

Exploration Strategy for the Outer Planets 2013-2022: Goals and Priorities

Outer Planets Assessment Group White Paper

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Executive Summary

Important scientific discoveries continue to be made in the outer Solar System through NASA missions and research programs, such as via the ongoing Cassini mission at Saturn and Titan, the New Horizons encounter with Jupiter in 2007, and Earth-based studies of Uranus and Neptune. The Outer Planets Assessment Group (OPAG) was established by NASA in 2004 to identify scientific priorities and pathways for outer solar system exploration, because the outer solar system provides critical clues to unraveling the mysteries of how solar systems form and evolve, and through the study of bodies like Europa, how planetary systems become habitable and how life has evolved in our solar system. Addressing such scientific questions requires a balanced strategy of outer solar system exploration that includes steady support for vigorous programs of basic research, data analysis, and technology development. Fundamental new discoveries are best made with a mixture of mission sizes that includes large (flagship) missions, along with medium-sized and smaller-sized missions. Such a strategy is most efficiently implemented as a coherent Outer Planets Exploration Program.

Missions to the outer solar system are major undertakings. **1) OPAG recommends that the Decadal Survey explore the possibilities for a program structure/categorization that could allow ‘small flagship’ class missions to be considered,** providing a greater range of choice and capabilities in the mix to balance the size of program elements and science return. With the Galileo mission concluded, the Cassini Equinox Mission in progress, and Juno in development, **2) OPAG strongly endorses the prioritization by NASA of the Jupiter Europa Orbiter (JEO) as the next Outer Planets Flagship and as part of the Europa Jupiter System Mission (EJSM) with ESA.** This collaboration includes a Ganymede Orbiter and an increased focus on Jupiter system science; OPAG strongly recommends support of JEO and EJSM in the Decadal Survey. **3) In addition, OPAG strongly endorses approval by NASA of the Cassini Solstice Mission,** including the Juno-like end-of-mission scenario, given the likely phenomenal return on investment. **4) OPAG also advocates the need for a focused technology program for the next Outer Planet Flagship Mission, which should be to Titan and Enceladus, in order to be ready for a launch in the mid-2020s.** Technologies that require long-term investment for missions beyond the next decade should also be considered. **5) New Frontiers class missions that should be considered in the interim include (but not in priority order) a Titan in-situ explorer or probe, a giant planet probe, an Io observer, a Neptune/Triton/KBO flyby, and exploration of the Uranus system.** OPAG recommends that these be studied, costed, and added to the approved New Frontiers mission set.

I. An Outer Solar System Program

The richness and diversity of the outer planets and their satellites are second to none in the Solar System. The Outer Planets (OP) play a fundamental role in 4 of the top 5 objectives in NASA's 2006 *Solar System Exploration Roadmap*: 1) How did the Sun's family of planets and minor bodies originate? 2) How did the Solar System evolve to its current diverse state? 3) What are the characteristics of the Solar System that led to the origin of life? and 4) How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System? (See, e.g., Hand et al. white papers for the astrobiological importance of OP.)

It is OPAG's goal that its findings represent the broad consensus of the scientific community: meetings are held semiannually, each attended by ~100 scientists and engineers. The meetings consist of a broad range of presentations from NASA HQ representatives, mission PIs, individual scientists, and technology researchers. In our 2006 Report, *Scientific Goals and Pathways for the Exploration of the Outer Solar System* (www.lpi.usra.edu/opag/pathways.pdf), the following elements were identified as key to a successful outer planets program (not in priority order): 1) a mix of mission sizes (for program balance); 2) periodic, large (“flagship”) missions; 3) sustained and focused technology development; 4) supporting research and analysis (R&A); 4) mission concept studies; and 5) strategic planning. A well-thought-out systems approach incorporating all key elements is required to accomplish a successful exploration plan.

Balance Among Mission Size/Architecture

The very scale of the outer solar system presents a fundamental problem for program architecture. In the thirty-plus years since Pioneer and Voyager many advances have been made in spacecraft, sensors, telecommunications, radiation hardening, and mission design. It remains a fact, however, that missions to the outer solar system are major undertakings, often requiring large and expensive launch vehicles, long mission durations, highly reliable (sometimes radiation hardened) and autonomous spacecraft, and radioisotope power sources in most cases. The expense, duration and difficulty of such missions dictate that any given destination in the outer solar system is unlikely to be visited more than a few times during the professional lifetime of a researcher. This contrasts with missions to the Moon, inner planets and small bodies, where major scientific goals can be reached by accumulating results from multiple smaller missions in the course of one or two decades. This situation provides much of the rationale for recommending flagship class missions as a major program element for achieving outer solar system science objectives, as outlined in previous OPAG reports.

The desire to have more frequent access to space for missions with goals that are beyond the capability of the Discovery program led the previous Solar System Exploration Decadal Survey to recommend a line of cost-capped missions intermediate in scale between Discovery and flagship missions. The New Frontiers program responds to this recommendation, and the first two NF missions achieve significant outer solar system goals – New Horizons to Pluto/Charon and the Juno mission to Jupiter. In the course of preparing for the larger studies of flagship missions to Jupiter and Saturn, NASA supported preliminary study efforts to assess whether some of the proposed science objectives for Europa and Titan/Enceladus focused mission concepts might be accomplished within the scope of New Frontiers.

The \$1B Mission Feasibility Study (www.lpi.usra.edu/opag/TitanEnceladusBillionDollarBox.pdf) validated the concept that flagship-class missions are needed to achieve the highest priority scientific objectives for the next stage of Europa/Jupiter system and Titan/Saturn system exploration. However, the results of these studies, as well as other advanced mission concepts studied by the community for possible NF candidates, also suggested that there may be a valuable category of missions which can achieve significant outer planet science goals but which lie somewhat beyond the current resource cap for NF missions, while still being significantly less expensive than a traditional flagship class mission (see also 2006 Solar System Exploration Roadmap).

OPAG recommends that the current Decadal Survey committee explore the possibilities for a program structure/categorization that could allow these ‘small flagship’ class missions to be considered, providing a greater range of choice and capabilities in the mix to balance program elements in size and science return.

II. Technology and Supporting Strategic Investment

Technology investment priorities are guided by the requirements established in mission and system studies focused on the highest priority science objectives. The next Outer Planets Flagship Mission (after EJSM) may involve orbiting one or both of the saturnian satellites Titan and Enceladus. Other potential OP missions include atmospheric probes of the giant planets, *in situ* exploration at Titan and Europa, and flybys or orbiters to the ice giants Neptune and Uranus. The breadth of technology needed for OP exploration calls for an aggressive and focused technology development strategy that aligns with the Decadal Survey recommended mission profile, and includes technologies developed by NASA, as well as acquisition of applicable technologies from other government and commercial sectors. OPAG specifically advocates the need for a focused technology program for the next Outer Planet Flagship in order to be ready for a launch in the mid-2020s. NASA's current plans for an OP flagship program indicate that a mission to Titan and Enceladus will be the highest priority. The challenges common to all OP – large distances, long flight times, and stringent limitations on mass, power, and data rate – mean that all missions can significantly benefit from technical advances in a number of broad areas. A full discussion of technology needs can be found in a companion white paper (P. Beauchamp et al.).

Orbital vs. In Situ in Exploration

Remote sensing, especially from orbiters, is valuable for understanding such *current* physical-chemical processes as radiative transfer, formation and loss of trace neutral, ion and plasma species, meteorology and dynamics, surface composition, as well as existence and size of a core in the giant planets. On the other hand, fundamental questions of the *formation* of the giant planets and the *origin* of their atmospheres depend on a knowledge of elemental abundances, particularly of the heavy elements (mass >4 AMU), which often require measurements in the well-mixed part of an atmosphere, which is less accessible to remote sensing. Similarly, for the study of the icy satellites, in situ measurements are critical for assessing complex chemistry and addressing astrobiology questions.

In situ measurements of Jupiter by the Galileo probe in 1995 revealed that contrary to previous notions, the heavy elements were all enriched relative to solar by a factor of 4 (± 2), with the exception of oxygen (from water, its main reservoir), which could not be determined in the well-mixed atmosphere because the probe entered a very dry spot of Jupiter. The Juno mission is designed to measure water vapor in Jupiter's deep atmosphere by microwave remote sensing. The enriched heavy elements at Jupiter have led to new hypotheses of the formation of the planet and the origin of its atmosphere, clearly demonstrating the need for in situ measurements of the giant planets. For a comprehensive understanding of the outer planets and their satellites, both orbital and in situ measurements are essential.

Aerocapture

OPAG has repeatedly noted that the capability of many outer solar system missions (notably Titan and Neptune orbiters) could be significantly enhanced by the application of aerocapture. Aerocapture requires no new technologies in its own right – it is essentially a variant of the entry system used by Apollo and planned for use on Mars Science Laboratory (MSL) and Crew Exploration Vehicle (CEV) – but it seems to be perceived as sufficiently novel as to require flight validation. A prompt (and thus inner solar system) validation is therefore urged. One programmatic possibility might be a competitive call for studies analogous to the Discovery and Scout Mission Capabilities Extension (DSMCE) call which recently stimulated Discovery-class mission studies using Advanced Stirling Radioisotope Generators (ASRGs).

Earth-based Astronomy

Earth-based observations of solar system bodies play an important role in the present and future goals of NASA. Earth-based observations include Earth-orbiting telescopes (such as HST and Chandra) and sub-orbital missions, which include sounding rockets and long duration balloon experiments. Earth-orbiting observations have been enormously productive in planetary science over the last 4 decades at low cost to NASA's Solar System Exploration program, and have provided critically important measurements that have complemented deep space missions. Sounding rocket and suborbital research programs provide special benefit to our space exploration efforts in key areas that are essential to long-term success. Suborbital research offers a unique combination of cost, flexibility, risk tolerance, and support for innovative solutions that make it ideal for the pursuit of unique scientific opportunities, the training of new instrumentalists, the development of new technology, and infrastructure support.

The scientific importance of solar system observing programs using Earth-orbiting observatories is demonstrated by the hundreds of papers published over the past 30 years, including numerous covers of Science and Nature. While these programs are financed by other divisions at NASA, the missions need to include specific capabilities for planetary tracking and science support. It is important that the scientific merit of these observations be emphasized as a key element in the Decadal Survey, even where specific mission funding is not required.

Laboratory Measurements

Laboratory measurements provide the “ground truth” for interpreting a wide range of data sets. Without them some observations can be undecipherable, or worse yet, misinterpreted. Currently a library of historical laboratory measurements, some recent, some more than a century old, provides the basis for a huge range of important, *reliable* conclusions in planetary science. But there remain gaps where, for instance, 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. Laboratory experiments potentially span the vast range of physical phenomena involved in making stars, planets, satellites, etc., and in their evolution.

A strong program of laboratory measurements is a cornerstone of a successful, sustained national planetary exploration program. This requires not only materials to study, but also the facilities and the skilled researchers, both experienced and new, to conduct them. The outer solar system is an immense region of materials and environmental conditions largely alien to Earth, so a laboratory measurements program is especially important for progress in this vital arena.

Research and Analysis (R&A)

R&A programs are at the core of NASA's scientific research. These programs fund in in full or in part the vast majority of all of the US's outer planet researchers. R&A encompasses telescopic and Earth-based observations, laboratory measurements and experiments, 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 planetary future planetary missions. R&A 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.

International Partnership

Over the past two decades Planetary Science and NASA have benefited tremendously from international cooperation in planetary exploration. Since the late 1980's, most of the large missions – including Galileo, Cassini-Huygens, and Juno – have all taken advantage of substantial foreign contributions, enabling NASA to jointly explore Titan *in situ* (via ESA's Huygens Probe delivered by Cassini) and more cost-effectively explore Jupiter's system. NASA's relatively modest investments in foreign missions such as ESA's Mars Express and Venus Express missions have led to remarkable discoveries and contributions by US planetary scientists. The current plan to conduct synergistic exploration of the jovian system with a joint collaboration between NASA and ESA via EJSM will undoubtedly lead to more remarkable discoveries achieved on a very cost-effective basis to NASA.

Cooperation between space agencies allows the best technical minds across the world to become engaged and results in better measurements, instruments, and analysis techniques. Cooperative missions also enhance efficiency and add balance to the overall exploration programs. Such remarkable scientific enhancements and cost savings by complex international missions can only be reliably achieved, however, if international cooperation is implemented at Phase A or earlier, as occurred for Galileo, Cassini-Huygens, and Juno, and is currently occurring for EJSM. Inclusion of discrete, straight-forward instruments and/or science team in Phase B can also lead to successful, high return-on-investment science, but the degree of sophistication of such involvement is markedly enhanced when implementation begins earlier.

To explore the outer solar system requires advanced technology, a balanced measurement approach, supporting Earth-based observations, laboratory measurements, and R&A, and benefits markedly from international cooperation. OPAG recommends the following to enable this exploration (please also see Beauchamp et al. for greater context for technology recommendations):

- 1. NASA should work with the relevant agencies to ensure that Pu-238 production is restarted and provides enough material for future outer planet missions.**
- 2. A focused technology program for the next mission in an Outer Planet Flagship Program (after EJSM) should be initiated in order to be ready for a launch in the mid-2020s.** Current plans indicate a mission to Titan and Enceladus is the highest priority.
- 3. NASA should expand the funding of communication and radio science technologies required for the outer planets, especially making Ka-band operational.**
- 4. NASA should continue to invest in development of underlying technologies (thrusters, power and control, propulsion technologies) for solar-electric propulsion.**

5. **NASA should invest in aerocapture technologies** and conduct a space-flight validation of aerocapture.
6. **For planetary probes, OPAG recommends investment in maintaining heritage or developing alternative thermal protection systems (TPS) materials.**
7. **Support for underlying Research & Analysis, Laboratory Studies, and Earth-based observations should continue.**
8. **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.**

III. Destinations and Mission Architectures

Europa Jupiter System Mission (EJSM)

OPAG encouraged NASA to begin comprehensive mission studies toward destinations in the outer solar system in order to assess the technical feasibility, realistic cost and time frame of viable missions. OPAG affirmed the findings of the first Decadal Survey, COMPLEX, and SSES, that Europa is the top-priority science destination in the outer Solar System. At that time, Titan and Enceladus were seen as important and compelling scientific destinations as well, and OPAG urged NASA to evaluate potential missions to these targets. This was accomplished, and on the basis of two rounds of scientific, technical, cost and management reviews, EJSM was prioritized ahead of the Titan Saturn System Mission (TSSM). The science for both missions was rated equally excellent; the prioritization was based on technical readiness.

EJSM would be an international mission with the overall theme of investigating the emergence of habitable worlds around gas giants. Its two fundamental goals are to *1) determine whether the Jupiter system harbors habitable worlds, and 2) characterize the processes within the Jupiter system.* The baseline EJSM architecture consists of two primary elements operating in the Jovian system: the NASA-led Jupiter Europa Orbiter (JEO), and the ESA-led Jupiter Ganymede Orbiter (JGO) (future contributions by JAXA and Russia are also possible). JEO and JGO would execute an intricately choreographed exploration of the Jupiter System before settling into orbit around Europa and Ganymede, respectively. (see white papers by Pappalardo et al., Phillips et al. and Collins et al.)

EJSM would investigate the potential habitability of the active ocean-bearing moons Europa and Ganymede, detailing the geophysical, compositional, geological, and external processes that affect these icy worlds. EJSM would also investigate Io and Callisto, Jupiter's atmosphere, and the Jovian magnetosphere. By understanding the Jupiter system and unraveling its history, the formation and evolution of gas giant planets and their satellites would be better understood. Most important, EJSM would shed new light on the potential for the emergence of life in the celestial neighborhood and beyond. The EJSM architecture provides opportunities for coordinated synergistic observations by JEO and JGO of the Jupiter and Ganymede magnetospheres, the volcanoes and torus of Io, the atmosphere of Jupiter, and comparative planetology of icy satellites. Each spacecraft would conduct both synergistic dual-spacecraft investigations and robustly stand alone (see white paper by Pappalardo et al.).

Engineering advances are needed for JEO (radiation designs) and JGO, but no new technologies would be required to execute either EJSM element. Risk mitigation activities are under way to ensure that the radiation designs are implemented in the lowest-risk approach. The baseline mission concepts include robust mass and power margins. The EJSM architecture provides an optimal balance between science, risk, and cost using three guiding principles: achieve high-priority science; build on lessons learned; and leverage international collaborations.

Europa and Ganymede are two worlds of fundamental planetological and astrobiological interest. OPAG supports the prioritization of JEO as NASA's next Outer Planets Flagship, and as part of the EJSM collaboration with ESA, and vigorously recommends its support in the Decadal Survey.

Cassini Solstice Mission

Our understanding of the Saturn system has been enormously enhanced by the Cassini-

Huygens mission. Fundamental discoveries have altered our views of Saturn, Titan, Enceladus, and the other moons, the rings, and magnetosphere of the system. The proposed 7-year Cassini Solstice Mission would address new questions that have arisen during the Cassini Prime and Equinox Missions, and observe seasonal and temporal change in the Saturn system to prepare for future missions.

The proposed Solstice Mission would provide new science in three ways: first, by observing seasonally and temporally dependent processes on Saturn, Titan and other icy satellites, and within the rings and magnetosphere, in a hitherto unobserved seasonal phase from equinox to solstice; second, by addressing new questions that have arisen during the mission thus far, for example providing qualitatively new measurements of Enceladus and Titan which could not be accommodated in the earlier mission phases; and third, by conducting a close-in mission at Saturn that would provide a unique comparison to the Juno observations at Jupiter. In addition, we plan to study the evolution of activity on Enceladus and continue searching for activity on Titan and other icy satellites. Most of these types of observations, absent Cassini, could not be fulfilled for decades to come (see white papers by Spilker et al. and Hurford et al.).

Titan and Enceladus are two satellites of great planetological and astrobiological interest. OPAG strongly endorses approval by NASA of this extension to the Cassini mission, including the Juno-like end-of-mission scenario.

Future Missions to Titan and Enceladus

Cassini-Huygens began to uncover the complexities of Titan and discovered plumes on the fascinating moon, Enceladus. It continues to do so, but is limited by on-board instrumentation. Exploration of Titan, a diverse and active world, beyond Cassini's equinox and solstice investigations of seasonal change will require landed studies, airborne sounding platforms (most plausibly from a balloon), and an orbiter. The 2008 Titan Saturn System Mission (TSSM) encompassed the scientific requirements of both these remarkable bodies. It is possible that a mission to each could be accomplished individually, but a flagship mission would provide the rich and comprehensive volume of science data that orbiting and in situ elements are capable of generating. For complete discussions, see white papers by Lunine et al., Coustenis et al., Allen et al., and Hurford et al.).

OPAG strongly recommends that NASA pursue development of the next outer planet flagship mission to Titan and Enceladus by funding a program to retire the associated technological risks. It also encourages the NASA to further investigate the possibility of lower-cost missions to these objects.

Giant Planet Probes

While Jupiter has been studied in situ by the Galileo entry probe, no other giant planet has been so. It is essential to compare the elemental composition of Jupiter with the only other gas giant planet, Saturn, to have confidence in the formation scenarios of the gas giant planets and their atmospheres. This would require in situ measurements at Saturn by entry probes. A comparison between the gas giant planets and the ice giant planets, Uranus and Neptune, is also essential for understanding the formation and evolution of the entire giant planet system and, by extension, the solar system (see the white papers by Atkinson et al. and two by Hofstadter et al.).

A Saturn in situ mission would require either (a) deep entry probes to 50-100 bars, or (b) shallow probes to approximately 10 bars, complemented by Juno-type remote sensing with microwave radiometers (MWR) from a separate spacecraft for determination of water vapor. Whereas deep Saturn probe must overcome technological challenges of data transmission, survival to and operation in an extreme environment, shallow probes to 10 bars require no new technology development. The determination of critical heavy elements, C, N, S, noble and light gases and their isotopes, can all be accomplished at less than 10 bars. Combined with a Juno-like MWR, the remaining critical heavy element, oxygen, can be determined also. Complementary data on disequilibrium species, deep winds, pressure vs. temperature, and determination of the core and internal magnetic field are highly desirable, and provide vital information about evolutionary processes. An orbiter (with probes) is preferable over a flyby for best science return and broad community engagement. At least two probes are needed for

unambiguous elemental composition data. The feasibility of doing a (two) probe-orbiter mission under the New Frontiers cost cap needs to be carefully assessed. It may turn out that such a mission is an ideal candidate for a small flagship class.

The Saturn probe mission should be followed by a probe mission to either Uranus or Neptune. A Neptune polar orbiter with probes, with an option of a Triton lander, would be most desirable as the next probe mission, as also recommended in the previous Decadal Survey. This would be a large flagship mission. Finally, a return to Jupiter with multiprobes should be considered following the Juno mission, whose results would be a valuable guide to the location, depth, and the number of probes.

Io Science

Jupiter's satellite Io is the most geologically dynamic solid body in the Solar System. Io undergoes severe tidal heating, induced by the orbital eccentricity forced by Jupiter and the Laplace resonance between Io, Europa, and Ganymede. Io is a primary body for studying tidal heating directly (the other being Enceladus), a process that is fundamental to the evolution of giant planet satellite systems, and one that may greatly expand the habitability zone for extrasolar planets. By understanding Io, where manifestations of tidal heating are displayed to extremes and are easily observed, we can better understand the importance of tidal heating in a wide range of circumstances, including the history of satellites in our own Solar System. Io is directly linked to the evolution of the one of most promising sites for extraterrestrial life, Europa (the primary target of EJSM), via the coupled orbital evolution of the two bodies. Because of this tidal heating, a huge variety of interconnected phenomena operate at a scale not seen active anywhere elsewhere in our Solar System. Io offers an extremely rich array of geophysical, geological, geochemical, atmospheric, and magnetospheric plasma phenomena for study (see white papers by Williams et al.). Most remarkably, geology can be observed as it happens on Io, and as one of the most spectacular places in the Solar System, Io has unique public appeal, and Io exploration offers many opportunities to attract and engage public interest in planetary science.

Neptune and Uranus

There are two types of giant planets in our solar system: gas giants and ice giants. The ice giants, Uranus and Neptune, are distinctly different from Jupiter and Saturn in composition and structure, and we assume in their formation and evolution. Extrasolar planet hunting has matured to the point of not only detecting ice-giant-sized bodies around other stars, and even mapping out the physical characteristics of these extrasolar planets, yet many basic aspects of our own nearby ice giants remain elusive. Uranus and Neptune have been visited by just one spacecraft, Voyager 2, over 20 years ago. Since Voyager's brief snapshots many aspects of the uranian and neptunian systems as observed from Earth have changed. Our understanding of the evolution of the solar system has also changed dramatically, with new models indicating that Neptune may have formed inside of 20 (the so-called Nice model).

A flagship Neptune orbiter mission, noted above, was recommended by the previous Decadal Survey, a recommendation OPAG still supports, but realistically such a mission is decades away. It is time to reexamine the case for a sophisticated flyby mission to an ice giant, using modern instrumentation, and one that might be combined with a dwarf planet or other KBO flyby (see white papers by Hansen et al. and Barr et al. for science context), or the potential for an orbiter of Uranus or Neptune to fit within the NF or small-flagship mission class (see white papers by Hofstadter et al.).

Based on the above, OPAG recommends that the following missions be assessed for inclusion in the approved New Frontiers mission set (not in priority order): 1) a Titan in-situ explorer or probe; 2) a shallow Saturn probe (with microwave sounder); 3) an Io Observer, i.e., an Io-dedicated Jupiter orbiter capable of multiple Io flybys over several years (on the present New Frontiers list); 4) a Neptune/Triton/KBO flyby; and 5) a Uranus orbiter.