I will not say much about this discovery, as Adam Burgasser (who was on the TRAPPIST team) will presumably cover this topic in his testimony. At least three of these planets are within their star's habitable zone, and so characterizing these planets spectroscopically has already become a major science goal for JWST. This discovery, like the two that follow, was made using ground-based telescopes.

<u>Update #3</u>: A new transiting, habitable-zone planet was announced just last week orbiting the M star LHS1140 (J.A. Dittmann et al., *Nature*, 2017). This planet was found by the MEarth survey, headed by David Charbonneau of Harvard University. The star is roughly twice as massive as TRAPPIST-1, weighing in at ~0.15 times the mass of our Sun. This will be another likely target for JWST.

Update #4: There is a rocky planet orbiting within the habitable zone of the nearest star, Proxima Centauri. This should actually be update #1, as it was announced at the end of last summer, well before the workshop. It caused quite a buzz at the workshop, and we had a talk by one of the co-discoverers, Matteo Broge. Broge works at the European Southern Observatory (ESO) in Chile and is a member of the HARPS team. HARPS is a high-resolution spectrograph used for making radial-velocity measurements on stars. This discovery is quite unlike the TRAPPIST-1 and LHS1140 discoveries, because Proxima Centauri b, as the planet is called, does not transit. It therefore cannot be observed by JWST in the same way that the TRAPPIST-1 planets can. Instead, if we wish to characterize this planet spectroscopically, we will have to do *direct imaging*: separating the light reflected by the planet from that emitted by the star. This can be done either by placing a *coronagraph* within the telescope or, if the telescope is in space, by placing a *starshade* at some distance in front of the telescope to block the light from the star. Because Proxima Centauri is an M star, it may be possible to directly image its planet from the ground. Broge and his colleagues are designing instruments for one of the 8-m ESO telescopes in the hopes of doing this. Whether they will succeed is uncertain, according to him. Within the next 10-12 years, however, the astronomers in the US, Europe, and elsewhere hope to build 30-40 m ground-based telescopes with state-of-the-art coronagraphs, and Broge was optimistic that Proxima Centauri b can be studied in this way.

Direct imaging of Earth-like planets around Sun-like stars

The ultimate goal in the astronomical search for life is to look for Earth-like planets orbiting Sun-like (F-G-K) stars. Such planets are difficult to study in transit because i) the probability of a transit is small, and ii) the planet is small compared to the star. Think of it this way: an observer looking at the Sun from a great distance would have only a 0.5 percent chance of seeing the Earth transit. That means that we would need to look at ~200 Sun-like stars to find one that had a transiting Earth-like planet, even if every one of them had such a planet going around it. Or, to say this another way, most of the nearby stars probably *do* have planets (based on Kepler), but they remain invisible to us because the plane of their orbit is not within our line of sight. We can only observe such planets by using direct imaging. And, for an Earth-like planet around a Sun-like star, the *contrast ratio* (relative brightness) between the star and the planet is 10^{10}, i.e., the star is 10 billion times brighter. We don't think that we can do this level of coronagraphy from the ground; rather, we need a big, direct imaging telescope up in space.

The good news is that NASA is once again studying such telescopes. (I was involved in such a study 12 years ago for TPF-C, Terrestrial Planet Finder-Coronagraph, but the project was cancelled after only 6 months.) At the Biosignatures Workshop, Shawn Domagal-Goldman from NASA's Goddard Space Flight Center talked about two possible designs for such a telescope. The Habitable Planets Explorer (HabEx) would be a 4-to-6 m diameter telescope designed specifically for planet-finding. The Large UltraViolet-Optical-InfraRed space telescope (LUVOIR) would be a 9-to-15 m diameter general purpose telescope that could also do exoplanets. Both telescopes would be positioned at the Earth-Sun L2 Lagrange point, where JWST is slated to operate. It is my great hope to have a telescope fly while I am still around to see it.

Remote detection of life as we don't know it

For completeness, I will briefly mention the fourth quadrant of the search for extraterrestrial life: searching remotely for life as we don't know it. This quadrant is filled in with a '?' in Fig. 1, because it is not particularly well-defined. Sara Seager at MIT and her colleague William Bains have speculated in the literature about rocky planets with H_2-rich atmospheres in which ammonia, NH_3, is a byproduct of photosynthesis. They have termed such planets "Haber-worlds". Whether or not such planets might exist is unknown. We invited Bains to give a talk at the Biosignatures workshop, though, simply because we did not want to be exclusionary. I personally would not optimize a space telescope to look for such planets. However, if we had a telescope like HabEx or LUVOIR and were using it to make observations, I would agree that one should not ignore the possibility of such planets. With a good direct-imaging telescope, we will simply look at all the nearby planetary systems and see what is there. With luck, we may even find evidence for life. But, in any case, we will learn whether Earth is a special place in the galaxy, or whether Earth-like planets abound. Sara Seager, whom I just defamed earlier in this paragraph, is quite eloquent when she speaks of this search. She calls it 'the second Copernican revolution'. I agree with her perspective. It is within our power, at this time, to make some of the greatest astronomical discoveries ever. I hope that we can find the scientific and political will to make it happen.

With that, I conclude my testimony and I would be happy to address any questions you may have. Thank you, Chairman Smith and Committee Members, for your attention.

James F. Kasting -- Biographical sketch

James Kasting is an Evan Pugh Professor at Penn State University, where he holds joint appointments in the Departments of Geosciences and Meteorology. He earned an undergraduate degree in Chemistry and Physics from Harvard University in 1975 and a Ph.D. in Atmospheric Sciences from the University of Michigan in 1979. Prior to coming to Penn State in 1988, he spent 2 years at the National Center for Atmospheric Research in Boulder, Colorado, and 7 years in the Space Science Division at NASA Ames Research Center south of San Francisco. He co-chaired the Science and Technology Working Group for NASA's proposed (but later cancelled) Terrestrial Planet Finder—Coronagraph in 2005, and he chaired NASA's Exoplanet Exploration Program Analysis Group from 2009-2011. His research focuses on the evolution of planetary atmospheres and climates and on the question of whether life might exist on planets around other stars.