Testimony of
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before the

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Chairman Smith, Ranking Member Johnson, and members of the Committee, thank you for the opportunity to testify today on the subject of the past and future of astrobiology. I do so not as a practitioner in the field, but as a historian of science who for four decades has documented the debate over life beyond Earth, including in the context of NASA (Steven J. Dick and James E. Strick, *The Living Universe*: *NASA and the Development of Astrobiology* (Rutgers University Press, 2004). In that role I can say this is a subject rich in history and promise, and one that fascinates the American public. During my time as NASA Chief Historian, everywhere I went people of all ages wanted to know about life on other worlds. Astrobiology raises fundamental questions and evokes a sense of awe and wonder as we realize perhaps there *is* something new under our Sun, and the Suns of other worlds.

Key Discoveries in Astrobiology Over the Last Decade

The key discoveries in astrobiology over the last decade have evoked that sense of awe and wonder. High on the list must be must be the discovery of planets beyond our solar system, those so-called exoplanets that are the very first goal of the NASA Astrobiology Roadmap. Ground-based telescopes, as well as the Hubble and Spitzer space telescopes, have all contributed to these discoveries. But NASA's Kepler spacecraft has opened the floodgates. Twenty years ago no planets were known around Sun-like stars. As of the end of 2013 more than 1000 planets have been confirmed, and thousands more are awaiting confirmation. Smaller and smaller planets are being detected, including Super Earths and Earth-sized planets. Kepler-37b is only slightly larger than our Moon, one of at least three planets in its system. Kepler-62e and Kepler-62f are only about 50% larger than our Earth, and orbit in the habitable zone of their system. Scientists at the Kepler Science Conference last month reported that smaller planets are now being discovered at the most rapid rate, that most stars in our galaxy have at least one planet, and that one in five Sun-like stars are likely to have Earth-sized planets orbiting in their habitable zone.

A second highlight is the continued search for life in our solar system – Goal 2 of the Roadmap. Past spacecraft, including the Mars Global Surveyor, Mars Odyssey, the Mars Exploration Rovers (Spirit and Opportunity), the Mars Reconnaissance Orbiter, as well the Curiosity Rover, have demonstrated that Mars had enough liquid water in the past to be hospitable for life. In 2008 the Phoenix Lander detected the presence of shallow subsurface water, and only a few months ago researchers reported that Curiosity's first sample of Martian soil was composed of about 2 percent water. The Martian polar caps harbor large amounts of frozen water and carbon dioxide. Meanwhile, spacecraft have probed the icy moons of the outer solar system, including the Jovian moon Europa and the Saturnian satellite Enceladus. Europa almost certainly has an ocean under its icy crust, and Enceladus outdoes its Jovian counterpart by spouting jets of water vapor from beneath its icy surface. The still-ongoing Cassini/Huygens mission has found an atmosphere, believed to be rich in prebiotic organic compounds on the Saturnian moon Titan, and in 2006 discovered lakes of methane on the satellite. In a broader activity, just a few months ago Cassini captured an image of Earth, a pale blue dot against the darkness of space, as seen through the rings of Saturn.

Another of the highlights over the last decade has been to demonstrate further the tenacity of life in extreme environments – Goal 5 of the Astrobiology Roadmap. Life has been found in hydrothermal vents at high temperatures and pressures deep below the ocean; it has been found three kilometers below the ground employing radioactivity rather than photosynthesis for its metabolic processes; it has been found way above the boiling point of water in the brilliant hot spring of Yellowstone and way below its freezing point in the deserts of Antarctica, under conditions of extreme radiation, salinity, acidity and so on. The point is that life is much more tenacious than once thought, and so may arise on planets under conditions once thought unfavorable. Genomic analysis of these microorganisms continues to shed light on how they function.

Recently scientists have found evidence of microbial life in 3.48 billion year-old rocks in Australia, the oldest biosignatures yet found on Earth. These findings also feed into the origins of life debate, and if true, indicate that life arose relatively quickly after the late heavy bombardment of the Earth that ended about 3.8 billion years ago. These findings are likely to remain controversial over the next decade, similar to the Braiser-Schopf controversy that erupted in 2002 over the 3.45 billion year old Apex chert microfossils. Such controversy is an integral part of the scientific enterprise.

These are only some of the highlights of the numerous studies undertaken under the banner of astrobiology. More details are found in the Annual Reports of the NASA Astrobiology Institute (https://astrobiology.nasa.gov/nai/reports/annual-reports/). Uniting all these studies is the concept of cosmic evolution – the 13.8 billion year unfolding of the universe, resulting in galaxies, stars and planets – and in at least one case, life. Cosmic evolution provides the context for astrobiology, which among other things seeks to follow the evolution of organic compounds from the interstellar medium through protoplanetary disks to habitable planets, possibly including delivery by comets, and to understand how these organics gave rise to life on Earth.

Critical Issues and Challenges for Next Decade

The challenge now from an observational point of view is to classify and characterize the newly discovered planets, as well as to search for even smaller ones, especially those in the habitable zones of their parent stars. Over the next decade spacecraft such as the Transiting Exoplanet Survey Satellite (TESS) will search for rocky planets around stars, and the James Webb Space Telescope will further characterize these planets and their potential for life by searching for biosignatures in their atmospheres, Goal 7 of the Astrobiology Roadmap. Already in February of this year detection of carbon monoxide and water absorption lines were reported in a massive planet circling the star HR 8799, revealing the planet's chemical composition, atmospheric structure, and surface gravity (Konopacky et al., Science, 339, 1398). Ever more detailed spectra of ever more planetary atmospheres will surely be a major priority over the next decade. At the same time theoretical studies of the formation of circumstellar disks and planets will shed light on how other solar systems came to exist, illuminating their structure and how unique our solar system is. Numerous theoretical challenges exist, not least to explain how so many planets came to orbit so close to their parent stars.

Among the critical issues in the search for life will be a continued research program on past or present life on Mars, employing spacecraft such as MAVEN just launched two weeks ago. Mars Odyssey, Mars Express, the Mars Reconnaissance Orbiter, the Opportunity Rover, and the Mars Science Laboratory (Curiosity) will continue to return data as long as batteries and funding last. Meanwhile, Mars remains a planet of mystery in many ways. Claims of methane of possible biogenic origin have been made based on observations from Earth and from Mars orbit, but the Curiosity rover, using its laser spectrometer, has not detected any. Mars clearly had surface water in the past, as evidenced by channel and outflow features. Where and when did all the water go? Why did the climate of Mars change so remarkably? Results from the Phoenix lander in 2008 in the form of perchlorates on the Martian surface – a toxic compound of chlorine and oxygen – have even reopened the interpretation of the results of the biological experiments aboard the Viking landers from the late 1970s. These questions, and other, will likely be resolved over the next decade.

Research on the origins and limits of life on Earth will continue with the goal of elaborating a "universal biology" that applies not only to Earth but also to other planets. Today the debate is at the level of the molecular assembly of life, determining the geochemical steps that led to the origin of life on Earth. A major task will be to identify the origin of the first replicating molecules, which some researchers believe to be found in the "RNA world," in which RNA is able to both store information and catalyze reactions. In this scenario RNA was the predecessor to current life, based on DNA. Major gaps remain in this scenario, however, and the next decade could determine whether this, or another theory, comes to the fore. Origins of life work also incorporates the work of the late Carl Woese, who showed that single-celled organisms on Earth ("prokaryotes") actually consist of two distinct domains, archaea and bacteria, and that the archaea are actually closer to the third domain of life, eukarya (including plants and animals).

Work on biosignatures will continue in the atmospheres of other planets, but also in rocks and microbial ecosystems with environments analogous to early Earth. The results from studies of ancient biosignatures on Earth can be used to search for biomarkers on other planets.

One of the most appealing characteristics of astrobiology is that the discipline forces us to ask questions that put in perspective our place in the universe: What are life, consciousness, and intelligence in a universal context, and what are the metaphysical assumptions that underlie our understanding of these concepts? Is there a general theory of living systems, a universal biology as there is a universal physics? What are culture and civilization? What is our place in the 13.8 billion-year unfolding of cosmic evolution? Some of these questions bearing on consciousness and intelligence are beyond the scope of the current NASA astrobiology program, but they are nevertheless an important part of the search for life in the universe. Almost exactly twenty years ago, in the same session that saw the demise of the Superconducting Super Collider, the 103rd Congress terminated the NASA Search for Extraterrestrial Intelligence (SETI) program. In addition to a renewed search with the latest technology, the reinstatement of funding for SETI would allow a systematic examination of these intriguing questions. It would also repair the artificial programmatic divorce between the search for microbial and intelligent life, which, despite engaging different scientific communities, are part of the same research problem. And I believe SETI would be supported by the public, which as always is interested in life beyond Earth, whether microbial or intelligent.

The work described here is carried out by the 15 teams of the NASA Astrobiology Institute (NAI), plus individual grantees in NASA's Exobiology and Evolutionary Biology grant programs. In 2012 alone, NAI teams issued 172 project reports and 849 publications. These teams are guided by the NASA Astrobiology Roadmap, initially developed in 1998, and updated in 2003 and 2008. The 2008 Roadmap is now being updated as part of the 2014 Astrobiology Strategic Plan. The consolidation and expansion of astrobiology's goals over the last two decades demonstrate how the field is rapidly changing based on new ideas and new evidence. (see http://astrobiology.nasa.gov/roadmap/ for all three versions of the Roadmap).

Other institutions in the United States and around the world are also involved in such research. Astrobiology continues to become an ever-more robust discipline, defying past labels as a "science without a subject." That label is a misrepresentation of science. Every science is looking for its subject until it finds it, as in the case of planetary systems, the Higgs boson, and gravitational waves. From an epistemological point of view, the methods of astrobiology are as empirical as in any historical science such as astronomy or geology, though it is true that astrobiological observations and experiments are often especially difficult.

Astrobiology and Society

I would be remiss if I did not mention that among the issues and challenges for the next decade are those related to astrobiology and society. Indeed the Astrobiology Roadmap recognizes as one of its four implementation principles "a broad societal interest in its endeavors." Just as the American Association for the Advancement of Science and the National Science Foundation recognize the importance of studies of Science and Society, and just as some university programs across the country study the interactions of Biology and Society, including the ethical, legal and social implications of the Human Genome Project, so astrobiology raises profound questions with respect to the impact on society.

What will be the effect on our worldviews, philosophies and religions if we discover microbial or intelligent life beyond Earth? Are there useful analogies, such as the changes in worldview in the wake of the Copernican and Darwinian revolutions? A study of the nature of discovery indicates that the discovery of life beyond Earth is likely to be spread over an extended period of time, as in the debates over the Viking spacecraft results, and the ALH84001 Mars rock controversy. A second quite different critical issue in the domain of Astrobiology and Society may be formulated as follows: What are the ethical issues in pursuing the search for extraterrestrial life? How do we balance planetary protection and stewardship with the human exploration imperative, of which astrobiology is a significant part? NASA has for decades had a Planetary Protection program to address these issues, to ensure protection of "all of the planets all of the time." The gravity of the issues can hardly be over-emphasized, not only because of the real prospect of forward contamination of planets, but also because a single "Andromeda Strain" scenario would be enough to jeopardize the terrestrial biosphere.

These are the kinds of humanistic aspects of astrobiology I am studying as part of my time at the Library of Congress, where, in a related event a few weeks ago, we celebrated the opening of the papers of Carl Sagan, known worldwide for his work in astrobiology. Others are also studying these societal impact questions, especially since 2011 when the NASA Astrobiology Institute supported a Roadmap and a focus group on Astrobiology and Society (Margaret Race, Kathryn Denning et al, "Astrobiology and Society: Building an Interdisciplinary Research Community," *Astrobiology*, 12 (2012), 958-965.

Finally let me say that in my view astrobiology embodies the most important ideals of discovery and exploration. I like to quote Nobelist Baruch S. Blumberg – the first Director of the NASA Astrobiology Institute and the inspiration behind the Blumberg NASA/Library of Congress Chair in Astrobiology that I hold at the Library's Kluge Center, which brings together scholars and policymakers. Astrobiology, Dr. Blumberg said, counters the usual academic trends by drawing in numerous disciplines rather than compartmentalizing knowledge and increasing specialization. Moreover, it is in the best tradition of our species, and in the best American tradition dating back to Lewis and Clark to ask great questions, to explore our world and other worlds, to infuse our culture with new ideas, to be changed for the better because of that exploration, and to evoke that sense of awe and wonder as we discover the true place in the universe of our pale blue dot.