EXPLORATION STRATEGY FOR THE OUTER PLANETS 2023-2032: Goals and Priorities
Outer Planets Assessment Group White Paper

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I. Introduction: The Outer Solar System

Exploration of the outer solar system is central to NASA's objectives. It addresses NASA’s top-level strategic goal as expressed in its 2018 Strategic Plan: to understand the Sun, Earth, solar system, and universe, including searching for habitable conditions and life elsewhere, understanding the origin and evolution of the solar system, and answering fundamental scientific questions about the processes that continue to shape our solar system. The 2018 NASA authorization act from Congress includes “the search for life’s origins, evolution, distribution, and future in the universe.” The outer solar system provides critical evidence for how our solar system formed and evolved, and is home to extensive liquid water oceans, potentially hosting life.

This White Paper summarizes the Outer Planets Assessment Group’s (OPAG’s) priorities as they relate to the Decadal Survey. Our top-priority large, directed missions are, in order, completing development and launching the Europa Clipper mission, a new start for a directed Ice Giant System mission with atmospheric probe(s), and a directed Ocean Worlds mission. Continuation of Discovery and New Frontiers programs is essential to OPAG. In addition, we note the necessity of maintaining a healthy Research and Analysis (R&A) program, which includes a strong laboratory measurements component, and a robust Earth-based observing program. International partnerships are key components of these activities. OPAG’s top two technology priorities are rapid development of a next-generation radioisotope power source for an Ice Giant System mission and development of key life detection technologies in support of an Ocean Worlds mission.

II. Fundamental Science Questions and Outer Solar System Mission Concepts

Decadal Surveys represent an opportunity to review fundamental science questions that are at the forefront of planetary science. At the request of NASA’s Planetary Science Division Director, OPAG undertook a recent survey of its community and devised a set of three “Big Questions” and one unifying theme that encompass NASA Science Divisions for the upcoming Planetary Decadal Survey. Table 1 lists each “Big Question” along with high-level, OPAG-specific sub-questions; the order of the Big Questions does not imply priority. These science questions and sub-questions are consistent with the OPAG Goals Document and with the Roadmap to Ocean Worlds (ROW) document, both of which were developed with substantial community input. In this paper, we evaluate which of the three potential Flagship missions (summarized in Table 2) could address each OPAG science question. OPAG encourages the Decadal Survey to promote destinations, missions, technologies, and supporting strategic investments that address these questions, particularly as they relate to outer solar system investigations.

Big Question #1: What is the distribution and history of life in the solar system? One of the primary opportunities afforded by outer solar system exploration is the chance to explore subsurface oceans. The outer solar system is replete with ocean worlds including Europa, Ganymede, Callisto, Enceladus, Titan, and likely Triton and others. In the inner solar system, only Earth has an ocean today, and oceans may be key to understanding the origin(s) and evolution of life. Ocean worlds may be the best places to search for extant life beyond Earth.

OPAG’s top priority is to complete the Europa Clipper mission, which will provide the knowledge needed to plan a future in-situ search for life. Likewise, the Cassini mission provided required knowledge for future exploration of Titan (i.e. Dragonfly) and Enceladus. Enceladus and Europa are generally considered most likely to be habitable, and have relatively accessible oceans beneath their ice shells. NASA has invested in mission studies to both of those targets, including a large Europa Lander and an Enceladus Flagship concepts. In addition, several Enceladus proposals have been submitted to the Discovery and New Frontiers programs.
| Table 1: OPAG Big Questions and Possible Flagship or Directed Missions that Address them |
|---------------------------------------------------|
| **Outer Planets Assessment Group (OPAG) Big Questions** | **Possible Flagship Missions** |
|                                                      | Uranus System | Neptune System | Ocean Worlds |
| **Big Question #1: What is the distribution and history of life in the solar system?** |             |               |              |
| – Does life or do habitable conditions exist beyond the Earth? | x            | x             | x            |
| – What controls the habitability of ocean worlds? | x            | x             | x            |
| – Do ocean worlds host life now, or did they in the past? |               |               |              |
| – What is the potential for prebiotic chemistry in ocean worlds, and how far towards life has this progressed? |               |               | x            |
| – What role did the giant planets play in the emergence of life on Earth or elsewhere in the solar system? | x            | x             | x            |
| **Big Question #2: What is the origin, evolution, and structure of planetary systems?** |             |               |              |
| – What was the initial chemical profile of the protoplanetary disk as informed by noble gas content in the giant planets, and how did this profile impact the overall formation and evolution of our solar system? | x            | x             |              |
| – What are the possible architectures of planetary systems, and how do these different configurations affect planet formation and evolution (e.g., giant planet migration, tidal evolution, etc.)? | x            | x             |              |
| – What controls the formation, evolution and internal structures of gas giants, ice giants, planetary satellites (particularly ocean worlds), rings, and small bodies in the outer solar system? | x            | x             | x            |
| – How do planetary crusts/cryospheres, oceans, atmospheres, and magnetospheres form and evolve in the outer solar system, and how do they influence the evolution of bodies in those systems? | x            | x             | x            |
| **Big Question #3: What present-day processes shape planetary systems, and how do these processes create diverse outcomes within and across different worlds?** |             |               |              |
| – How do the chemical and physical processes in the solar system scale between planet size and location within the solar system? | x            | x             |              |
| – What is the dynamic relationship between the planets, rings, and moons of giant planet systems, and how do these relationships influence their constituent members? | x            | x             | x            |
| – How do the magnetospheres of gas and ice giants influence the dynamics, composition and structure of the atmospheres, rings, and moon surfaces? | x            | x             | x            |
| – How do the aurorae and induced magnetic fields of ocean worlds characterize the coupling between planets, moons, and magnetospheres? | x            | x             | x            |
| – What are the mechanisms, drivers, and rates for transporting heat and materials within, and ejecting them from, (cryo-) volcanically active worlds? |               |               | x            |
| – How does coupled orbital evolution and tidal heating affect the interior structures and activity of satellites, and how does the interior evolution of the primaries affect this evolution (e.g., resonance locking)? | x            | x             | x            |
| – What drives the transport of energy and materials within the deep interior of the giant planets? | x            | x             |              |
| – How do the atmospheric dynamics, cloud microphysics, radiative transfer, and chemistry interact to form stable and transient features observed in outer planet and satellite atmospheres? | x            | x             | x            |
| – How do the ice giant magnetospheres and atmospheres respond to the impulsive solar wind forcing created by their unusual geometries, and what effect does solar insolation play on weather and upper atmospheric structure? | x            |               | x            |
| **Total number of x’s** | **15** | **17** | **13** |
Big Question #2: What is the origin, evolution, and structure of planetary systems? In a prevailing hypothesis of solar system origin and evolution, the outer planets played a pivotal role in molding our solar system in a complex process that included orbital migration of the giant planets, scattering of planetesimals into the inner solar system, and the delivery of water and other materials that are essential to life to the terrestrial planets. In addition, studies of the ice giants (Uranus and Neptune) have revealed limitations in our understanding of basic planetary formation processes. Models predict that ice giants should be rare, yet exoplanet surveys find that they are abundant. Studying the composition and internal structure of all the giant planets provide insights into how, when, and where they formed. Critical measurements (e.g., noble gases and isotopic ratios) require in-situ measurements by an atmospheric entry probe. While the Jupiter and Saturn systems have had dedicated orbiter missions (e.g. Galileo, Juno, Cassini), and an atmospheric probe has been sent into Jupiter, Uranus and Neptune have never had an orbiter mission. Given the importance of dedicated orbiter missions in understanding the origins of our solar system, exploration of ice giants was a top recommendation in the previous Decadal Survey (Vision and Voyages, 2011). While both Uranus and Neptune systems are compelling scientific targets, critical differences exist between them. Ultimately, both must be explored if we are to understand ice giants as a class of planet. However, because Triton has been identified as a higher-priority Ocean Worlds target than any Uranian satellite, OPAG favors a Neptune mission first.

Big Question #3: What present-day processes shape planetary systems, and how do these processes create diverse outcomes within and across different worlds? The tremendous diversity of bodies in the outer solar system provides the opportunity for a wide variety of scientific investigations. The satellites of the giant planets, some comparable in size to terrestrial planets, and the dwarf planets of the Kuiper Belt (“KBO planets” hereafter) offer opportunities to study extreme environments on worlds that have experienced very different histories. Tidal heating of satellites leads to current activity and conditions potentially favorable to habitability. The rings and magnetospheres of the giant planets illustrate currently active processes (of collisions and momentum transfer) that played important roles in early stages of solar system formation. The volcanism of Io and atmosphere of Titan inform important processes on the terrestrial planets and exoplanets. The vast dynamic atmospheres of all four giant planets also serve as natural laboratories to understand fundamental meteorological processes, which are applicable to other planets including Earth. PI-led New Frontiers and Discovery missions should support these investigations.

Cross-Divisional Theme: How can knowledge of the solar system advance our understanding of the Earth, Sun, and Exoplanets? This question spans NASA’s Planetary, Heliophysics, and Astrophysics Divisions. More specific questions highlighted by the OPAG community are: How does the study of our planet inform our understanding of the outer planets and their moons? How do studies of the diverse present-day oceans in the solar system advance biological, chemical and physical oceanography? How do studies of solar wind interactions at bodies in the outer solar system improve our understanding of the Sun and the propagation and evolution of its dynamic atmosphere? How can solar system bodies inform our understanding of bodies in exoplanetary systems? All missions discussed in this document support the OPAG Cross-Divisional Theme.

For each “Big Question” in Table 1, the number of x’s are summed and then normalized with the results presented in Table 2. The science questions are all equally weighted for this exercise, although some questions are more significant than others. The Neptune system mission, with its possible ocean world, Triton, has the highest score, and is OPAG’s top priority for a directed mission.
Table 2: Summary of Big Questions addressed by each Potential Flagship or Directed Mission

| OPAG Big Questions Summary                                                                 | Possible Flagship or Directed Missions |
|-------------------------------------------------------------------------------------------|----------------------------------------|
|                                                                                            | Uranus System | Neptune System | Ocean Worlds |
| Big Question #1: What is the distribution and history of life in the solar system?         | 0.6           | 0.8            | 1.0          |
| Big Question #2: What is the origin, evolution, and structure of planetary systems?        | 1.0           | 1.0            | 0.5          |
| Big Question #3: What present-day processes shape planetary systems, and how do these processes create diverse outcomes within and across different worlds? | 0.9           | 1.0            | 0.7          |
| Normalized Total                                                                          | 2.5           | 2.8            | 2.2          |

III. Future Missions for Outer Planet Exploration

The science rationale for OPAG's three highest-priority missions was discussed in the previous section. For large directed missions, our top recommendation is to complete the development of and execute the Europa Clipper mission. The Europa Clipper is the first dedicated Ocean Worlds mission, and will provide the necessary knowledge to plan a future in situ search for life. Our top recommendation for a new start is an Ice Giant System mission with atmospheric probe. Flying to either ice giant is scientifically compelling, but Neptune is preferred since Triton is a higher-priority Ocean Worlds target than the Uranian satellites. We note that the rapid development of a next-generation radioisotope power source is critical for an Ice Giant System mission (see Section V).

After an Ice Giants mission, our next large directed mission priority is a mission to search for life or biosignatures on an Ocean World, most likely Europa or Enceladus. OPAG strongly recommends that the next Decadal Survey include a Priority Question about life or biosignature detection rather than just the study of habitability, and that Ocean World mission concepts be evaluated in this context. To support that search, we strongly support ongoing development of life detection technologies.

For New Frontiers class missions, OPAG supports opening competition to all solar system destinations. In particular, we support the continuing exploration of the Ocean Worlds after the Dragonfly mission to Titan, and advocate for the inclusion of an Enceladus as an Ocean World mission along with Io Observer (unless selected in the ongoing Discovery competition) and Saturn probes. Other concepts deserve consideration as well, including missions to KBO planets. Given the abundance of interesting worlds to explore in the outer solar system, target restrictions are particularly onerous for our community.

IV. Earth-Based Activities

Research and Analysis (R&A)

R&A programs are at the core of NASA's scientific research. These programs fund in full or in
part the vast majority of all of the U.S.'s outer planet researchers. R&A encompasses telescopic and Earth-based observations, laboratory measurements and experiments, field work, computer simulation and theory, all of which combine to help us understand the origin, evolution, and destiny of planets and satellites. These results are the fundamental products that drive NASA's future planetary missions. A healthy R&A program is essential to ensuring that our missions make the most useful and scientifically valuable measurements, and are thus key to mission success. These programs also inspire the public, educate youth, and train future scientists and engineers.

**Earth-based Astronomy**

Earth-based observations of outer solar system bodies play an important role in the present and future goals of NASA. These observations, which include those made by Earth-orbiting telescopes, sub-orbital missions (e.g. sounding rockets and long duration balloon experiments), and ground-based optical and radio telescopes, have been enormously productive for planetary science at low cost to NASA’s Solar System Exploration program, and have provided critically important measurements that have complemented deep space missions. While many of these programs are funded by other divisions at NASA, it is important that the scientific merit of outer solar system observations be emphasized as a key element in the Decadal Survey. It should also be noted that sounding rocket and suborbital research programs provide a unique combination of cost, flexibility, risk tolerance, and support for innovative solutions that make them ideal for the pursuit of unique scientific opportunities, the training of new instrumentalists and PIs, the development of new technology, and infrastructure support.

**Laboratory Measurements and Field Work**

Laboratory measurements and field work provide the “ground truth” for interpreting a wide range of data sets. Without them some observations can be undecipherable, or worse yet, misinterpreted. As our space-borne instruments have advanced, and as we probe deeper into extreme environments on other planets, there are new needs for such ground truth measurements. For example, many observed spectral features remain unidentified, extrapolated mechanical or rheological properties of materials cannot explain observed geophysical behavior, and sources of observed atmospheric radio opacity are unknown beyond educated guesses. Similarly, the search for Earth-analogs of geologic features that might exist on other planets, and testing instruments and techniques in those environments, is crucial.

**International Partnerships**

The science community and NASA have benefited tremendously from international cooperation. Recent missions such as Cassini-Huygens and Juno have taken advantage of substantial foreign contributions, enabling NASA to jointly explore Titan in-situ (via ESA’s Huygens Probe delivered by Cassini) and to more cost-effectively explore the Jupiter system, respectively. NASA’s relatively modest investments in foreign missions such as ESA’s Mars Express and Rosetta have led to remarkable discoveries with contributions by U.S. planetary scientists. Cooperation between space agencies allows the best technical minds across the world to become engaged and this results in better measurements, instruments, and analysis techniques, which add balance to the overall exploration program. These benefits can be most reliably achieved if international cooperation is implemented at Phase A or earlier, as occurred for Galileo, Cassini-Huygens, and Juno, and is currently occurring for JUICE. Effective international involvement is strongly encouraged in the planning, development, and analysis phases of all space missions to the outer solar system, beginning at the earliest stage possible.
V. Technology

The outer planets inhabit a vast region populated by a rich collection of diverse objects, each with stories to tell about the origin and evolution of our solar system. Their large heliocentric distances and large planetary masses result in technological challenges common to any mission of scientific exploration to the outer solar system. These challenges call for technologies at or near the forefront of current capabilities, except for the challenge of providing electric power, which requires performance beyond what is currently available. At this time, there is no radioisotope power system (RPS) suitable for a long-duration outer solar system orbiter, making that a top technological priority. The only RPS currently under active development is NASA's NextGen RTG, and the schedule for that development might not accommodate launch opportunities for high-priority outer solar system missions. Advances in other areas can greatly enhance the science return of outer solar system missions.

The goal of detecting life on an Ocean World (or any other planet in our solar system) is also an open challenge which is under significant development. Issues could arise from investigations that are insufficiently agnostic (i.e. too ‘Earth-centric’), and measurements may be complicated by interfering species or sampling limitations. Optimal biosignature detection strategies will likely involve multiple, independent tests for life, such that all possible abiotic explanations for the results may be effectively ruled out. OPAG strongly encourages continued investment in development of life detection instruments, as well as supporting technologies (sampling systems, contamination control, planetary protection, etc.) to address this ‘civilization-level’ science in the next decade.

Aerocapture, while not enabling of the priority missions we recommend, is potentially enhancing across the solar system. For OPAG, it has particular relevance for missions to Titan and Neptune. Essentially a variant of guided entry methods already in use, aerocapture itself requires no new technologies, and as concluded by engineering studies does not require flight validation before use at less challenging destinations such as Titan, Mars or Venus. OPAG urges a prompt (and thus inner solar system) use of aerocapture. Performance characteristics gleaned from such a mission would prepare for subsequent use of aerocapture at more challenging destinations such as Uranus and Neptune. Those destinations might require technology development in such areas as high-L/D aeroshells, drag modulation systems, and advanced thermal protection system (TPS) materials.

The breadth of technology needed for outer planet exploration calls for an aggressive and focused technology development strategy that aligns with the Decadal Survey's recommended mission profile, and that includes technologies developed by NASA as well as acquisition of applicable technologies from other government and commercial sectors. OPAG specifically advocates for a focused technology program for the next Outer Planet Flagship to be ready for a launch in the late-2020s. A full discussion of technology needs can be found in a companion white paper (T. Spilker, et al.).

To explore the outer solar system requires advanced technology. OPAG recommends the following to enable this exploration:

- NASA should work with the relevant agencies to complete the development of the full 1.5 kg/year Pu-238 production capacity on a schedule consistent with providing needed material for future outer planet missions.
- A focused technology program for the next mission in an Outer Planet Flagship Program should be initiated in order to be ready for a launch in the late 2020s. This must include a next-generation radioisotope power system suitable for a long-duration orbiter.
• NASA should expand the funding of advanced communication and radio science technologies required for outer planets, especially increasing data rate capabilities from ice giant planets.
• NASA should continue to invest in the development of underlying technologies (thrusters, power and control, propulsion technologies) for solar-electric propulsion.
• NASA should invest in aerocapture technologies and implement incentives for its use at less-challenging destinations.
• For planetary probes, OPAG recommends investment in maintaining heritage and developing alternative thermal protection system (TPS) materials.
• NASA should invest in life detection technologies suitable for use on an Ocean World.

VI. Summary

Exploring the outer solar system is difficult but immensely rewarding. Voyager, Galileo, Cassini-Huygens, and New Horizons rank among humankind’s great voyages of exploration. The OPAG Goals Document outlines an exciting course to continue this epic exploration in the upcoming decade. For large directed missions, our top recommendation is to complete Europa Clipper. Our top recommendation for a new start is an Ice Giant Systems mission with atmospheric probe. Flying to either ice giant is scientifically compelling, but Neptune is preferred since Triton is a high-priority Ocean World. A next-generation RPS system is needed for this mission to proceed.

After an ice giant, our next large directed mission priority is a mission to search for life or biosignatures on an ocean world, most likely Europa or Enceladus. Biosignature detection technology development could prove essential to either mission, so we strongly support these ongoing technology development efforts. We strongly recommend that the next Decadal Survey include a Priority Question about life or biosignature detection rather than just the study of habitability.

For New Frontiers class missions, OPAG supports opening competition to all solar system destinations. If not entirely open, OPAG recommends continued exploration of the Ocean Worlds after the Dragonfly mission. The outer solar system has an abundance of interesting Ocean Worlds to explore, so ending the Ocean Worlds exploration under the New Frontiers program after Dragonfly would be particularly onerous for our community. OPAG considers continuation of New Frontiers and Discovery missions to be essential.

Key References
NASA 2017 Ice Giant Study Report: https://www.lpi.usra.edu/icegiants/mission_study/
Roadmaps to Ocean Worlds (ROW) study report: https://www.lpi.usra.edu/opag/ROW/
OPAG Science Goals document, https://www.lpi.usra.edu/opag/goals-08-28-19.pdf