NASA Science in the 21^{st} Century

Life in the Cosmos

Intelligent life is how the Universe contemplates itself.

NASA space exploration in the 21^{st} Century is poised to do nothing less than revolutionize how all of humanity thinks of itself, how we contemplate our place in time and space, how we live together on this planet, and how we enable our destiny beyond our planet of origin.

When our descendents look back on this particular moment in time, we will be envied, for NASA is preparing to embark on the great adventure of discovery that will rival all previous voyages of discovery. If we are resolute and creative, we will learn how to sustain and nourish life on Earth and understand the complex web that interweaves our planet with the nearest star, our Sun. We yearn to know whether we are alone in the cosmos, and we will build the exquisite missions of discovery necessary to seek life's other origins at Mars and on planets orbiting distant stars.

Only scientific discovery from space will make this possible and only NASA has the human and technical resources to move from a possible future to humanity's defining adventure of this new century.

The scientific understanding of life's place in the cosmos is embodied within NASA's Vision: *To improve life here, To extend life to there,* and *To find life beyond.*

Our Earth is unique, so far as we know, with flourishing life, and ***To improve life here*** humanity must understand and be able to predict the complexities of a dynamic world, warmed by a nearby star that interacts with our space environment in ways that are far from understood.

We have the basic knowledge of how the Earth and Sun operate and interact, but critical questions remain: How do the changes on Earth affect life? How might humanity contribute to nurturing our planet's environment? What extra-terrestrial processes, such as space weather and cosmic collisions, have the greatest potential impact on life? What does the fate of neighboring worlds tell us about the evolution of Earth? How does the Earth's dynamic climate connect to life of all kinds?

There is much to learn, but understanding is not possible if we remain hobbled to observations only from Earth's surface. Space-based observations with new generations of science facilities will give us the necessary vantage to investigate the interplay of life and the cosmic environment that surrounds it, as played out on the Earth.

Humanity's most buoyant characteristic is exploration and discovery. Such exploration is intrinsic to our nation and is central to the defining charter of NASA. ***To extend life to there*** will achieve our most challenging scientific goals, by using the most effective capability that we can deploy – humans – to make possible that which is otherwise impossible.

NASA has not embraced scientific priorities that can be achieved within only a very few decades using the technologies that we will soon have in hand. That would be unworthy of an agency and a nation that has accomplished so much in the brief period of space exploration. Instead, the nation's scientists have charted surpassing goals that will require equal measures of dedication and imagination, and the capabilities to achieve in the future what today are humanity's greatest dreams. Only NASA has the capability to motivate and support people to develop the technologies, answer the essential scientific questions, and make possible the complex science capabilities and facilities in space that will extend our imagination's reach far into the cosmos.

As humanity travels more frequently and deeper into space, we ask, What can we discover about the nature of life by taking life beyond Earth? How is fundamental biology affected by environments never before experienced? And, what must humanity learn, if we are at some future time to live beyond the Earth?

As we understand life on Earth and begin to extend life beyond our planet of origin, we wonder whether life is a ubiquitous or, alternatively, a small and precious part of the cosmos. Humanity yearns ***To find life beyond*** and NASA has accepted that challenge as the essential core of a long-range plan to search for life, both in our Solar System and on habitable planets around other stars.

There may be no question that science can ask for which the answer will have a more profound effect on humanity's concept of itself than *Are we alone*? Indeed, in centuries to come, people may divide human history into two great epochs, the period of time before we knew the answer and the period of time that followed. Only NASA can lead humanity's grand campaign to answer that question, which will forever change the way that people think of themselves.

As we search for life's abodes, we will enquire as to how it is that the Universe and its fundamental characteristics created the conditions necessary for life. Where and why did life arise on other worlds than our own, both in our Solar System and beyond? And, what is the very nature of life itself? And, if life is discovered, our next challenge will be to seek and understand the origins of intelligence.

***Life in the Cosmos*: the NASA Science Priorities**

To Improve Life Here

We currently have a basic understanding of the Earth system and how it works in general terms. Some of the most significant advances in that understanding: e.g. weather prediction, ocean circulation, ozone characteristics, crustal deformation, and countless others, were enabled by revolutionary satellite observations. However, many key questions remain, and the pursuit of answers to these questions is critical to not just improving life on Earth, but also to helping insure its health and prosperity. We can answer these questions, but only using the vantage point that space offers, both looking toward the Earth and outward deeper into space.

1) How is the Earth changing and what are the consequences for life on Earth?

Life can be effectively improved and protected by: (a) *anticipating* changes in the Earth system, (b) avoiding those that are harmful before they happen, (c) adapting to those that are unstoppable, and (d) capitalizing on those that offer benefits. The key to achieving all of these is ***understanding*** these processes, their causes, the response of the Earth system and associated consequences, ultimately leading to significant improvement in predictability. Achieving these capabilities requires advancement on a number of fronts.

First, we must determine how to improve climate predictions. What is the natural variability of the climate system? How resilient is the climate system? What is the relative importance of various climate feedback processes in regulating the global climate and keeping the planet habitable? It is only by observing the large-scale variability on appropriate temporal and spatial scales that such planet-altering processes can be detected and understood. As we investigate the Earth system with greater sophistication, we will also look outward, investigating how climate is controlled by events such as large-body impacts or solar variability. In addition, we can investigate Mars and Venus to gain unique insights into the major processes that dominate a planet's climate.

Second, on shorter time scales, accurate weather prediction – today already heavily dependent upon observations from space – is still limited to reliable forecasts only a very few days into the future. NASA will lead in using advanced spacecraft, thereby giving more extensive views from space ultimately significantly reducing the uncertainty in weather prediction.

Third, we need to understand how the cycles of water, carbon, and energy, the fundamental components to support life on Earth, will change in the future. Freshwater distribution on this planet is not uniform, and access to this crucial resource has been influential in the success or failure of past civilizations. Similarly, the distribution of solar energy on the planet is variable in geography and time. Being able to predict changes in nature's cycles is critical to our future prosperity as well as the destiny of life on Earth.

Next, the composition of the atmosphere changes over time, and in order to insure that the atmosphere that surrounds us remains sustaining, we need to observe and understand the processes that govern changes, and determine how they are likely to behave in the future.

Finally, NASA intends to open new windows in observing the Earth's surface, which will make it increasingly possible to predict natural hazards. Doing so requires frequent, high-spatial-resolution measurement of three-dimensional structure and changes in active regions on the Earth, such as earthquake zones, volcanic regions, and ice sheets. Moreover, just as we increase our capabilities to study the Earth system in detail, we must also look outward, for example to evaluate the likelihood of "external" hazards, such as meteor impacts, which may require understanding of such events as recorded on the Moon and Mars.

We can achieve these goals using innovative orbits, not yet frequently exploited. Geostationary orbits allow constant long-term viewing for studying rapidly changing processes, such as atmospheric composition, ocean circulation patterns and energy exchanges, and even volcanic deformations (as precursors to major eruptions). We can achieve a quasi-stationary observation capability over higher-latitude regions and the Earth's poles, using continuous-thrust technologies (e.g. solar sails, electric propulsion, etc.) now under development. Observations of three-dimensional atmospheric structure, as well as detailed Earth surface observation, can be achieved from Sun-Earth Lagrange points. Similarly, these Sun-Earth Lagrange points (particularly L1 and L2) provide vantage points for observing how the sun influences the Earth. The multiple Sun-Earth and the Earth-Moon Lagrange points may be ideal sites to survey for extra-terrestrial threats.

2) How do solar variability and disturbances affect life on Earth?

The Sun is the primary forcing mechanism of Earth's climate and is the only external source of energy that supports life on Earth. However, despite its importance, we do not yet understand the effects on Earth of variability in solar output. We have a basic understanding of an 11-year solar cycle, but this has been determined from a short period of observations. Through direct solar observations from space the energy inflow for our planet and our Solar System can be understood in much greater detail.

The behavior of the Sun can most effectively be investigated by solar orbiters, which could include polar, inclined or equatorial. By combining these with sensors at the Sun-Earth libration points, L1 and L2, and sensors at the top of our atmosphere, a comprehensive view of the Sun's physical processes and its interaction with the Earth will be possible.

3) What is our planet's history, and what is its future?

The celestial bodies in our Solar System have evolved in very different ways, and the nature of this evolution holds important clues about our own planet's history as well as its future. Life on Earth is supported through the delicate balances maintained in the cycling of water, carbon, and energy. We need only look to Venus and Mars to appreciate just how different these factors can be in the evolution of the planetary environments.

Mars is particularly intriguing because there is evidence that liquid water was once persistent at its surface, although perhaps not continuously, suggesting that Mars may not have been very different from Earth in some respects. The planet contains abundant water ice in its polar regions, which may hold clues to its evolution, as well as to its cycles of climate variability, which may lead to understanding ice ages on the Earth: exploring Mars history through ice records to determine the similarity of the two planets. Insights into the likely history and fate of our own planet should be profound.

Today, we see Mars as a planet whose earliest history may have mirrored aspects of our own, all of which have long been eradicated in the chemical records that are preserved in rocks. Gaining access to preserved remnants of "early Mars" may reveal clues to the chemical and environmental conditions from which life arose on Earth and, perhaps, Mars.

Closer to home, the surface of the Moon offers potentially remarkable insights into an unknown part of our planet's past. The cosmic impact history of our Earth and the Moon are apparently similar, yet tectonic and erosional processes on Earth have erased much of that past between

~3.4 and 4.7 billion years ago. By examining preserved features of the early Moon, we may understand a part of our planet's history that is not achievable any other way, including the possible history of water as preserved in "old ices" entrapped in unique settings on the present-day lunar surface.

The Moon and Mars are the logical places for such exploration into our planet's history and future because they are within reach, given our current and near-future capabilities.

4) What can we learn about processes in the extra-terrestrial environment that will benefit humans on Earth?

Extra-terrestrial environments influence basic physical and biological processes ways very different from environments on Earth. Consequently, fundamental understanding of how the Universe works must include understanding how our Earth system works, the relationship between life and our physical surroundings, and yet-to-be-discovered possibilities of how life might be influenced by variations in the terrestrial and extra-terrestrial environments.

Therefore, a priority within NASA's science program is understanding the influence of space environments on physical, chemical, and biological processes. Changing the pull of gravity, for example, allows new insights into fundamental physical processes observed in nature, such as fluid flows, material solidification, crystal growth and fundamental chemical kinetics. Similarly, the effects of a planet's magnetic field, such as protection from particle radiation, may be fundamental to life.

As a major goal, we will investigate how structure and complexity arise in nature. Research into complex systems reveals the dynamics of interacting elements and the patterns and structures that result from those dynamics. NASA seeks to explain and predict how order arises from seemingly chaotic interactions.

Finally, we need to understand the biophysical mechanisms that control the cellular and physiological behavior observed in the space environment. The space environment offers a unique laboratory setting for researching complex problems in biotechnology, particularly in the areas of tissue engineering and biomolecular physics. Scientists have only recently arrived at the threshold of understanding interactions of the physical environment with living tissue and space provides a new and challenging laboratory in this critical field.

To Extend Life to There

Extending life beyond Earth not only provides unprecedented opportunities for biological discovery, it is necessary for understanding the nature of life in the Cosmos: whether life is constrained to one world; how life adapts over generations to profoundly different environments; and how to remove biological barriers that keep us close to Earth. Life on Earth evolved in the presence of constant gravity and varying radiation environments. Are these factors essential to the emergence and maintenance of life? What changes are seen in organisms after continued presence in reduced gravity or altered radiation or magnetic fields? The unique environments of space provide an opportunity to answer these questions. In addition, for humans to venture into space, NASA must be able to provide the capabilities to use humans effectively. What new knowledge and technologies are needed for humans to survive far from Earth?

1) What will we discover about life on Earth when we take it deeper into space?

As life has evolved on Earth, only gravity remained constant: all other aspects of the macroscopic environment have changed over time. We now have the opportunity to investigate the role of gravity in fundamental biology and in the evolution of life. Gravity may significantly affect life at all levels of biological organization: from the molecular biology of the cell to the physiology and structure of the tissues, from tissues to organs, from organs to organisms, from whole organisms to ecosystem studies over multiple generations. How will life in all its many forms respond, adapt, and change in response to varying levels of gravity, cosmic radiation, and altered magnetic fields? Extended research programs in various Earth orbits and on the surfaces of Moon and Mars would include species of increasing complexity used to study these forces singly and then in combination in ways not possible on Earth.

How will organisms respond at the molecular and cellular levels to space environments never before experienced by an Earth species? With the complete sequencing of a variety of genomes (from bacteria to humans) and new technologies, space exploration opens new understanding of the nature of life. New genetic and genomic tools can provide us with information on how life responds to unusual stresses at the most fundamental levels.

How do space environments affect organisms throughout their lives? Through experiments in space, we have already been able to solve mysteries in biology dating back to the 19th Century. For example, we have learned that gravity is not needed for plant and animal reproduction, and revealed underlying biological patterns that we never knew existed: unexpected and unique combinations of cancer and bone cells in the absence of gravity.

Is there a “threshold” effect of gravity on major biological and physiological processes? How much gravity is necessary for the normal functioning of essential biological responses? Answers to these questions may well determine the capability that life has for extended space travel. Determination of the minimum amount of gravity necessary for adequate physiological and biological function in free space will not only tell us much about the fundamental mechanisms underlying those biological responses, they can also reveal whether phenomena observed in microgravity – such as bone loss, muscle atrophy, and reduced immune responses – will remain a problem in higher gravity environments such as the surfaces of the Moon and Mars.

How do space environments influence interactions between organisms? Knowledge of the nature and dynamics of ecosystems in space is limited. Computational models of ecosystems on Earth do not yet include gravity as a variable. Understanding gravity’s influence on the fundamental processes of stable, productive closed ecosystems is essential for life support, food production, and waste recycling for long-duration space travel. In addition, the spacecraft, astronauts, and other organisms on board carry their own ecosystems of microbes that must be understood to be safely controlled over extended periods.

2) What do we need to know to survive beyond Earth?

Microgravity produces a range of physiological responses that are potentially risky upon return to gravitational environment or during extravehicular activity. For example, after four to six months in orbit, astronauts lose 30 percent of their muscle mass and 10 percent of their bone mass. How can we counteract those changes, promote adaptation, speed regeneration, and establish safe tolerance levels? In addition, space explorers are likely to experience many of the medical problems that individuals experience on Earth, including illness and accidents. What is needed to maintain a healthy and productive crew for performing science experiments beyond Earth? How can we optimize approaches for systems of human and robotic teams?

How does the human body adapt to space and what are the most effective and efficient ways to counteract those adaptive effects when hazardous? Focusing on understanding, characterizing, and counteracting the body's adaptations to microgravity will enable healthy explorers to accomplish mission objectives and return to normal life following extended periods in space. How can we maintain proper sleep and circadian rhythms of humans during missions of increasing duration and distance? Which medical care systems and the tools will be required to diagnose and treat medical events arising at increasing distances from Earth? The new knowledge and technology required will benefit not only exploration of the cosmos, but also health and safety of humans here on Earth.

How can we limit the risk associated with exposure of humans to space radiation? Understanding the effects of space radiation on humans is of paramount importance in protecting astronauts. Radiation exposure in low Earth orbit (LEO) is already the equivalent of eight chest X-rays per day and beyond 600 miles from Earth radiation levels are three times that and include galactic cosmic radiation (GCR), which is far more hazardous than what we are exposed to on Earth. Understanding and mitigating risks from space radiation requires scientific investigations into fundamental biology, physical and materials sciences, and applied biomedical research.

What technologies are critical for human exploration beyond low Earth orbit? As humans embark on missions of greater duration and distance, we must extend our current technologies for greater autonomy, efficiency, and reliability to create habitable systems capable of maintaining an environment that sustains and protects human health and safety. Development of advanced life-support systems and subsystems will require a thorough understanding of underlying biological and physical processes, including microbiology and the effects of gravity, and which plants and animals will be optimal for providing life support, food, and recycling in life support systems.

What materials/resources exist at the destination and how they can be used? In its report "Safe on Mars," the National Research Council recommends precursor measurements necessary to support human operations on the Martian surface. Instruments deployed to target destinations to make these measurements can characterize environmental hazards, determine the chemical, mechanical, and adhesive properties of soil and dust, and measure surface radiation environments. These are some of the "stepping stones" to understanding required for safe human travel to the surface of Mars.

Space offers an environment where these fundamental investigations about life can be undertaken. The International Space Station (ISS) is essential for determining the long-term effects of space environments and as a test-bed to assess and characterize risks, to begin to understand life's responses to space, and to test countermeasures and medical intervention. One of the most important components of ISS will come with completion of the Centrifuge Accommodation Module, which will allow determination of gravity thresholds for biological processes as well as replication of the 1/6th and 1/3rd gravity environments of the Moon and Mars. Beyond the ISS, additional locations are possible from which to perform biological and medical research. In particular, accessible planetary surfaces – the Moon and, perhaps one day, Mars – provide reduced gravity environments where biological experimentation can expand far beyond what is possible with ISS. The Moon provides the first opportunity to conduct a comprehensive study of life over multiple generations on another world: ten generations in the lives of laboratory animals would be enabled by human missions on the Moon.

With respect to the goal of extending life beyond Earth and low Earth orbit, the lunar surface may offer risk reduction in preparation for longer-duration Mars missions. As a test-bed, the Moon provides a site for human exploration while close enough to Earth for rescue and return. For example, the Moon might be the location to investigate:

- surface extravehicular activity and mobility
- operational strategies
- radiation shielding
- medical effects of partial gravity
- surface habitats
- closed loop life support
- activities associated with handling fragile molecules (i.e., "old ices")

This testbed concept allows for implementing and testing system performance and safety prior to application for longer-duration missions. The opportunity to use the Moon as a proving ground also applies to human performance: lunar surface expeditions would offer a better understanding of crew behavioral health as well as effective human-robotic operations.

To find life beyond

The search for life beyond our planet of origin is one of the most compelling quests in science. Are we alone in the Universe? Or is the Universe, like our planet, crowded with a variety of life that will challenge humanity's understanding of itself?

Does Mars possess life below its surface, as we know Earth does? Can life exist beneath the frigid icy crust of Europa, heated by tidal action and fueled by chemosynthesis? And what of life that we know well, that which consumes and produces oxygen? Are there worlds like the Earth in orbit around neighboring stars, waiting to be discovered by facilities that are still only in the planning stage? The observation of free oxygen in the atmosphere of a nearby Earth-like planet could be the "smoking gun:" evidence for the existence of extra-terrestrial life. And, if life exists beyond our Solar System, has intelligence also arisen?

1) Where and how has life arisen in the Solar System?

Life abounds on planet Earth in virtually all habitats in which liquid water together with energy and nutrients are available, however fleetingly. Given the evidence for life on Earth as far back as the preserved rock record permits, the natural question is whether similar forms of life may have gained a foothold on other planetary surfaces in the Solar System. Current spacecraft-based reconnaissance of the planet Mars points to the significance of liquid water and various sources of energy throughout the knowable history of the Red Planet. Breakthrough scientific observations of Mars in the past few years have pointed to a possible recent period in which liquid water gushes from shallow reservoirs. What is most intriguing about these new findings is the possibility that such cycles have extended far back in the geological record, and that the present-day frozen inventory of water on Mars may have been activated to liquid form for significant periods of time.

Is there evidence for life – now or in the past – on Mars? The Red Planet offers humanity its best opportunity to search for evidence of life beyond Earth by virtue of its somewhat similar geologic and environmental history to that of our own Earth. Evidence of standing bodies of liquid water, hydrothermal vent systems and related deposits, and other intriguing signs are now being discovered, thanks to the ongoing robotic Mars Exploration Program. However, to accelerate the pace of progress in the search for life beyond on Mars, a new spectrum of scientific activities will be needed in the upcoming decades, ideally including return of samples to Earth. Robotic laboratories equipped for biological, chemical, and geological exploration and even for direct life detection via next-generation experimental methods will also be required.

Ultimately, it may require human explorers to set foot on Mars to fully investigate the potential – and if it was ever realized – for life on Mars. In which case, is the environment on Mars tolerable for human exploration, and what must we understand and be able to predict to ensure the safety of future human explorers?

The Moon, under certain circumstances, may offer a kind of "scientific proving ground" for the specific activities in advance of the search for life on the planet Mars. As with Mars, the record of the first billion years of lunar geological activity has been preserved, and in some locations these materials are accessible to both robotic and/or human field explorers. In addition, a record of lunar volatiles (e.g., ices) may have been retained within specific locations. Gaining access to primitive lunar volatiles for evidence of the chemical building blocks of life could serve as an important pathfinder for the kinds of chemical records that must eventually be explored on Mars. As such, the Moon is scientifically one element of several scientific pathways involving the search for life on Mars.

Are there other locations in the Solar System where life may have arisen and gained a foothold? In the realm of the outer planets, there are targets of extreme interest in the search for habitats and, ultimately, life beyond our planet of origin. Compelling evidence for oceans of liquid water has been discovered beneath a frozen crust on Europa, the second of the largest satellites of Jupiter, and exploring the accessible subsurface to search for possible signs of biology associated with a gas-giant planet – similar to those already detected around more than a hundred nearby stars – is a key priority in the decades ahead.

Within the Saturn system, the giant moon Titan is now thought to display surface "lakes" of hydrocarbon materials, as well as having an atmosphere as dense as that of Earth, and composed largely of nitrogen gas. Titan may serve as a revealing natural laboratory for an early time in planetary evolution when primeval atmospheres interacted with rapidly evolving crusts to produce unique habitats prior to the onset of life. Beyond Saturn, the other objects of great significance in the search for life and its origins are Triton, the largest satellite of Neptune, and the mysterious Kuiper Belt Objects (KBO's). These enigmatic objects may contain prototypical organic compounds, some of which could have been transported into the inner Solar System, thereby serving as seed material for the appearance of life on Earth.

2) Is there life beyond our Solar System?

If there is life elsewhere in the cosmos, it is possible it will found outside the Solar System, where the number of potential planets on which life might be found is vast . . . at least so we currently believe: to date, the number of planet-like objects found in orbit around neighboring stars similar to our Sun exceeds 100. However, the objects so far discovered have all been very massive objects, presumably more like Jupiter or Saturn than the Earth, as these are the only types of objects that our technology currently permits us to detect. Within a decade, NASA will have completed the first survey for Earth-sized worlds outside the Solar System and we will have begun to answer some of the most compelling and significant questions about the nature of the cosmos: *How many Earth-like worlds are there? How were they born and how do they change? How might life arise on such worlds. . . and has it?*

Are there worlds like our Earth in orbit around stars like our Sun? We guess at this question today, but a series of increasingly ambitious telescopes and interferometers in space, where they will not be disturbed by vibration, dust, or wide temperature variations, will answer this question over the next two decades. To understand the nature of life, NASA intends to understand fully the nature of planets: What types of planets have formed around what types of stars? It may be that very special conditions are necessary for Earth-like planets to form, which may make life rare. Alternatively, relatively small rocky worlds like the Earth and Mars, warmed by a central star, may be common . . . and so might be life. But it will take large, sensitive optical systems deployed or constructed in space to answer these questions.

If worlds like the Earth and Mars are common, then how frequently does life originate on these worlds? It will be a significant enough challenge to find small rocky worlds in deep space, but an even greater challenge will be to determine whether or not life has arisen on them. To date, most search strategies for life involve attempting to determine the chemical composition of the planetary atmosphere and, subsequently, interpreting whether that composition has been altered by biological – as opposed to purely chemical – processes. The most common concept to achieve this goal is to use vast arrays of large telescopes, carefully pointed toward the target worlds, seeking the signatures in the light from the faint planets that signal that biology has altered a planet's atmosphere. It is a daunting technological task and these large complex facilities may be feasible only with the aid of astronauts and their robotic partners for their deployment and maintenance.

The ambitious missions that will be necessary to seek Earth-like worlds beyond the Solar System will also have significant capabilities to investigate other science priorities for NASA: the birth of the galaxies and the stars, from which the heavy elements are made that make life possible; the deaths of stars, filling the cosmos with the heavy elements that they created while they burned brightly; and the cosmic web of energy and matter, the interaction among the major components that make up the Universe – energetic stars and the matter between the stars.

3) How did life come into being?

There are deeper questions beyond *Are we alone?* That is, *What is the nature of the Universe itself that permitted life to arise? How did life come into being?* This is perhaps the most profound question in all of human inquiry. And NASA has a unique role in understanding this most miraculous event.

Why is there gravity, for example? Without gravity, there would be no galaxies, no stars, and no planets. Gravity is special, in that its force extends to infinity, far weaker than all the other fundamental forces, and only attracts, never repels. It is these characteristics that allow the existence of celestial bodies that can support life. Despite its ubiquity, however, gravity and its origins are still not well understood.

We owe our existence to a finely tuned Universe, where the fundamental constants that dictate the strengths of Nature's forces remarkably have just the right values to support life, at least here on Earth. Even the types of forces that exist seem to conspire to allow life. Consider, for example, when the very early Universe was filled with equal amounts of matter and antimatter. As the Universe cooled, matter and antimatter annihilated each other, producing pure radiation. Eventually, nearly all the matter and antimatter should have disappeared, leaving no massive particles out of which to form atoms, stars, or galaxies. Instead, a tiny, obscure, and as yet unexplained "force" converted one billionth of the antimatter into matter, so that after all the antimatter had annihilated there was a miniscule residue of matter. It is of this miniscule residue that we are made.

Were the fundamental constants of nature to be slightly different, it is likely that life would not be possible. Consider the miracle of carbon: all known life on Earth is based on carbon (organic) chemistry. This is not an accident. Carbon is unique in its chemistry: only with carbon can a vast number and variety of complex, biologically active molecules be formed. Carbon is created in the interior of stars, through the simultaneous collision of three helium nuclei, an extremely rare – almost impossible – interaction that occurs because of a fortuitous characteristic of the nucleus of carbon. Were the nuclear forces in carbon to be slightly different, the production of carbon in the cores of stars would be dramatically reduced, perhaps eliminating the possibility of life. Why is the nuclear force just exactly right? Water, like carbon-based molecules is unique, and it is no accident that it is essential to all life as we know it.

We can even ask why the Universe has three dimensions of space and one of time. If it had four spatial dimensions, could life exist? Remarkably, the number of dimensions of space may be better understood through future NASA missions that test the predictions of superstring theory. Superstring theory, a candidate "theory of everything," requires that Universe be a 10-dimensional space and time, in which we live on only three space dimensions. Why is this?

So many similar questions can be asked. The quest to learn how life came to be is ultimately tied to our understanding of the Universe. How was the Universe born, what is it made of, why is it so big, how did it evolve to its current state which can harbor life? These are questions that have occupied human societies through all of history. Many crucial experimental routes to the answers can only be performed in space. NASA will continue to make profound contributions to the greatest intellectual quest of humanity.

Where should we go in space to perform future investigations needed to answer the questions of "does life exist elsewhere" and "how is that our Universe allows life to exist?" Do we need human involvement in these missions?

Deep-space locations such as the Earth-Sun L2 Lagrange point or Earth-trailing heliocentric orbits are essential, as many future missions require an extremely stable thermal environment. Interferometers, such as those considered for future-generation gravity wave detectors and for detection and spectroscopic analysis of Earth-like planets, require ultra-stable structures and hence exquisite temperature control.

Future gravity wave detectors will be isolated from all external gravitational disturbances such as the nearby Earth. Others, such as large infrared telescopes designed to analyze extra-solar planetary atmospheres, require isolation from contaminating electromagnetic radiation from Earth. Again, for these, L2 Lagrange points or other deep-space locations are optimal.

Spectroscopic characterization and imaging of terrestrial-like planets require light-collecting apertures vastly greater than JWST, with diameters of tens of meters. Such large aperture telescopes would require unfolding, focusing, and alignment to very high precision.. This must be done by robotic automation or with the help of astronauts.

Summary

In summary, deep-space is essential for furthering our search for life beyond the Solar System and for understanding how life could be in our Universe. The complexity and size of the missions proposed to answer these priority questions almost certainly require the capabilities that only humans contribute: dexterity, adaptability, intelligence, and motivation. Such characteristics have always been hallmarks of exploration, even here on our own Earth, throughout the history of science.

Today we must go because the answers to who we are, why we are, and where humanity may be destined beyond this small, rocky world we call home. And NASA can take us there...