Astrobiology Research Priorities for the Outer Solar System

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Introduction

The outer solar system provides a rich and rewarding assortment of planetary diversity of high interest to astrobiology and related research. This White Paper for the 2009-2011 Planetary Science Decadal Survey evaluates the planetary bodies in the outer solar system and their value to the search for life and astrobiology in general. As reference point we chose the NASA Astrobiology Roadmap of 2008 (Des Marais et al. 2008). This roadmap was reviewed by the Executive Council of the NASA Astrobiology Institute and the Committee on the Origins and Evolution of Life of the National Academies of Sciences Space Studies Board. The NASA Astrobiology Roadmap of 2008 is thus the most recent guidance document against which to gauge our astrobiological priorities in the outer solar system.

Relevance to the Goals and Objectives from the Astrobiology Roadmap

Goal 1: Understand the nature and distribution of habitable environments in the universe. Determine the potential for habitable planets beyond the Solar System, and characterize those that are observable.

> *Objective 1.1: Formation and evolution of habitable planets.*
> Investigate how solid planets form, how they acquire liquid water and other volatile species and organic compounds, and how processes in planetary systems and galaxies affect their environments and their habitability. Use theoretical and observational studies of the formation and evolution of planetary systems and their habitable zones to predict where water-dependent life is likely to be found in such systems.

Spacecraft missions to the outer solar system, particularly the Galileo mission and the Cassini-Huygens mission, indicate the potential habitability of planetary bodies in the outer solar system and in effect extended our concept of habitability (which was previously limited to Earth-like planets) to water worlds which are covered by ice. Examples are Europa, Enceladus, and possibly Ganymede, Callisto, Titan, Triton, and even Pluto. Titan is a special case for which habitability may be linked to an organic solvent that forms large liquid pools on the moon's surface. These pools may provide an alternative to water as life-sustaining solvent, albeit in a very low temperature environment. Enceladus is another unusual case, lacking a global ocean but possibly containing subsurface reservoirs of liquid water. There are also many other planetary bodies in the outer solar system that would contribute to our understanding of the formation of habitable environments and acquisition of volatile compounds (e.g., Triton, Iapetus). Clearly, the outer solar system is one of the prime research areas to investigate the accumulation of water, organics, and other volatiles by planetary bodies and elucidate how diverse habitable environments may be.

Goal 2: Explore for past or present habitable environments, prebiotic chemistry and signs of life elsewhere in our Solar System. Determine any chemical precursors of life and any ancient habitable climates in the Solar System, and characterize any extinct life, potential habitats, and any extant life on Mars and in the outer Solar System.

> *Objective 2.2—Outer Solar System exploration. Conduct basic research, develop instrumentation to support astrobiological exploration, and provide scientific guidance for outer Solar System missions. Model the potential for subsurface habitable environments on icy moons such as Europa, Titan, and Enceladus. Support the development of missions to explore the surface ices and thin atmospheres of these bodies for evidence of subsurface habitable environments, organic chemistry, and/or biosignatures*

This NASA Roadmap goal directly applies to many of the outer solar system bodies as stated in Objective 2.2. Past habitable environments may have existed on several of these bodies shortly after their formation and after major impacts. Habitable environments may still persist in the putative subsurface oceans of the larger icy satellites such as Europa, Titan, Ganymede and Callisto. Europa, in particular, may harbor a global habitable ocean beneath its icy surface. Of the icy satellites which do not exhibit evidence for liquids at their surfaces or in their interiors many display spectral absorptions indicating the presence of volatile ices, including organic material. It is likely that deposits of organic and volatile materials persist on several icy satellites; investigation of these reservoirs would shed light on the nature and distribution of biogenic compounds in the outer solar system, and provide insights into the processes and pathways by which they have been created, accumulated, and transported. Smaller moons such as Enceladus may have liquid water reservoirs and organic compounds that could have led to prebiotic chemistry or even life. An even more promising locality for prebiotic chemistry and life may be the near-surface environment of Titan. This notion was reinforced by a recent National Academy of Sciences report suggesting that the environment of Titan meets the basic requirements for life, which include thermodynamic disequilibrium, abundant carbon containing molecules and hetero-atoms, and a fluid environment -- further concluding that "this makes inescapable the conclusion that if life is an intrinsic property of chemical reactivity, life should exist on Titan" (Baross et al. 2007). The primary significance of any life detection in the outer solar system would be that this life would most likely constitute a separate origin from life on Earth, thus allowing an assessment of how different (or exotic) life can be and insights into whether life is common in the universe or not. Also, the detection of life – if present - could be more easily accomplished on the icy satellites of the outer solar system due to the good preservation capacity of ice.

GOAL 3—Understand how life emerges from cosmic and planetary precursors. Perform observational, experimental, and theoretical investigations to understand the general physical and chemical principles underlying the origins of life.

> *Objective 3.1—Sources of prebiotic materials and catalysts.* Characterize the exogenous and endogenous sources of matter (organic and inorganic) for

> potentially habitable environments in the Solar System and in other planetary and protoplanetary systems.
> *Objective 3.2—Origins and evolution of functional biomolecules.* Identify plausible pathways for the synthesis of prebiotic monomers and their condensation into polymers. Identify the potential for creating catalytic and genetic functions, investigate their protobiological evolution, and explore primitive mechanisms for linking these two functions
> *Objective 3.3—Origins of energy transduction.* Investigate, conceptually and quantitatively, the relationship between energy, complexity, and information as applied to the origin of biological systems. Understand how the evolution of molecules, metabolic cycles, linked systems, and organisms is enabled and constrained by the development of energy transduction. Identify prebiotic mechanisms by which energy can be captured, stored, and coupled to energy-requiring processes.
> *Objective 3.4—Origins of cellularity and protobiological systems.* Investigate both the origins of membranous boundaries on early Earth and the associated properties of energy transduction, transport of nutrients, growth, and division. Investigate the origins and early coordination of key cellular processes such as metabolism, energy transduction, translation, and transcription. Without regard to how life actually emerged on Earth, create in the laboratory and study artificial chemical systems that undergo mutation and natural selection.

Goal 3 of the NASA Astrobiology Roadmap pertains to the question of life's origin. The outer solar system provides a rich environment for this quest, partly because it is the source of many of the precursors such as volatile compounds and organics, and secondly because of the environmental conditions existing on some of the larger icy satellites that might provide suitable conditions for the origin and evolution of complex organic chemistry, and possibly even life itself.

In regard to the possible presence of life, both Europa and Titan have a high priority for astrobiology. In the case of Europa, it makes sense to search for life that uses water and a similar suite of biogenic compounds to those used by life as we know it. Based upon NASA's "Follow the Water" strategy, Europa subsurface ocean has a higher probability for life than the subsurface oceans of the other icy satellites. While the likely subsurface oceans of Ganymede, Callisto and Titan are sandwiched between two ice layers, Europa's dynamic activity has us to conclude that an ocean/rock interface is likely and with it the continuous resupply of potential nutrients. Theoretical considerations also indicate the possibility of habitable niches within the ice shell, such as within rising buoyant diapirs (Pappalardo and Barr, 2004).

In regard to Titan, this moon represents a triple opportunity. Apart from potentially exotic life in the hydrocarbon lakes, it also (probably) offers an internal ocean, as well as sites where organics and water may have been temporarily heated up together As an analog to early Earth the study of Titan's atmospheric organic chemistry, and its climate and evolution is invaluable. We can again refer to the National Academy of Sciences report suggesting that the environment of Titan provides the basic requirements for life (Baross et al. 2007). Titan's near-surface environment is an ideal location to investigate a diversity of organic compounds for the possible origin of extraterrestrial protobiological systems. This would employ a "follow the carbon" approach as recently suggested by Shapiro and Schulze-Makuch (2009). If life is present near Titan's surface, it must use something other than water as its universal solvent, and therefore strategies must incorporate methods of detecting a life based on a set of compounds which we are unfamiliar with.

GOAL 7—Determine how to recognize signatures of life on other worlds and on early Earth. Identify biosignatures that can reveal and characterize past or present life in ancient samples from Earth, extraterrestrial samples measured in situ *or returned to Earth, and remotely measured planetary atmospheres and surfaces. Identify biosignatures of distant technologies*

> *Objective 7.1—Biosignatures to be sought in Solar System materials. Learn how to recognize and interpret any biosignatures either in ancient rocks on Earth or in the crustal materials and atmospheres of other Solar System bodies in order to characterize any ancient and/or present-day life.*

Recognizing signatures of life in the terrestrial rock record is an ongoing challenge and serves to demonstrate the complex issues facing astrobiology as we move forward with our search for life on other worlds. Numerous methodologies have been proposed, many of which were detailed in the National Academies report on ‘Signs of Life’ (Committee on the Origins and Evolution of Life, 2000). Chyba and Phillips (2001) summarized many of the key issues and lessons learned since the Viking experiments of the 1970’s. A number of methodologies have been proposed to recognize life unknown to us. For example, Shapiro and Schulze-Makuch (2009) suggested that patterns of monomers can provide evidence of alien life, and Bada (2001) and Aubrey et al. (2008) designed instruments that can provide a census of the subclasses of organic molecules that carry particular functional groups and could be intrinsic to life processes. Dalton et al. (2003) described infrared signatures of biogenic molecules that could be used in remote sensing assays of icy satellite surfaces. Schulze-Makuch and Grinspoon (2005) provided a list of search parameters for possible life on Titan. Given the cold temperatures found in the outer solar system, biomarkers and biological material could be well-preserved in the surface environments of icy worlds, were they collected from ice beneath the radiation and gardening depth. Finally, some biomarkers from outer solar system bodies could be collected from space, a point recently made by McKay et al (2008) for Enceladus, which would reduce mission expenses significantly.

To address the technological challenges facing future missions that will assess the habitability of worlds in the outer solar system a continued, robust research and analysis program is necessary and should be coupled with the science priorities of future missions.

Current Missions in Preparation

There are two major Outer Planet flagship missions currently in preparation by NASA and ESA. They are the Europa Jupiter System Mission (EJSM) and the Titan Saturn System Mission (TSSM). The Europa Jupiter System Mission has been given priority, but continued funding has also been extended to the Titan Saturn System Mission.

The EJSM concept consists of two primary flight elements operating in the Jovian system: the NASA-led Jupiter Europa Orbiter (JEO), and the ESA-led Jupiter-Ganymede Orbiter (JGO). JEO and JGO are designed to execute a choreographed exploration of the

Jupiter System before settling into orbit around Europa and Ganymede, respectively. JEO and JGO are anticipated to monitor dynamic phenomena (such as Io's volcanoes and Jupiter's atmosphere), map the Jovian magnetosphere and its interactions with the Galilean satellites, determine abundances and distributions of surface materials, and characterize water oceans beneath the ice shells of Europa and Ganymede. The scientific goal is to determine whether the Jupiter system harbors habitable worlds. The main science objectives relating to habitability (focusing on Europa and Ganymede) are to:

- Characterize sub-surface oceans
- Characterize the ice shells and any subsurface water
- Characterize the deep internal structure for Ganymede and the intrinsic magnetic field
- Compare the exospheres, plasma environments, and magnetospheric interactions.
- Determine global surface compositions and chemistry
- Understand the formation of surface features, including sites of recent or current activity, and identify and characterize sites for future in-situ exploration.

One unique feature of the EJSM flagship mission in the first in-depth exploration of Ganymede, the largest of the icy satellites and one of the more promising candidates for life. The anticipated time line of the mission in given in Figure 1.

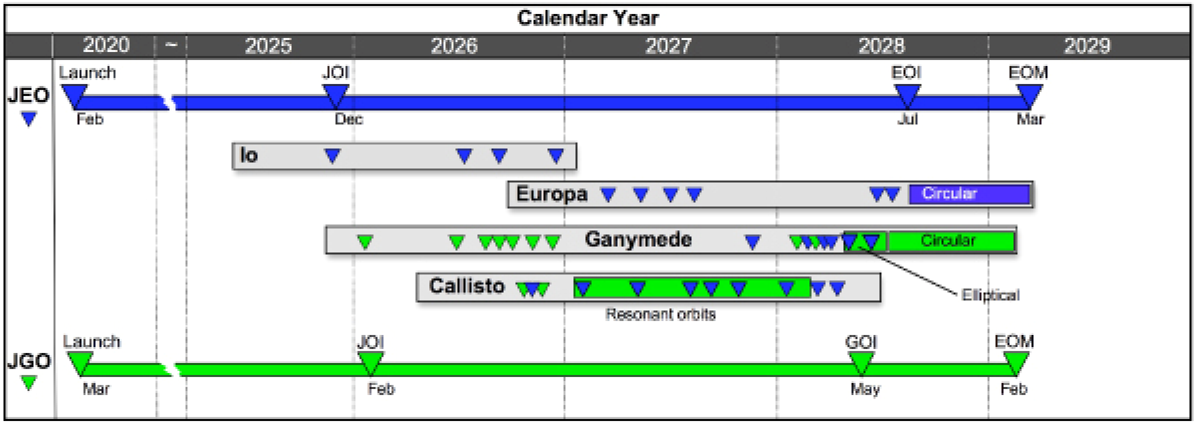

Figure 1. Timeline of the Jupiter Europa Orbiter (JEO) and the Jupiter Ganymede Orbiter (JGO) (http://opfm.jpl.nasa.gov/europajupitersystemmissionejsm/jupitereuropaorbiterconcept/ ; accessed 10 June 2009)

Recommendations: *An inclusion of one or more modest surface landers or penetrators into the EJSM flagship mission would be of special importance to enable sampling of possible subsurface biosignatures on the icy bodies, especially Europa. Potential strategies for a modest lander associated with the Europa Jupiter System Mission are under consideration at present. These would be of great interest to the planetary community at large and have a very high value for astrobiology as in-situ analysis raises the probability to detect biomarkers and is the only way to provide an unequivocal detection of life. Prior to the landing, it is important to gather as much information as possible to ensure that landing site selection optimizes the possibility of discovery.*

As for the EJSM, TSSM is a joint NASA/ESA study. At arrival, the spacecraft would perform an orbit insertion burn to capture into Saturn orbit. The hot-air balloon, targeted for Titan, would be dropped off just prior to the first Titan flyby following Saturn orbit insertion. Data relay from the balloon, floating at 10 km altitude around equatorial regions, would continue through its six-month (or longer) mission via the orbiter telecommunications system. The lander element, targeted for Kraken Mare (a northern lake) would be dropped off at the second Titan flyby and the orbiter would perform dedicated science data capture and relay for the nine-hour length of the lander's mission. During a two-year Saturn tour phase, the orbiter would perform seven close flybys of Enceladus as well as 16 Titan flybys. Finally, the Titan orbit phase would commence with a Titan orbit insertion burn, placing the orbiter in an elliptical orbit that would be used for concurrent aerobraking and aerosampling. The orbit would be circularized over two months, beginning a 20-month Titan orbit phase.

The scientific goals would be to further explore Titan as a comparable system to Earth, particularly to early Earth, to examine Titan's organic inventory as a path to prebiological molecules, explore Enceladus and Saturn's magnetosphere, and decipher clues to Titan's origin and evolution. The investigations would be centered around possible pre-biology or even life as this mission would allow "close and personal" contact on Titan with the balloon and lander, and also allow the direct sampling of compounds ejected from Enceladus into its atmosphere (Figure 2).

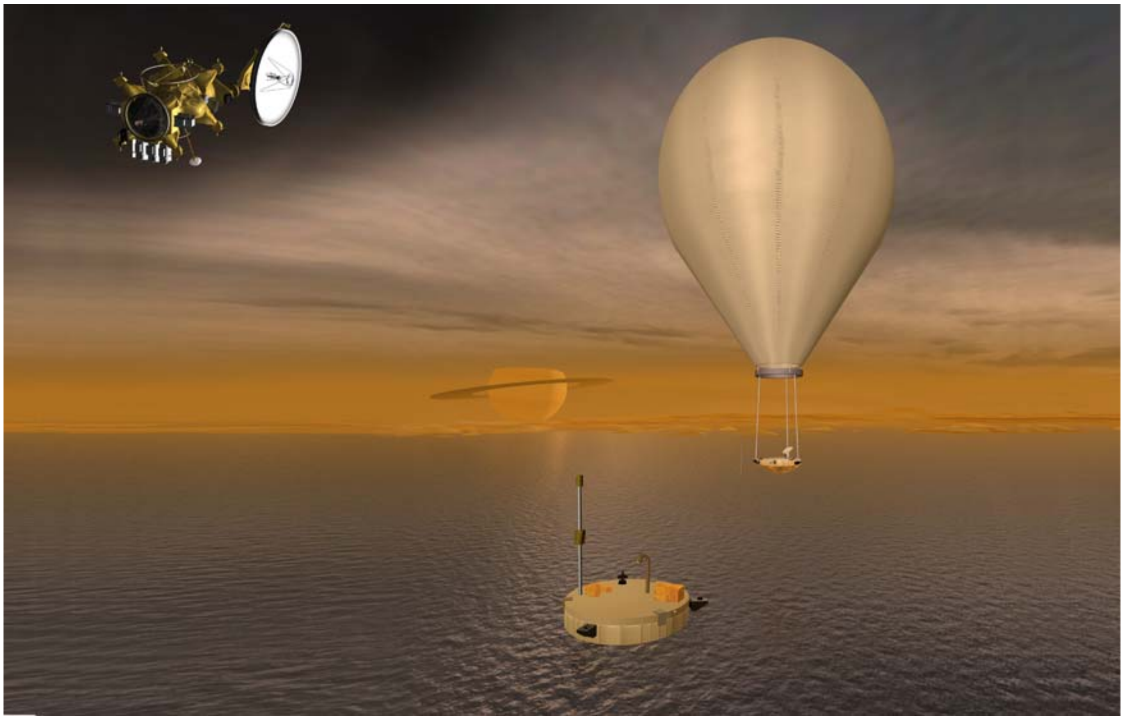

Figure 2. Artistic depiction of a possible scenario for the Titan Saturn System Mission (TSSM). While the Titan-dedicated orbiter provides global remote science, context information, and communications relay, a comprehensive in situ investigation is accomplished via a hot-air balloon and a probe with the capability to land on the surface of a hydrocarbon lake to study the liquid composition. (Credit: Corby Waste, NASA JPL)

While the highest priorities for astrobiology of the outer solar system are the moons of Jupiter (Europa, Ganymede) and Saturn (Titan, Enceladus), the satellites of Neptune and Uranus are largely unexplored and may offer many new and surprising discoveries. For this reason, a Neptune Orbiter designed to investigate the formation of Neptune; the origin, orbital evolution, and habitability of Triton; and the origin and evolution of Neptune's 12 small moons should be considered as a future mission. The same holds for an Uranus Orbiter designed to investigate the formation and dynamics of Uranus, and the origin and evolution of Titania and the other four significant moons of Uranus (Oberon, Ariel, Umbriel, and Miranda).

Conclusions

The astrobiological exploration of the outer solar system provides an enormous potential for discovery. There are many prime candidates to be investigated for habitability, organic inventory, and even life ranging from Titan with its plethora of organic compounds in the atmosphere, in the dunes and in the liquid surface bodies closely related to prebiotic terrestrial chemistry, to Europa, a dynamic, active moon with an internal ocean in direct contact with its upper crust. In the case of Enceladus we can access the organic inventory from space. There are also other intriguing potential targets that should not be neglected, which include Io, Iapetus, Triton, Rhea, Dione, Tethys, Pluto, and many more. Many of the icy worlds on which we have not found evidence for surface or subsurface liquids appear to have deposits of organic and other volatiles on their surfaces and in their subsurfaces, the study of which can inform our theories of how prebiotic materials are produced, accumulated, and transported. Some of this material is likely to have been transported to the early Earth, and could have served as part of our own origin. Compounds of biological and prebiotic chemistry are likely to be preserved in icy crusts of several worlds, and some of these may be easily detected via remote or in-situ methods. The current state of knowledge does not rule out the possibility that organisms of extraterrestrial origin may be found, and several lines of evidence exist suggesting that they may exist on one or another world. Having an example of life beyond the Earth, which may not even utilize water as its primary solvent, is a tantalizing prospect. This kind of discovery would have powerful implications for our theories of the origin of life and biology itself. The implications would engage the public interest and support in a fundamental way, paving the way for continued funding for future missions to the outer solar system and elsewhere.

General Recommendations

Given the huge scientific potential of the outer solar system, current NASA efforts are not satisfactory. One of the main priorities for the next generation of outer planet science exploration is the "in situ" probing through landers, penetrators, or mobile devises on the surface and into the subsurface. NASA should put priority to

develop both laboratory science backing and instrument development to strengthen our capabilities to undertake in-situ investigations of the outer solar system bodies. New missions, including New Frontiers or Discovery class missions, should be designed and flown with the goal to analyze organic compounds and possible biosignatures in situ on the promising target moons of the outer solar system. Undoubtedly, any surface contact would also excite the interest of the general public in solar system exploration and should be strongly encouraged for any major future mission.

Acknowledgements

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