



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

**Report to the Giant Planets & Satellites Panels,
Planetary Science Decadal Survey**

NASA Outer Planets Assessment Group

William B McKinnon, Washington University, Chair

August 24, 2009

Washington DC



What is OPAG?

The Outer Planets Assessment Group (OPAG) was established by NASA in late 2004 to identify scientific priorities and pathways for solar system exploration beyond the asteroid belt. The group consists of an ~15-person steering committee which actively solicits input from the scientific community and reports its findings to NASA's Planetary Science Division and the Planetary Science Subcommittee of NASA's Advisory Council.

It is OPAG's goal that its findings represent the broad consensus of the scientific community. OPAG holds meeting semiannually, each attended by ~100 scientists. The meetings consist of a broad range of presentations from NASA HQ representatives, mission PIs, individual scientists, and technology researchers. Meetings often include breakout sessions where scientists work in small groups to prioritize scientific questions and mission requirements at specific destinations (e.g., Europa, Titan, giant planets, midsize icy satellites such as Enceladus). Community input is solicited at the meetings and through the OPAG email list containing over 500 members.



Outer Planets Assessment Group Steering Committee

William McKinnon, Washington University (Chair, 2009-)

Fran Bagenal, University of Colorado (Chair, 2004-2009)

Sushil Atreya, University of Michigan

Kevin Baines, Jet Propulsion Laboratory

Pat Beauchamp, Jet propulsion Laboratory

John Clarke, Boston University

Jack Connerney, Goddard Space Flight Center

Frank Crary, Southwest Research Institute, San Antonio

Paul Geissler, US Geological Survey

Randy Gladstone, SwRI, San Antonio

Ron Greeley, Arizona State University

Heidi Hammel, Space Sciences Institute

Bill Hubbard, University of Arizona

Torrence Johnson*, Jet Propulsion Laboratory

Bill Kurth, University of Iowa

Ralph Lorenz, JHU/APL

Ralph McNutt, JHU/APL

Bill Moore, University of California – Los Angeles

Julianne Moses, Lunar and Planetary Institute

Jani Radebaugh, Brigham Young University

Amy Simon-Miller, NASA Goddard SFC

Henry Throop, SwRI, Boulder

Hal Weaver, JHU/APL

David Williams, Arizona State University

Curt Niebur, NASA HQ (Executive Officer)

*Ex Officio

Current members in **bold**. The Steering Committee is selected to represent the breadth of the scientific community. Each member typically serves for three years.



Executive Summary based on:

- 1) Scientific Goals and Pathways for the Exploration of the Outer Solar System, 2006 OPAG report***
- 2) Science, Technical, Management and Cost reviews of potential Outer Planet Flagship (“Large”) Missions, 2007-2009***
- 3) Continued outer planets community input, including white papers in progress for 2013-2022 Planetary Science Decadal Survey***



- **Finding 1: Compelling Science** – Important scientific discoveries continue to be made in the outer solar system through NASA missions and research programs. OPAG affirms the findings of the first NRC Decadal Survey and NASA's 2006 Roadmap that the outer solar system provides critical clues to unraveling the mysteries of how solar systems form and evolve, how planetary systems become habitable, and how life has evolved in our solar system.
- **Finding 2: Steady, Balanced Strategy** – Addressing these 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 (as practical) missions. A stable budget is crucial for continuity of scientific and technical capability. Such a strategy is most efficiently implemented as a coherent Outer Planets Exploration Program.
- **Finding 3: Mission Studies** – 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. Titan and Enceladus are also important, if not compelling, science destinations, and OPAG urged NASA to evaluate potential missions to these targets. This has been done!

OPAG

Outer Planets Assessment Group

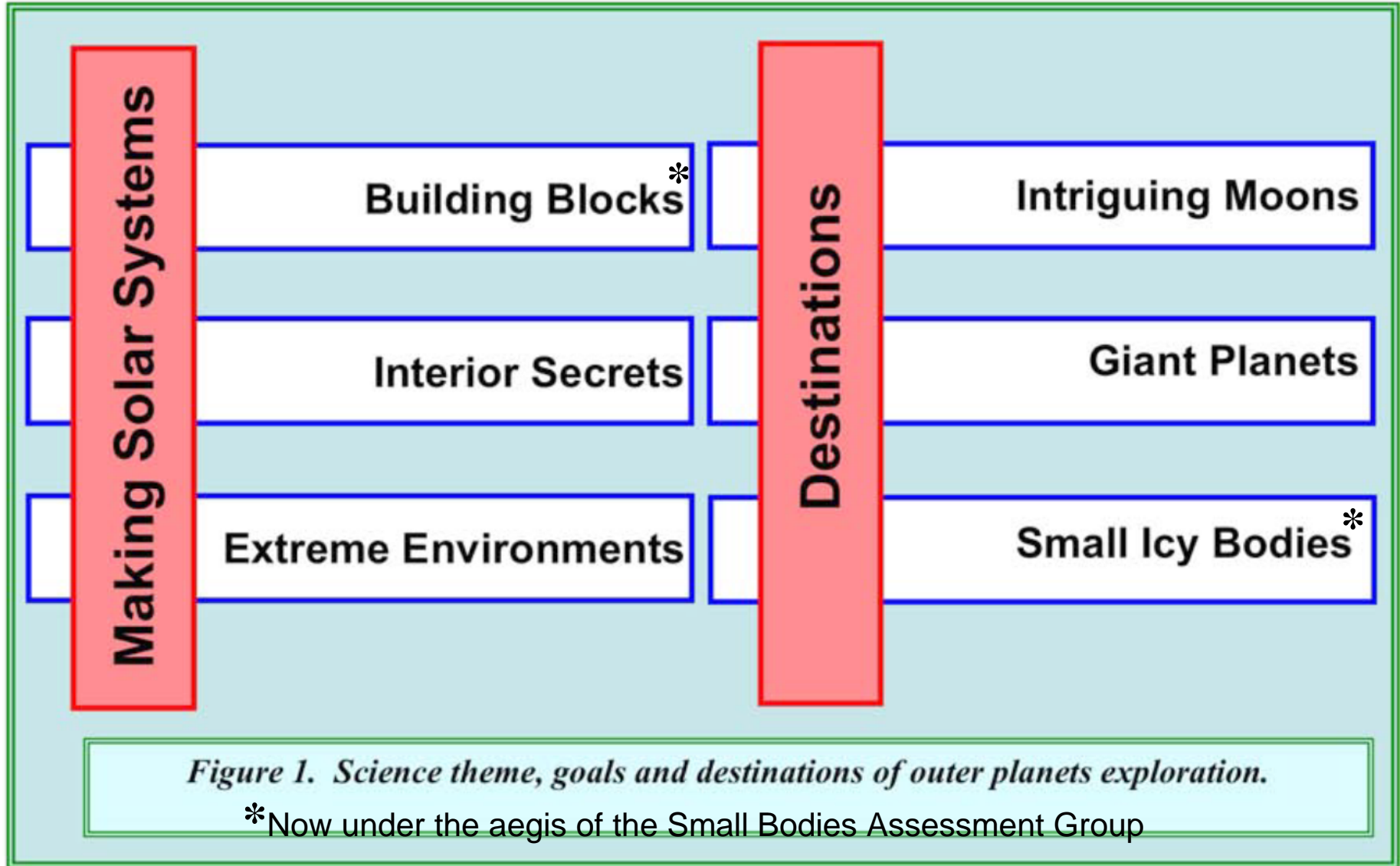


Figure 1. Science theme, goals and destinations of outer planets exploration.

*Now under the aegis of the Small Bodies Assessment Group

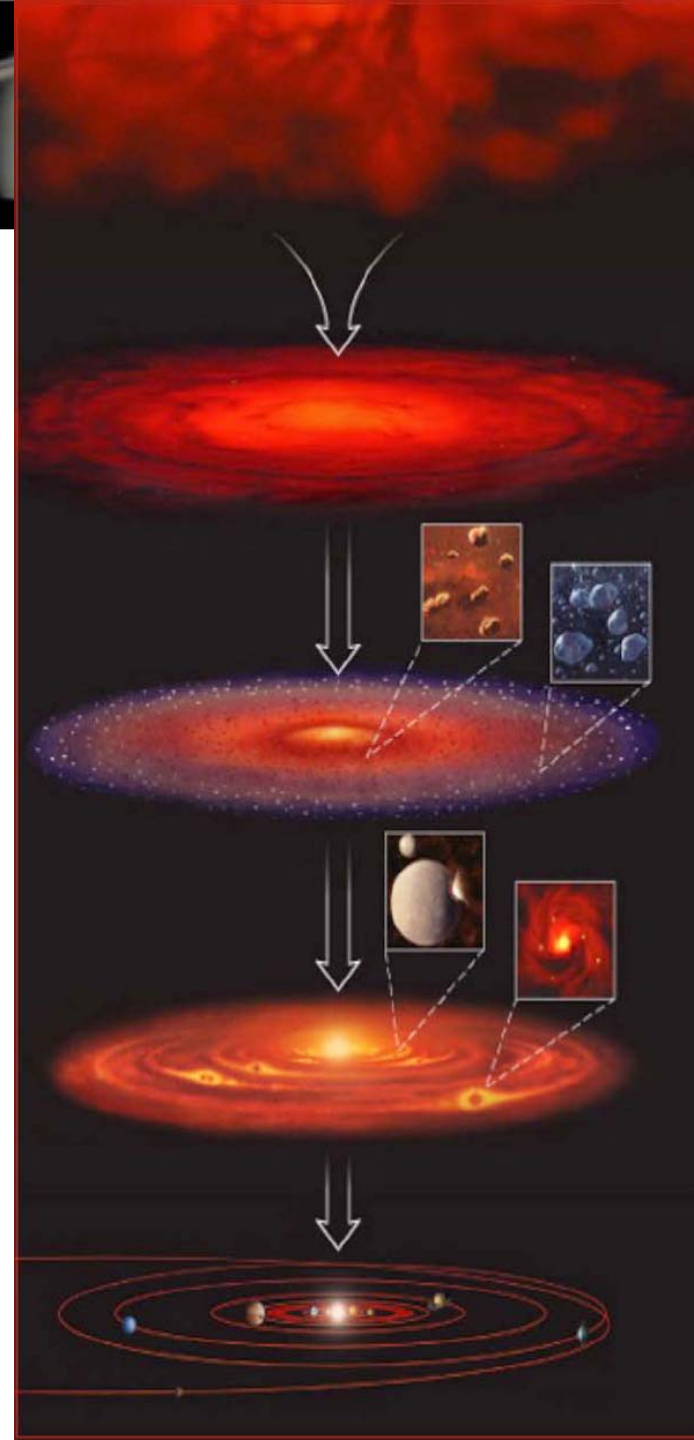


How does a planetary system become habitable?

2006 SSE Strategic Roadmap objectives

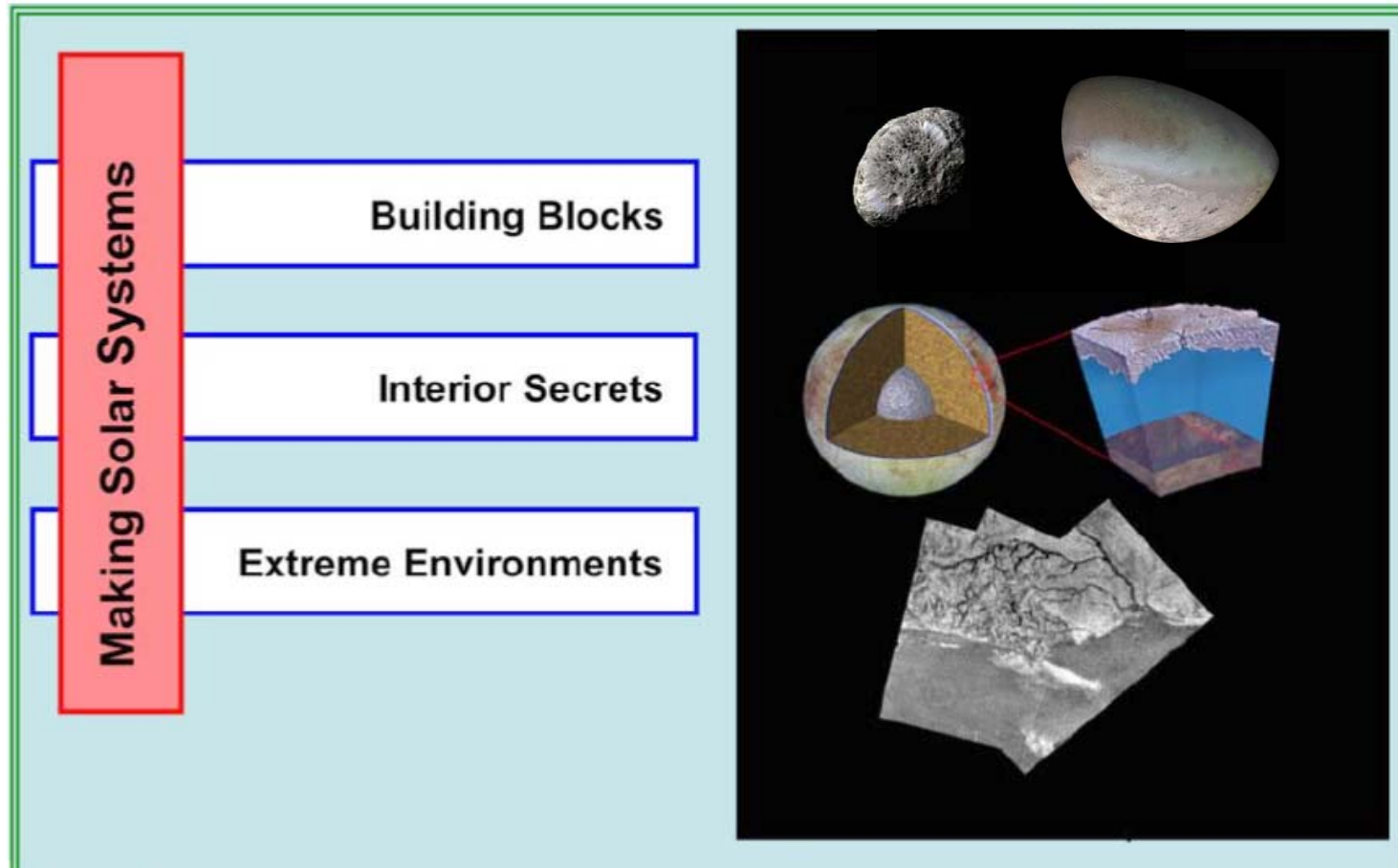
1. How did the Sun's family of planets and minor bodies originate?
2. How did the Solar System evolve to its current diverse state?
3. What are the characteristics of the Solar System that led to the origin of life?
4. How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?
5. What are the hazards and resources in the Solar System environment that will affect the extension of the human presence in space?

***Outer Solar System (sans small bodies)
Plays Key Roles in first 4 Objectives***



OPAG

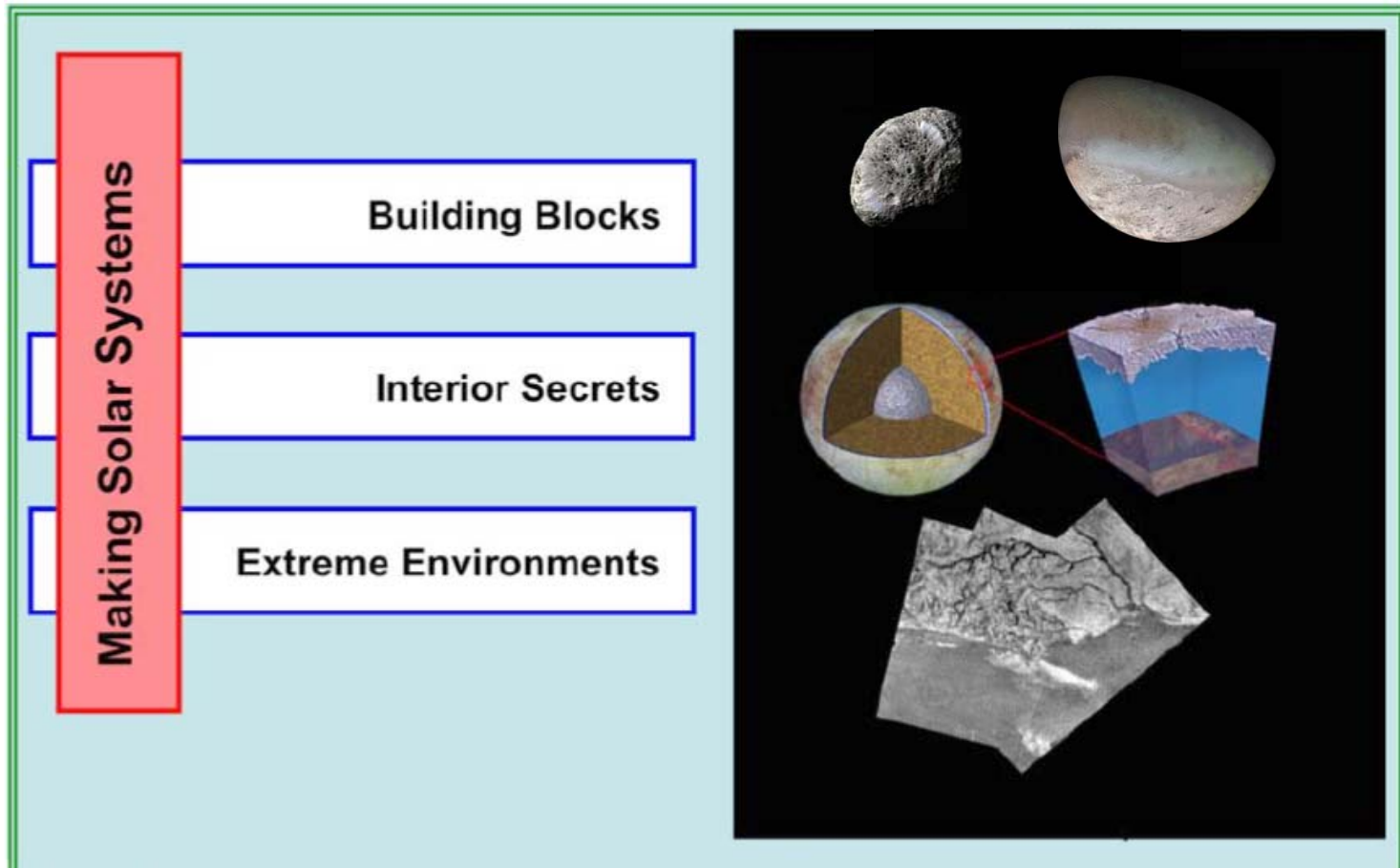
Outer Planets Assessment Group



- ***Interior Secrets:*** Determine composition, structure, and other properties of the interiors of planetary bodies to provide vital clues about planetary formation and evolutionary processes.
- ***Extreme Environments:*** Ascertain the range of conditions that can support life and what planetary processes are responsible for generating and sustaining habitable worlds.

OPAG

Outer Planets Assessment Group



- **Intriguing Moons:** The larger moons of the giant planets are varied worlds whose interiors, surfaces and atmospheres reveal processes at different stages of planet evolution.
- **Giant Planets:** Comprising the bulk of the planetary mass of the solar system, the giant planets are key for understanding solar system formation and evolution.



Elements of a Successful Outer Planets Program (not in priority order)

- Mission size mix (program balance)
- Periodic large (flagship) missions
- Sustained and focused technology development
- Research & Analysis
- Mission concept studies
- Strategic planning

A well-thought-out systems approach incorporating all key elements is **required** to promote **and accomplish** a successful exploration plan



The Three Classes of Missions to the Outer Solar System

- **Discovery:** (~5 years, $\leq 450M$) Quick implementation, addresses focused questions, innovative
- **New Frontiers:** (~10 years, $\leq 900M$) Discovery-style missions to more challenging targets
- **Flagship:** (15-20 years, $> 900M$) Missions to strategic targets and addressing broad scientific goals, high return from several coordinated scientific investigations, lowest cost-per-science-instrument, complex or multiple targets

Missions to the outer solar system are major undertakings, requiring large and expensive launch vehicles, long mission durations, highly reliable (frequently radiation hard) and autonomous spacecraft, and radioisotope power sources in most cases.

OPAG recommends that the current Decadal Survey committee 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 program size and science return.

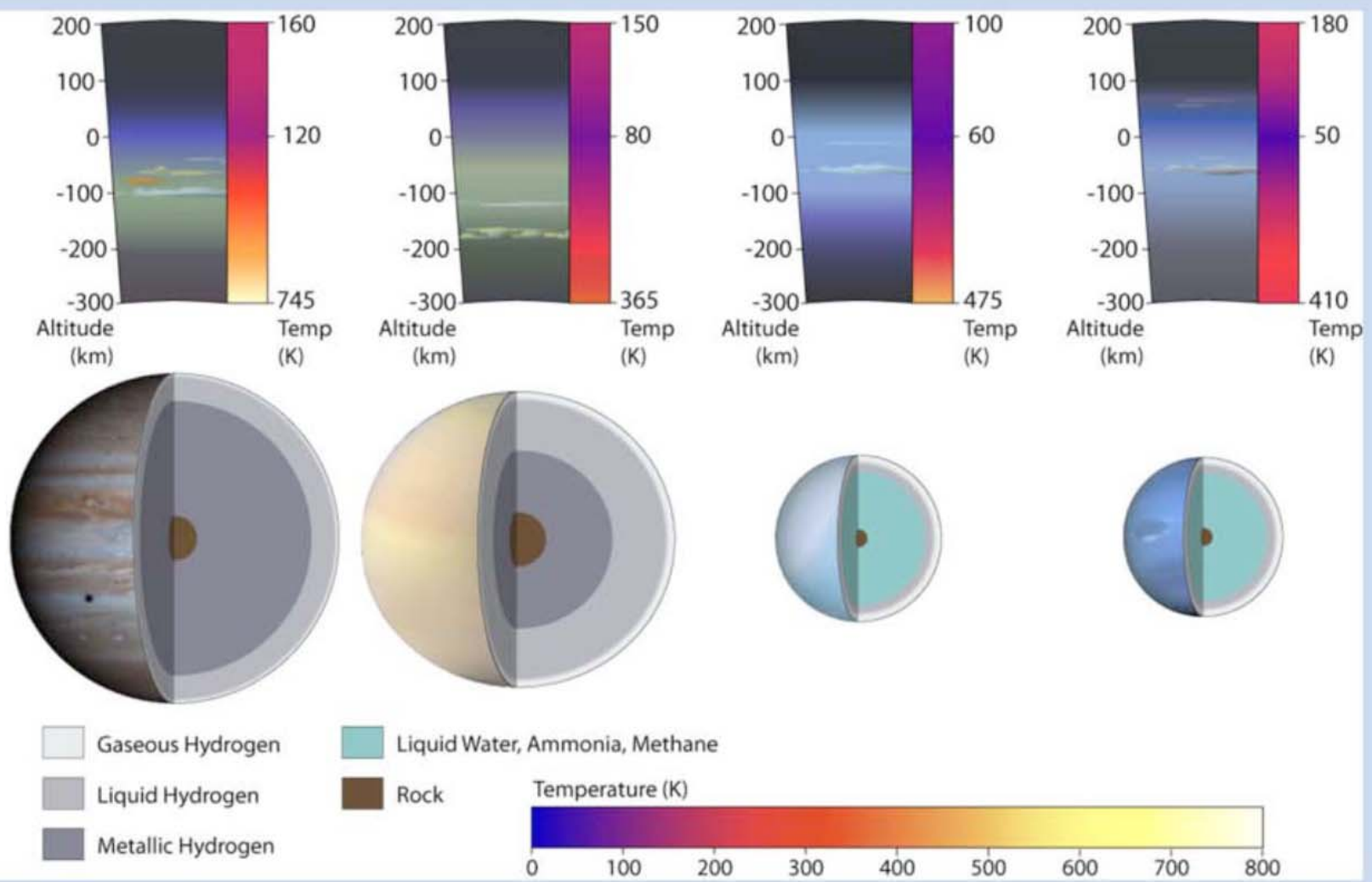
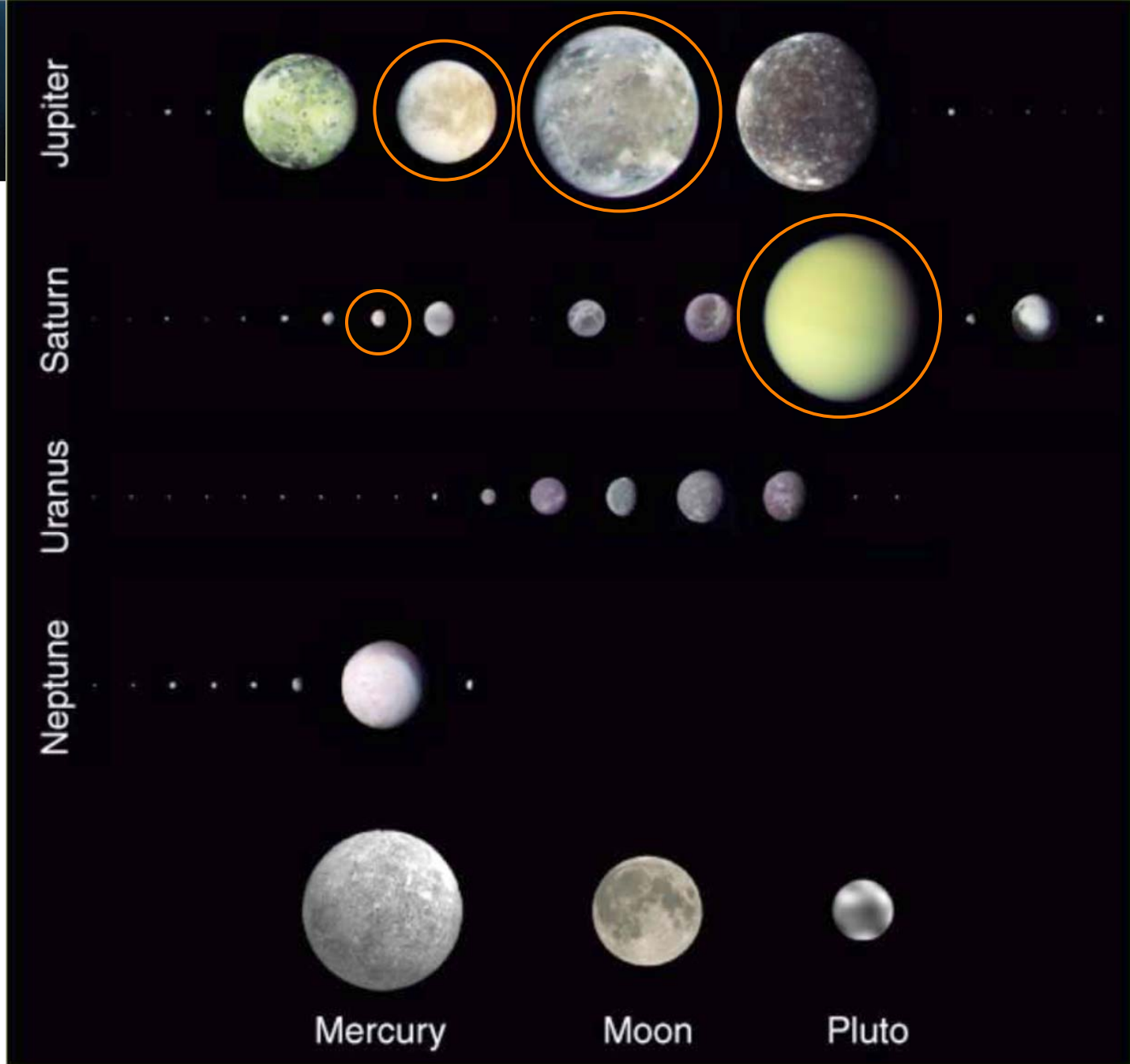


Figure 15 - Interiors and atmospheres of the giant planets. The giant planets form two distinct pairs. Jupiter and Saturn - primarily hydrogen: gaseous, liquid, then metallic at increasing pressures towards the planets' centers; Uranus and Neptune - hydrogen overlies a liquid layer comprising a mixture of water, ammonia and methane. It is not clear whether the planets have small rocky cores. The clouds that are visible from the exterior form distinct layers at specific pressures and temperatures in the thin outermost gaseous layer. The altitude scale is referenced to the locations where the atmospheric pressure is 100 mbar which is also the approximate altitude where atmospheric temperatures are a minimum (ranging from 50K at Neptune to 120K at Jupiter). Temperatures rise with higher pressures towards the interior of the planet. Absorption of sunlight also increases temperature in the upper atmospheres. None of these planets have been explored except for the thin layer above the clouds. These diagrams are based on theoretical models constrained by parameters such as bulk density.

Giant Planets



Satellites: Worlds in Their Own Right

Europa: The Ocean World

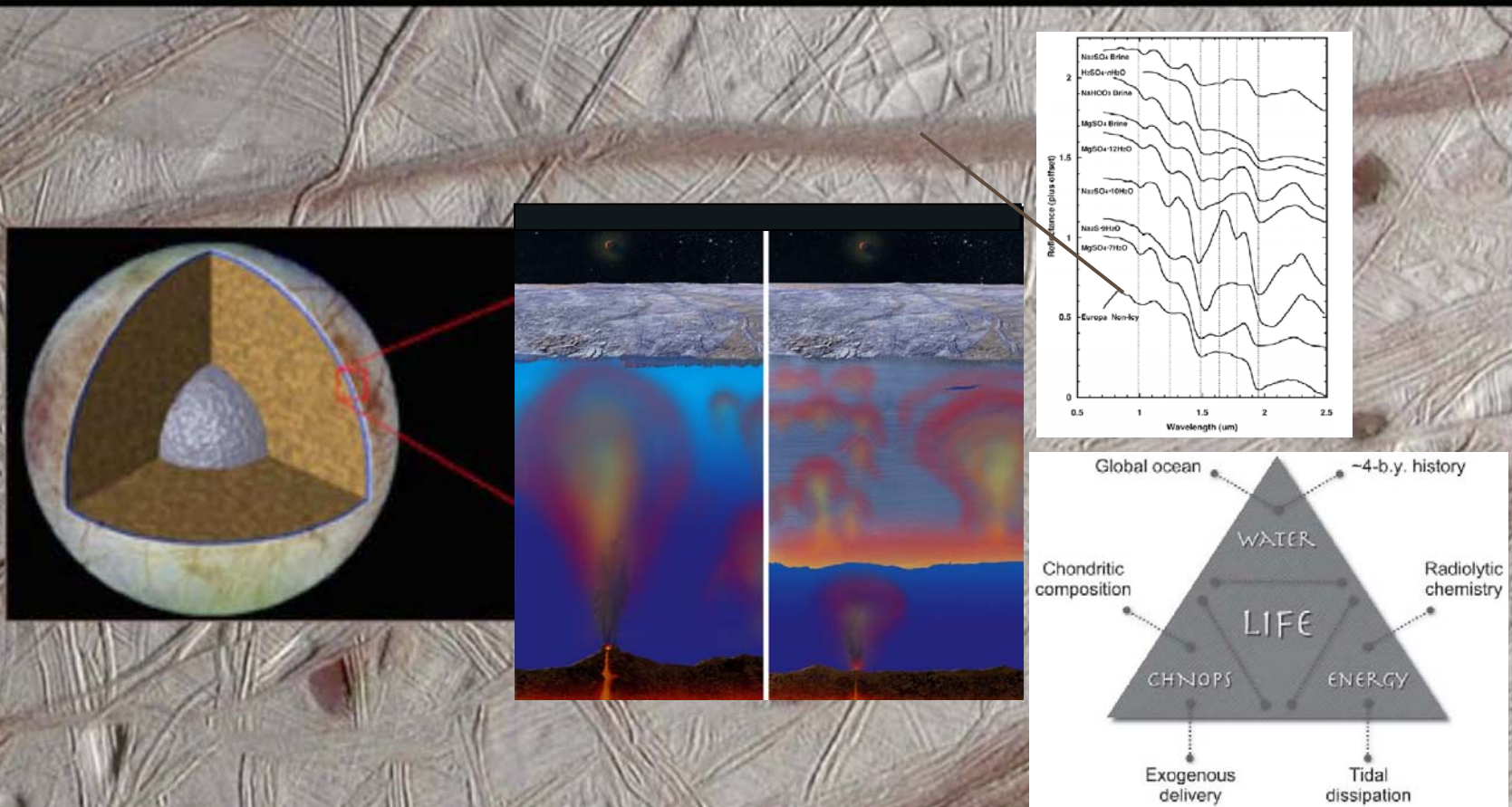


Figure 9 - "Europa, tidally heated by Jupiter, is a warm rocky body possessed of an icy shell that is melted to some extent. That is, a global ocean of liquid water exists under an ice crust of indeterminate thickness. Yet the extent to which this subsurface ocean is endowed with organic molecules, the stuff of life, is unknown."

Titan: Organic Phantasmagoria

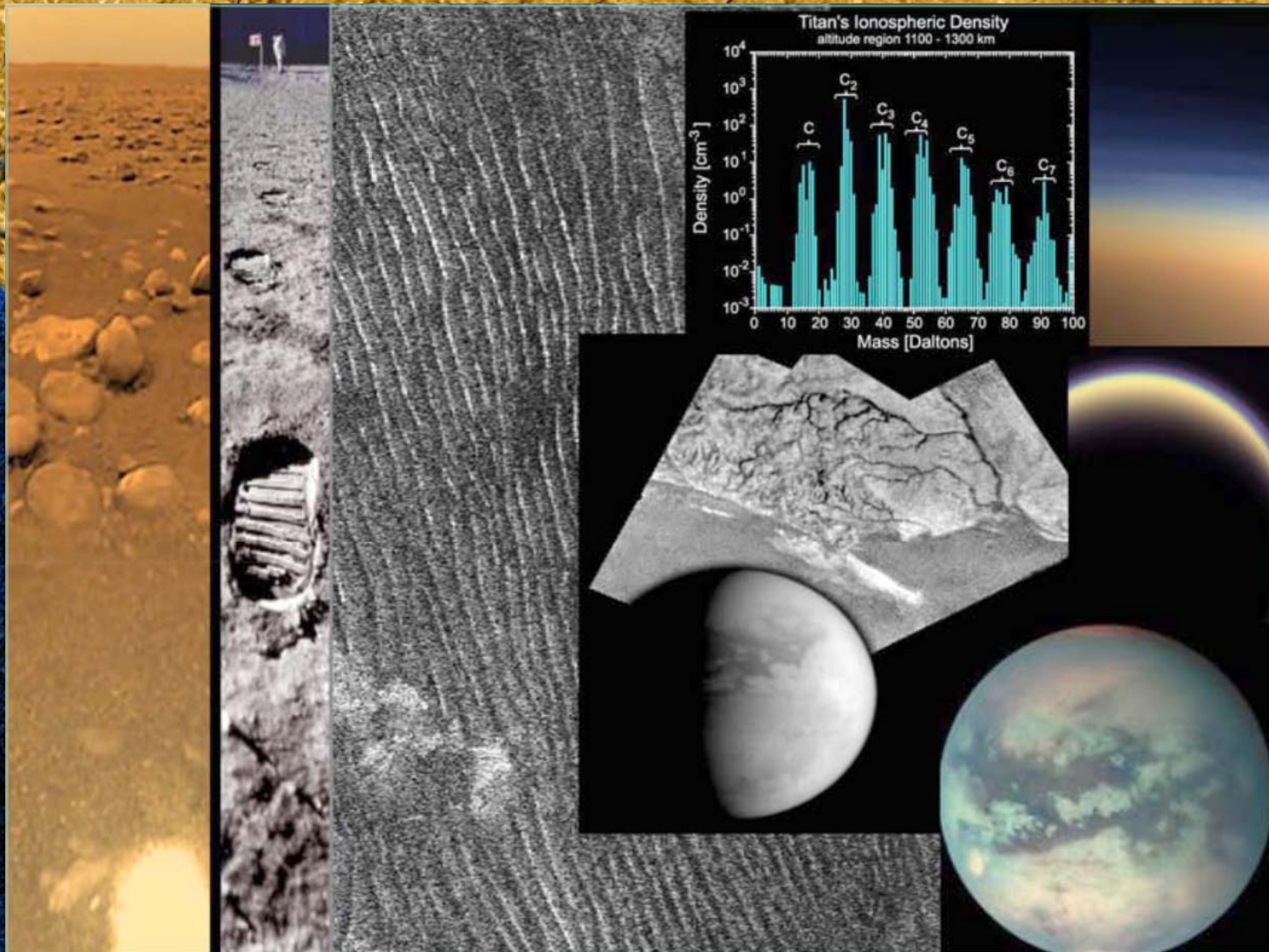


Figure 11 - Titan is a complex organic-rich world, inviting exploration of both its surface and atmosphere. Earth-like landforms such as river valleys and sand dunes result from methane rainfall and winds, while seasonal changes occur high in the organic smog-laden atmosphere. The view from the Huygens probe (*left*) is shown next to a vista of Apollo astronauts on the Moon to illustrate the scale of the Titan landscape.

Enceladus: The Little Moon That Could

180

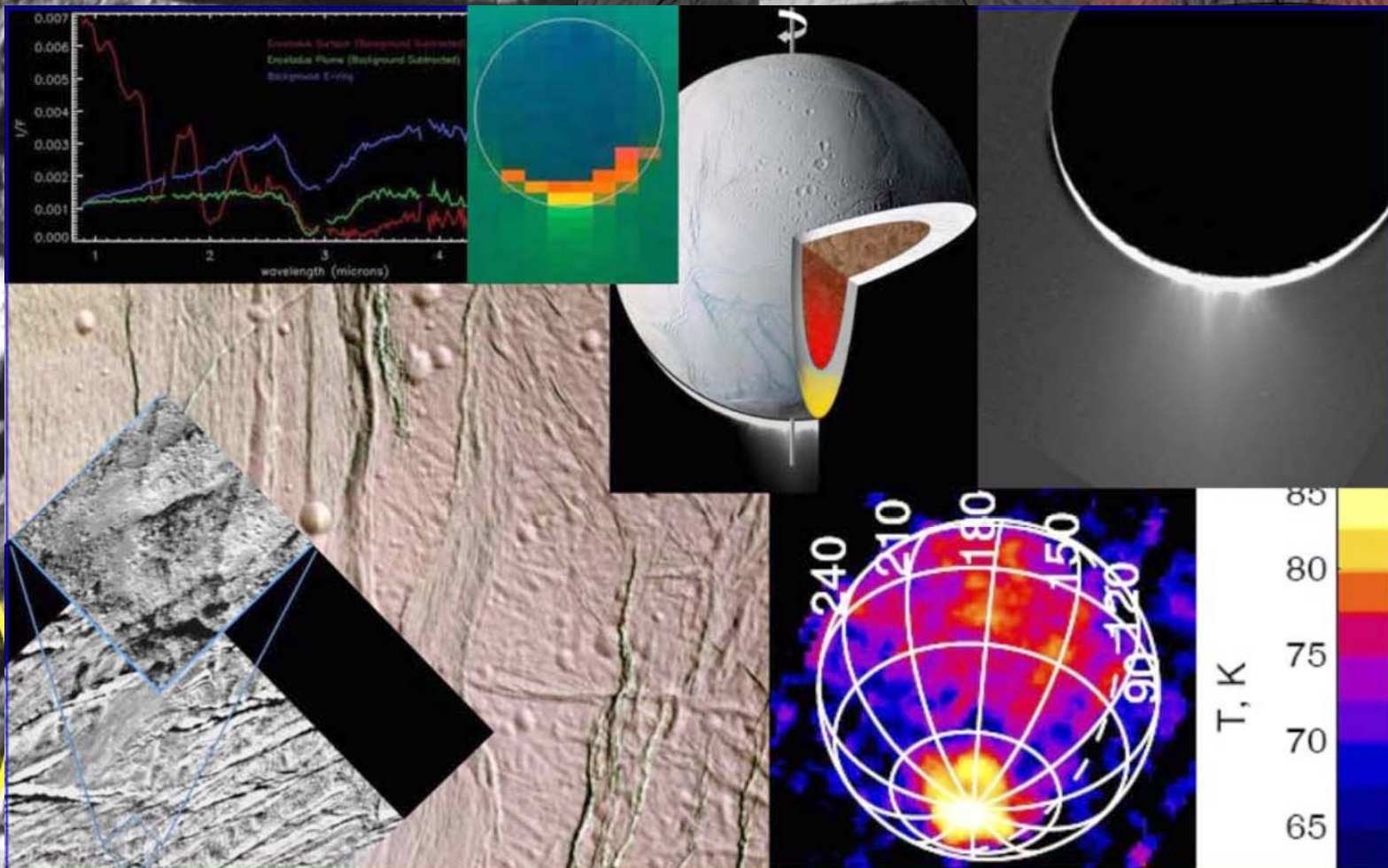
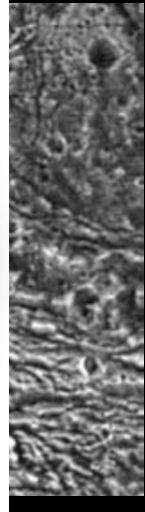
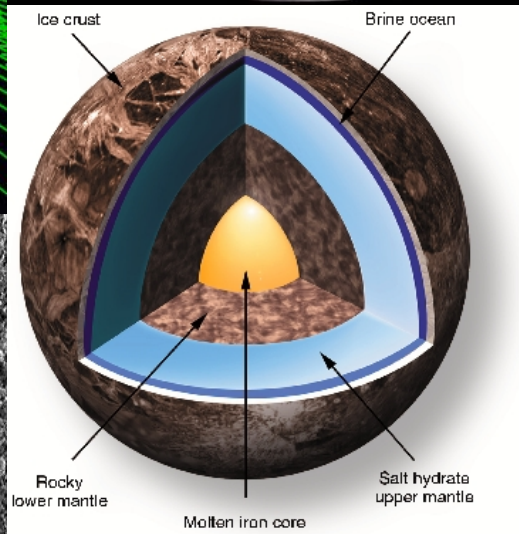
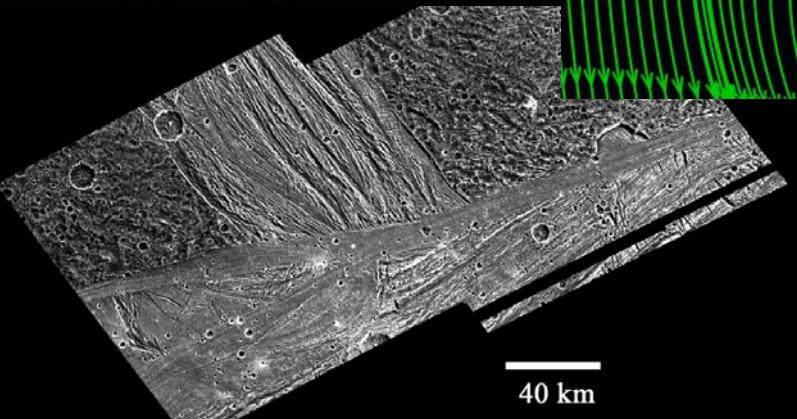
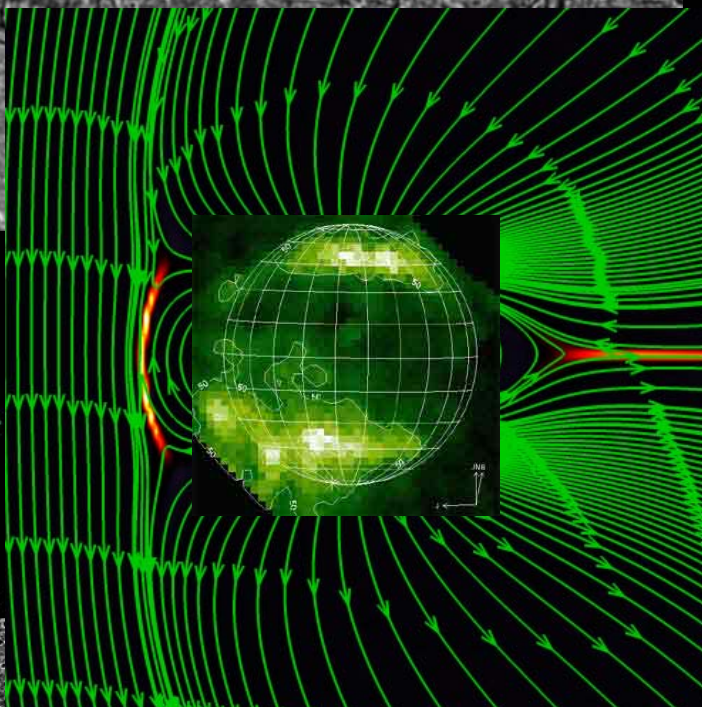
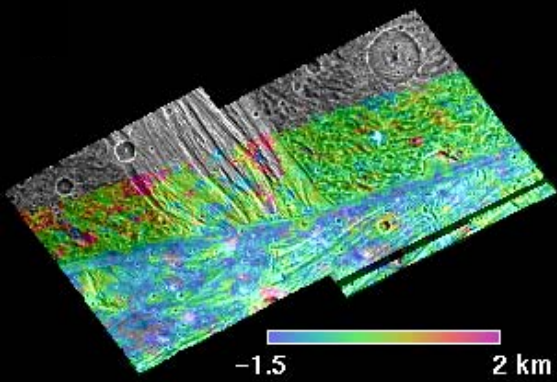
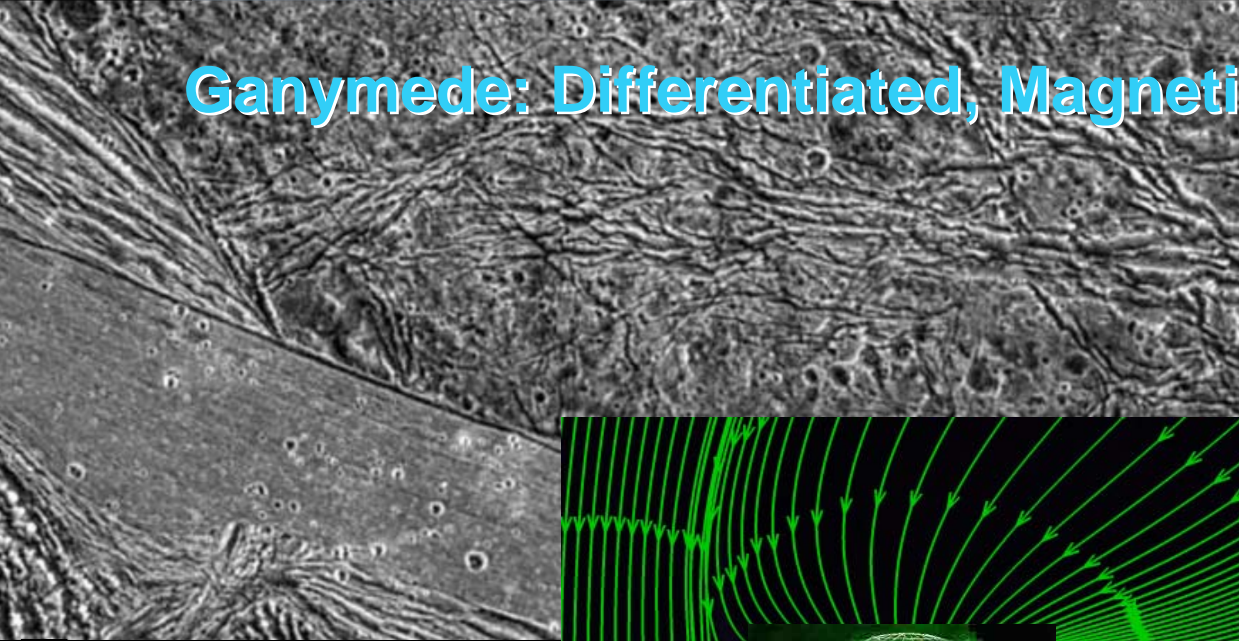


Figure 13 - Enceladus. The Cassini spacecraft shows that Saturn's small moon Enceladus has plumes of ice and gas rising from warm active fractures in its south polar region, probably the action of localized tidal heating. Water is the dominant plume constituent, and trace amounts of the simple organic molecules acetylene and propane are also detected. If water exists in the shallow subsurface of Enceladus, then this moon joins the shortlist of icy bodies that may be habitable environments.

Ganymede: Differentiated, Magnetic, and Grooved





Flagship Studies

2007: Europa Explorer, Titan Explorer, Enceladus Flagship,
Jupiter System Observer (Ganymede Focus)

2008: Europa Jupiter System Mission (EJSM), Titan Saturn
System Mission (TSSM)

Science ranked equally excellent; apple (E) vs. orange (T)

Prioritization of EJSM based on technical readiness

OPAG was prepared to back any (positive) outcome



Flagship Studies

The announced prioritization of the **Outer Planets Flagship sequence**, with the Europa Jupiter System Mission (EJSM) first, represents a victory for the entire outer planets community, which worked extraordinarily hard to see such a mission come to fruition. There nevertheless remains a great deal of work to be done to synchronize mission development with our European colleagues, and to reduce technical and cost risk.

OPAG vigorously encourages NASA to do its utmost to continue preparations for the *JEO/EJSM* mission, including support for instrument development, continued international collaboration, and reduction of radiation risk, and culminating as soon as practical in a new start.

OPAG supports the selection of JEO as NASA's next Outer Planets Flagship, and as part of the EJSM collaboration with ESA, and recommends its support in the Decadal Survey.

Summary of Technologies required for Outer Planet Missions

Technology Development	Missions								
	Titan Orbiter <i>In Situ</i> Sampler	Neptune Orbiter	Neptune Flyby to KBO Flyby	Uranus orbiter	Saturn Probe	Jupiter Probe	Neptune Probe	Enceladus Sample Return	Europa Lander
Transportation									
Electric Propulsion	e	E	e	e	e		e	e	
Aerocapture		E		E					
Power									
RPS	E	E	E	E			*E	E	e
Low light Solar Arrays				e	e	e			
Communications									
Expanded Ka capability	e	e	e	e			e		e
Improved Proximity Links	e				e	e	e	e	e
Improved UHF systems	e				E	e	E	e	e
Planetary protection measures	e							e	e
Planetary mobility	E								e
Autonomy	e								
Extreme environments	e				E	E	e	e	E
Entry systems (includes TPS)	e	E		e	e	E	E	E	E
Planetary Probe Technologies					e	E	E		
<i>In situ</i> sensing of surface and atmospheres	E				e	E	E	E	E
Components and miniaturization	E	e	e	e	e	E	E	E	E
Remote sensing	e	e	e	e	e	e	e	e	e

Legend: E = enabling, e= enhancing (reduces cost and/or risk, increases performance) Spacecraft Systems); *need RPS or radio science for carrier-relay spacecraft that delivers probe.

Technology priorities for Outer Planet exploration

	Technology	Priority	Comments
Spacecraft Systems	Transportation	1	Electric propulsion would be strongly enhancing for most OP missions, including a Titan/Enceladus Flagship, & aerocapture technologies would enable a Neptune orbiter mission. These technologies provide rapid access, increased mass &/or lower mission risk.
	Power	1	Radioisotope power systems would be needed for the next Titan/Enceladus Flagship mission, requiring a sufficient supply of ²³⁸ Pu. Advances in power conversion efficiencies would reduce the quantity of ²³⁸ Pu needed for a given power requirement, along with a mass savings.
	Communications	1	The science return from every mission would benefit from improvements in communications infrastructure, including Ka band and direct-to-Earth communications. <i>In situ</i> exploration with orbital assets would be greatly enhanced by improved proximity links.
	Planetary protection	2	New planetary protection approaches and technologies will be required to meet the anticipated requirements for <i>in situ</i> exploration to targets of interest for astrobiology.
<i>In situ</i> Exploration	Planetary mobility	1	Access is critical to <i>in situ</i> exploration central to a Titan Flagship mission concept, making various types of mobility systems enabling e.g. montgolfière balloons for Titan. Advances in autonomous mobility technologies could also provide alternatives for various New Frontiers mission concepts.
	Extreme environments	1	The proposed missions span a number of diverse environments, requiring technology advances in fields ranging from low T and P, to high heat flux and pressure during atmospheric entry. <i>In situ</i> sampling and instruments would benefit from technology program.
	Entry systems	2	New propulsive landing systems would enable operations on satellites without atmospheres. Investments required in key technologies for entry systems and planetary probes, including extreme environment systems, miniaturized and low power integrated sensors, transmitters, and avionics, thermal materials, power management systems, and on-board processing.
Instruments	<i>In situ</i> instrument systems	1	New technologies and instruments would be required for improved science return to targets of astrobiological interest, enabling the proposed Titan/Enceladus Flagship mission. The instrument technologies would require associated development in sample acquisition and handling systems. Advances in thermal management are critical. Atmospheric probe instruments required.
	Components and miniaturization	1	Every mission is either strongly enhanced or enabled by improvements in miniaturization and advanced component design. A Titan/Enceladus Flagship mission would be strongly enhanced by development of miniature long-lived, low power cryogenic electronics.
	Remote sensing instrument systems	1	All missions with orbital or extended aerial operations would be strongly enhanced by improved technologies for passive and active remote sensing and radio science. High resolution and sensitivity instruments that are low in mass and power are required for a Titan/Enceladus Flagship.

1 Highest priority—New developments are required for all or most future OP missions

2 High priority—Either the applications are more limited or NASA could effectively leverage existing work



Technology overview

OPAG advocates the need for a focused technology program for the next Outer Planet Flagship Mission after the Europa Jupiter System Mission (EJSM), in order to be ready for a launch in the 2020s.

Current planning shows that a mission to Titan and Enceladus will be highest priority.

Technologies that require long-term investment for missions beyond the next decade should also be considered.

See **Technologies for Outer Planet Missions White Paper**, Pat Beauchamp, JPL, lead author



OPAG Technology Recommendations

Spacecraft Technologies

- *Recommendation 1:*

NASA must continue to work with the relevant federal entities to ensure that ^{238}Pu production be re-initiated within the next few years. NASA must also support development, at a pace consistent with planned missions, more efficient power-conversion technologies to make the best use of the ^{238}Pu in the inventory.

- *Recommendation 2:*

NASA should continue to invest in development of underlying technologies (thrusters, power and control, propulsion technologies) for solar electric propulsion, bringing them to *flight readiness*, and to make the capability affordable to and within the risk posture of small, medium and large missions.



OPAG Technology Recommendations (Spacecraft)

- *Recommendation 3:*

NASA should invest in aerocapture technologies and conduct a space-flight validation of aerocapture in advance of the decision points of identified missions.

- *Recommendation 4:*

Aerodynamics R&A should be supported.

- *Recommendation 5:*

NASA should expand the funding of communication and radio science technologies required for the OP especially making Ka band operational and furthering proximity and direct-to-Earth communication technologies.

- *Recommendation 6:*

NASA should define the Planetary Protection category for Titan and Enceladus, decide on an approach for OP Planetary Protection and invest in technologies that would enable the missions to achieve that goal. OPAG strongly recommends that solutions for planetary protection and contamination control be addressed jointly.



OPAG Technology Recommendations

In Situ Exploration

- *Recommendation 7:*
NASA should fund the development of both the Montgolfière balloon and the autonomy required to operate such a platform at Titan and the lander technologies required for sampling in the high latitude lakes, dunes and cryovolcanic regions.
- *Recommendation 8:*
NASA should initiate a technology development program for extreme temperature and pressure environments. Many of the needed technologies are currently at a very low TRL and the gestation period of development is long. Initiating this program as soon as practicable will have a major impact on the feasibility of the Flagship mission and will also enable Discovery and New Frontier missions.
- *Recommendation 9:*
For planetary probes, OPAG recommends investment in the development of alternative TPS materials and periodic limited manufacturing and testing demonstrations to ensure heritage TPS manufacturing is kept current.



OPAG Technology Recommendations

Science Instruments

There are serious gaps in support of instrument programs, particularly in taking development from the concept stage to TRL 6. Programs that have historically funded instrument component technologies no longer exist and critical gaps remain in developing the appropriate capabilities.

- *Recommendation 10:*

NASA should re-examine its planetary instrument programs to achieve a better balance between component development, *in situ* and remote sensing (active and passive) instrument definition, and instrument development, with a focus *on demonstrating complete instrument systems and bridging the gap to flight.*

An OP instrument program should focus on developing high resolution, high sensitivity instrument systems that are miniature, low mass and require low power, raising the instrument *systems* to TRL 6.

- *Recommendation 11:*

NASA should initiate a program in cryogenic sample acquisition and sample handling. Each of the Titan environments has its own unique requirements that need to be developed to achieve and maintain scientific integrity of the sample prior to analysis.



What Planetary Science R&A Programs Do:

- Analyzes data returned from spacecraft missions.
- Use telescopes, both from the ground and in space, to discover new objects in our solar system and to characterize known objects.
- Study in the laboratory Moon rocks, comet dust, and meteorites, and other materials that may make up the planets.
- Make theoretical and computer models to tie these data to our understanding of physics, chemistry and geology. And experiments!
- Combine all these results to understand the histories of planets, moons, asteroids and comets.
- Use what we've learned to help plan where to send the next mission.
- Educate our youth - our future scientists and engineers.



Outer Planets Program

OPAG strongly endorses the concept of a sequence, or line, of flagship missions to the outer Solar System, or more generally, an *Outer Planets Program*.

OPAG recommends that NASA develop a program to reduce or retire technological or other risk associated with a major mission to Titan (either New Frontiers or large class), which may include such enhancing technologies as aerocapture.

OPAG recommends that NASA evaluate the possibility of having a new mission class above New Frontiers (so-called small Flagship).



New Frontiers class missions for Outer Solar System (not necessarily in priority order)

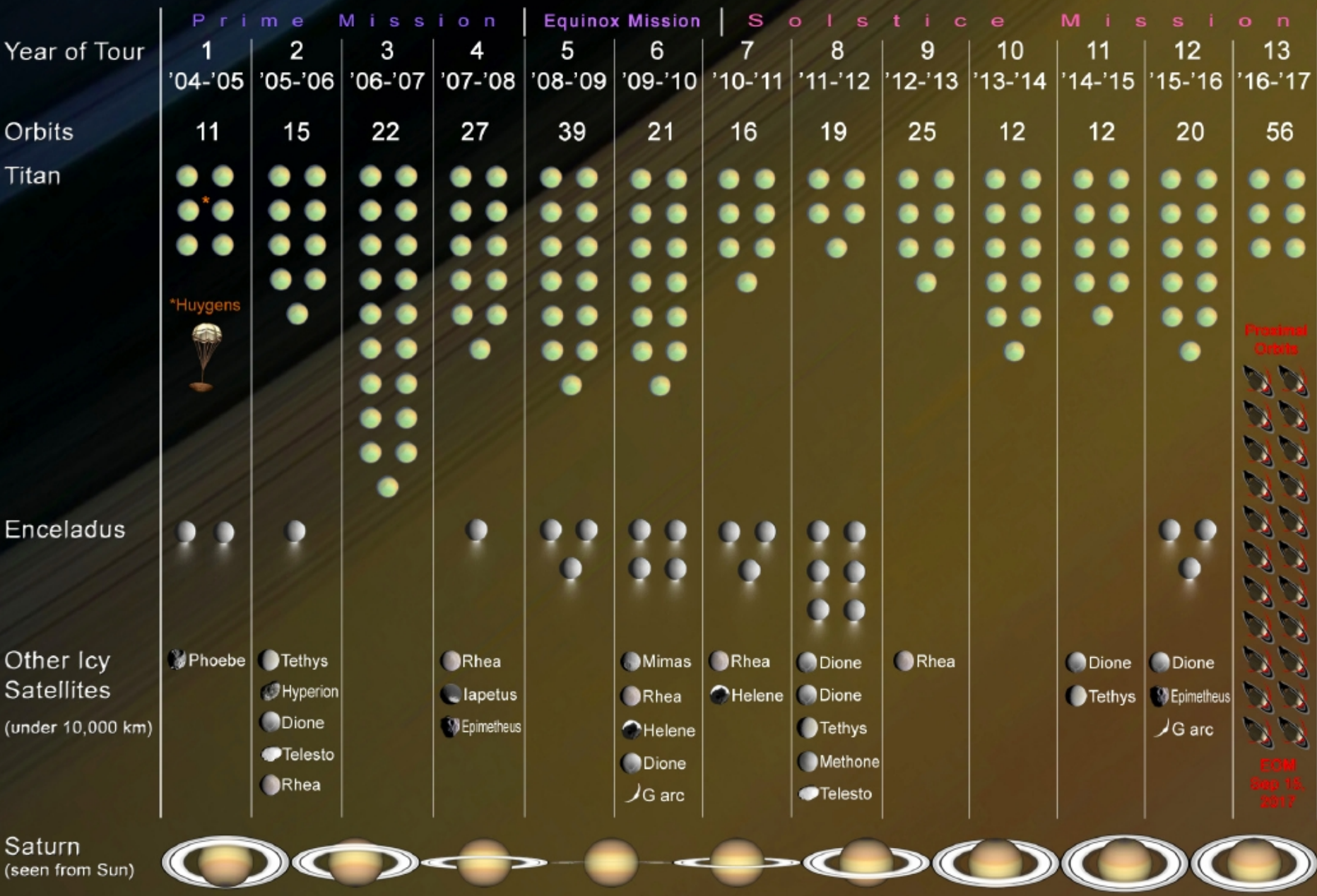
Probe missions to the giant planets have been on the agenda for years. A shallow probe mission to **Saturn** (perhaps in concert with microwave sounding) may be technically feasible, and fit within NF budget.

Io Observer, as exists in present NF mission suite (D12 with ASRGs and LV as GFE is effectively NF).

Neptune/Triton/KBO rendezvous would fit within NF budget (a Flagship-class Neptune Orbiter mission has long been part of OP community thinking).

Cassini Mission Overview

Four-Year Prime Tour, Equinox Mission, and Solstice Mission (Proposed), July 2004 - July 2017



Proximal Orbits



EOM
Sep 15, 2017



Cassini Solstice Mission

CSM, or Cassini Extended-extended Mission (XXM), whether viewed as an extension of a highly successful Flagship mission, or a stand-alone Discovery-class mission, represents a phenomenal return on investment.

OPAG strongly endorses approval by NASA of this extension to the Cassini mission, including the Juno-like end-of-mission scenario.

OPAG

Outer Planets Assessment Group



Half-full!

