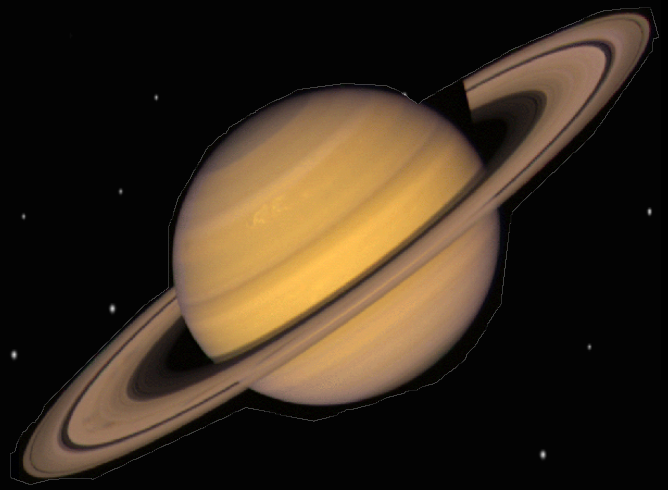
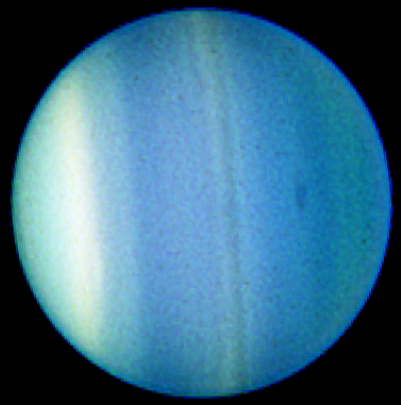
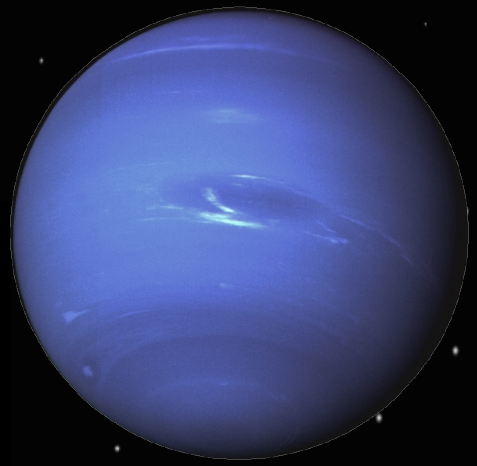
Outer Solar System Exploration







Outer Planets Assessment Group (OPAG) Report to PSS

October 2015

OPAG Charter and Meetings

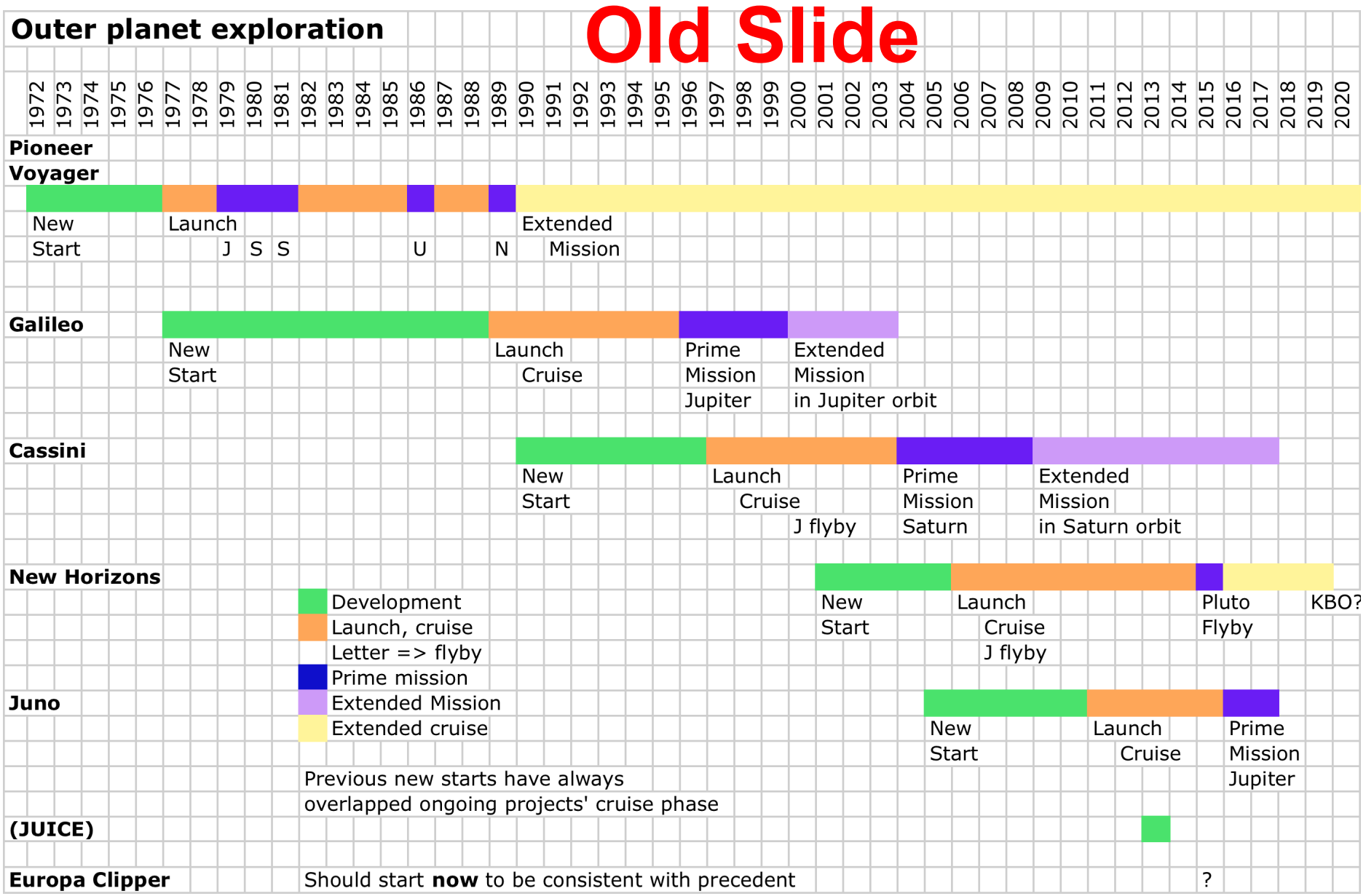
- OPAG regularly evaluates outer solar system exploration goals, objectives, investigations and required measurements on the basis of the widest possible community outreach. The group assembles twice per year to assess the current state of outer solar system exploration, goals for future exploration, and technology development needed to achieve those goals.

- The most recent OPAG meeting was 24-26 August 2015 at JHU/APL

- The next OPAG meeting will be Feb 1 - 2, 2016 hosted by SWRI in San Antonio, TX

Major objectives for the August meeting

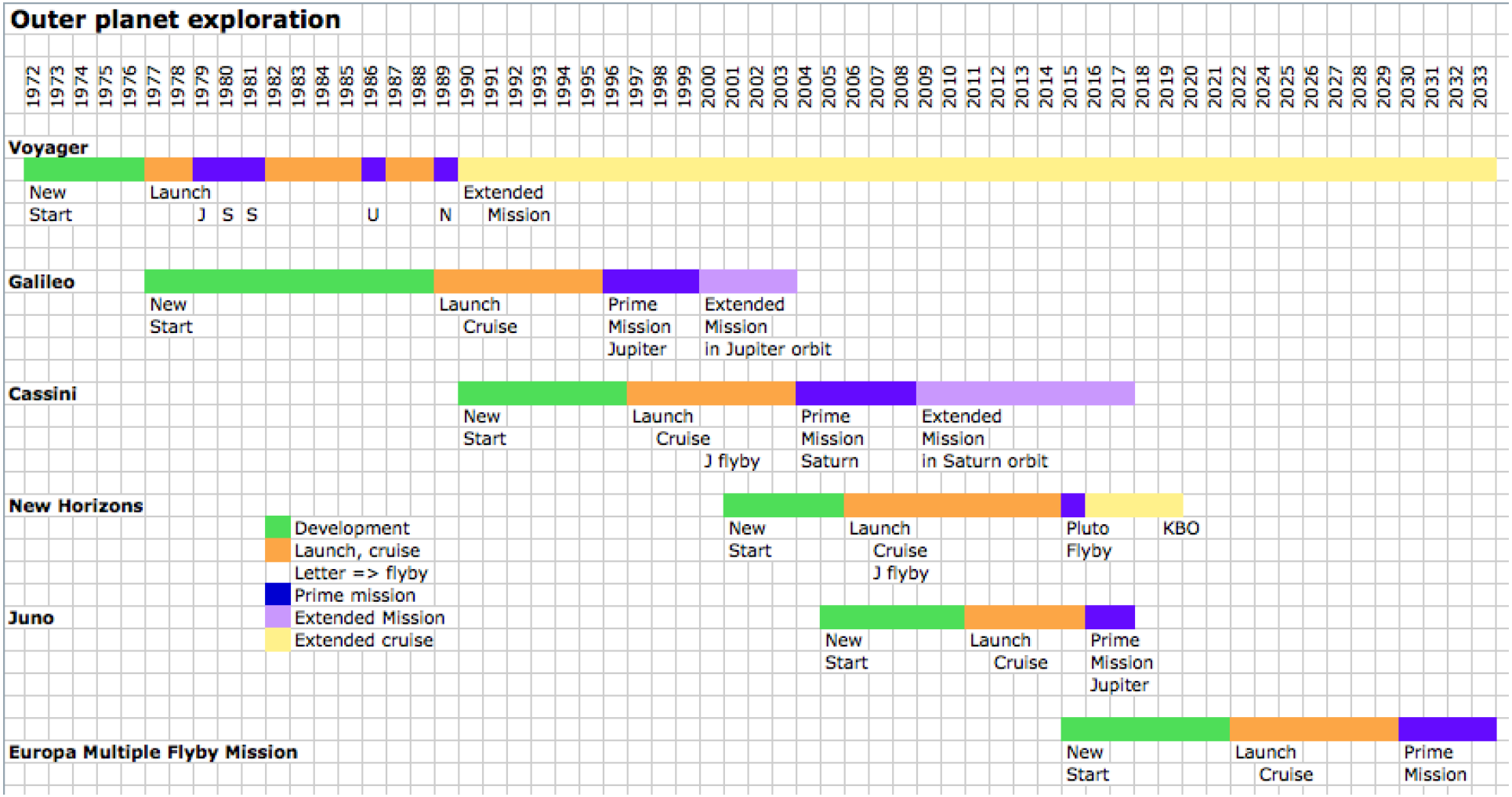
- Celebrate the present – it's a great time to be an outer solar system scientist
  - New Horizons at Pluto!!
  - Cassini and Juno less than a year away from intense orbital operations in high inclination orbits
  - **Europa Mission new start and payload selection**
- What we need to explore the outer solar system
  - Power for spacecraft
  - Technology development
- Defining our science goals
  - Progress on the new science goals document
  - New idea for the over-arching science theme -> ***Explore Ocean Worlds***
  - Preparing for the next decadal survey
- Challenge: How to keep outer solar system science vibrant through the decade gap to the Europa multi-flyby mission operations
  - The importance of R&A -> Science nuggets
  - Telescopic opportunities



WAS

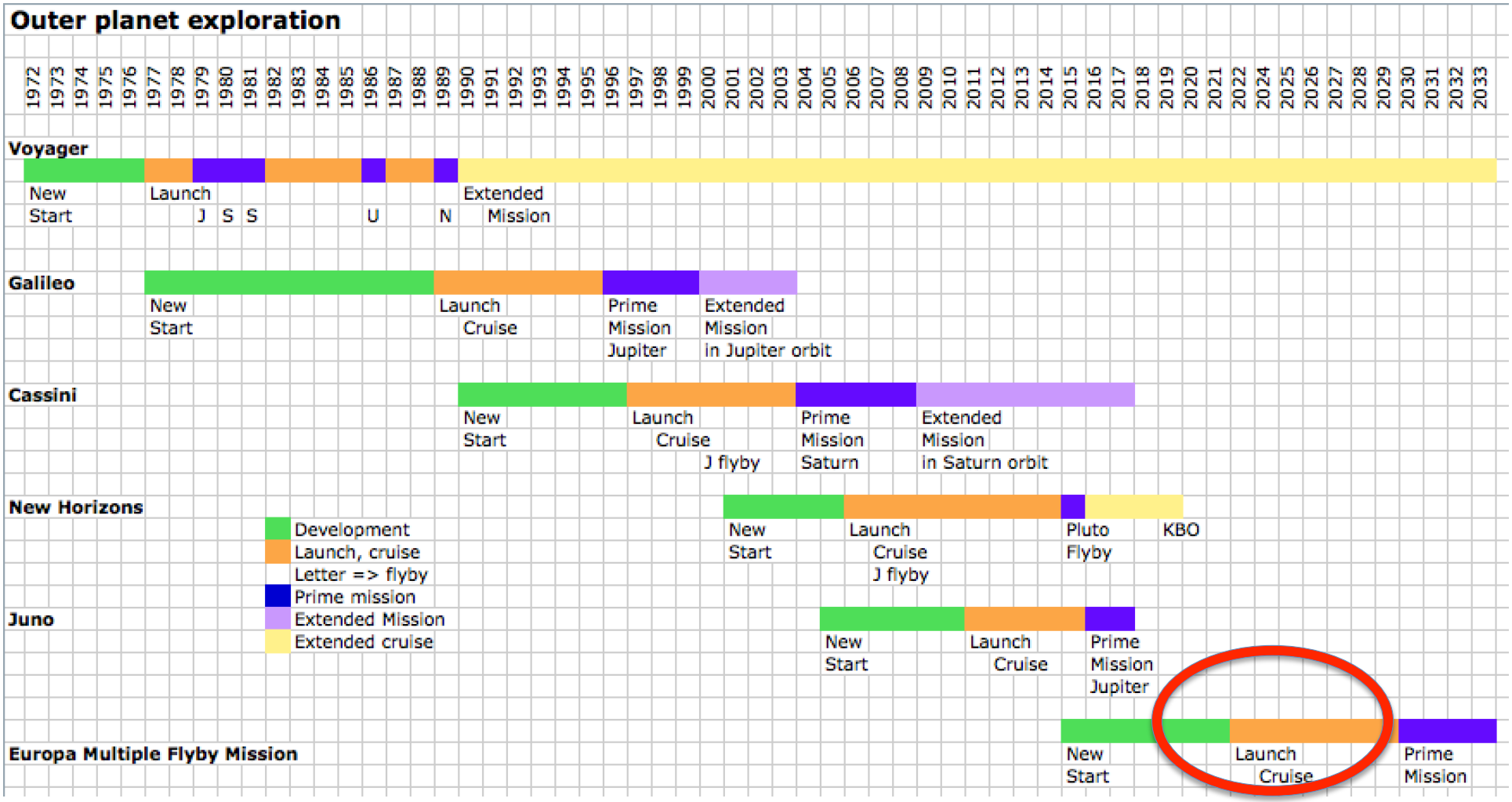
The lights go out in 2018 with no new US-led missions in development

Now: Outer solar system exploration has a future!



- With the new start of the Europa Multiple Flyby Mission the gap has an end

Now: The New Challenges



- How to keep the community vibrant until ~2030
- What comes next?

OPAG FINDINGS

From the August 2015 OPAG meeting

1. Europa Mission (a)

- OPAG lauds the progress being made on the new Europa Mission, in particular the selection of a comprehensive suite of very capable science instruments for the payload. OPAG continues to offer its firm support for the *Europa Multiple Flyby* mission. This mission is the ultimate result of more than a decade of ever more detailed study and down-selects, and offers paradigm-shifting, flagship-level science at Jupiter's ocean moon. We are pleased that the mission has passed KDPA and entered Phase A and that the selected instrument teams have begun work on designing their scientific instrumentation.

- ***OPAG finding: OPAG is pleased with the selection of a capable comprehensive payload and strongly encourages NASA to continue to move forward with the Europa Multiple Flyby Mission as quickly as possible.***

1. Europa Mission (b)

- **On-ramps for Europa Scientists.** We are very pleased with the selection of capable instrument teams. However, many talented scientists were not selected due to a variety of factors (e.g., pressure to keep teams small, or to join only a single team). Adding these scientists during phase A would allow the Project to tap a broader depth of experience in the design and integration of the instruments as well as mission design and science operations. Emphasis on the addition of early career scientists will also lead to a stronger and more diverse team of scientists ready for the future.

- ***OPAG finding: OPAG strongly encourages NASA to consider judiciously adding participating and interdisciplinary scientists to the Europa Mission. Adding these scientists during phase A would improve the overall scientific return of the Mission and help train a generation of young scientists.***

1. Europa Mission (c)

- **JUICE coordination.** We note that with two missions in operation at Jupiter at the same time, overall scientific return will be enhanced by the foundation of a standing Europa mission - JUICE coordination working group.

- ***OPAG finding: Science return of both JUICE and the Europa Mission will be enhanced by a standing science coordination working group, which we encourage NASA to form.***

2. Ocean World Exploration Program

- The 2016 budget proposal from the U.S. House Appropriations Committee calls for the creation of an "Ocean Worlds Exploration Program" which would fund new missions to explore ocean worlds. From the proposal: "Many of NASA's most exciting discoveries in recent years have been made during the robotic exploration of the outer planets. The Cassini mission has discovered vast oceans of liquid hydrocarbons on Saturn's moon Titan and a submerged saltwater sea on Saturn's moon Enceladus. The Committee directs NASA to create an Ocean World Exploration Program whose primary goal is to discover extant life on another world using a mix of Discovery, New Frontiers and flagship class missions consistent with the recommendations of current and future Planetary Decadal surveys."

2. Ocean World Exploration Program

- Exploration of the outer Solar System reveals a vast array of amazing worlds. Among the most astonishing discoveries are those of liquid water present at Europa, Titan, and Enceladus, in probable "oceans" beneath their icy surfaces (Triton may also be in this league). Ice giants may be more appropriately called "water worlds".

- OPAG supports an Ocean Worlds Exploration Program, reflecting the recognition by Congress that the discovery of potentially habitable environments in the outer solar system has the capacity to grip the public's imagination, increase programmatic attention and funding on outer solar system science, focus our best efforts for advanced exploration technologies (which can be tested in Earth's cryosphere and oceans), and generate historic astrobiology discoveries in our time.

- ***OPAG finding: OPAG strongly endorses the creation of an Ocean Worlds Exploration Program. The OPAG community looks forward to being deeply engaged in the definition of the science goals of this program to maximize science return.***

3. The Legacy of Cassini

- Cassini's data return from the Saturn system continues to inspire, enchant and challenge us. During its final year, the Cassini Grand Finale Mission will produce many hundreds of gigabits of fundamentally new data, including unique near-field gravity measurements, novel in-situ sampling of atmospheric constituents and magnetic fields and plasmas. OPAG is very pleased that NASA plans to continue the Cassini Data Analysis Program (CDAP) after the conclusion of the Cassini/Huygens Mission. We are concerned that to accommodate the need to analyze Cassini's wealth of unique new data at the end of the mission the normal level of support for the CDAP program may be inadequate. We encourage PSD to monitor the selection levels and be prepared to augment CDAP funding if needed in the future.

- ***OPAG finding: The CDAP program has been incredibly successful in funding analysis and modeling of the wealth of data collected by Cassini. Continuation of CDAP will help to bridge the large gap before the next outer solar system mission and ensure that a knowledgeable cadre of outer planet scientists will be ready to analyze data from the Europa mission, as well as other future outer planet missions. The wealth of new data collected at the end of the Cassini mission may require more time and resources than has typically been available to analyze adequately. .***

4. Invest in power sources needed for outer solar system exploration

- There are many potential planetary missions that require use of Radio-isotope Power Systems (RPS), including nearly all that would venture beyond Jupiter. These missions range from Discovery class to flagships. Ideally RPS would be offered GFE for Discovery missions in a continuing effort to "level the playing field" for outer solar system missions in the Discovery program. RPS is currently the only viable option for ice giant missions and long-duration missions to Titan's surface and lower atmosphere. OPAG supports continued investment in RPS production and efficiency-enhancing technologies, but is concerned that the planned 400 g/year production rate falls far short of the 1.5 Kg/year need identified previously. We also acknowledge the improved capability of solar power solutions, and support a smaller but significant investment in new solar and energy storage technology.
- ***OPAG finding: The re-start of domestic production of Pu238 is a significant achievement without which continued exploration of the outer solar system is severely curtailed. It is important to continue investments in future technologies that offer end-of-life improvement over the current MMRTGs. A small, but significant, investment in solar power and energy storage technologies is also***

5. New Frontiers

- **New Frontiers -** We celebrate the success of NASA's first New Frontiers mission, the New Horizons revelations at Pluto. OPAG welcomes and strongly supports NASA's continuing efforts to put the New Frontiers program on a healthy mission cadence with the news of an Announcement of Opportunity in 2016 for a New Frontiers mission. These medium-class PI-led missions allow the NASA planetary science community to target regions of great impor ce in the solar system with capable missions of moderate breadth.

- OPAG lauds NASA's efforts t duce a r supply of Radioisotope Power Systems (RPS) for use acros ssion ories and we encourage NASA to allow RPS's in the upcoming #4 (NF4) Announcement of Opportunity (AO). The seven missions ca e 2013 Decadal Survey for NF4 + NF5 each have their own challenges, a ng flexibility in how they are powered ensures that NASA and the community can field the most capable and scientifically compelling mission possible.

- ***OPAG finding: We are pleased that an AO for New Frontiers will come out in 2016. OPAG encourages NASA to make Radioisotope Power Systems an allowed option for the New Frontiers #4 mission.***

6. Vision and Voyages

- OPAG continues to support the Decadal Survey. The 2013 Planetary Science Decadal Survey document, Vision and Voyages, describes a compelling program for planetary exploration in the 2013 to 2023 time span. We support those recommendations for New Frontiers missions and we think that maximizing the choices available for the upcoming NF4 opportunity by combining the Vision and Voyages recommended lists for NF4 and NF5 will allow selection of the most compelling technology-ready science mission.

- ***OPAG finding: We suggest, from a scientific and technological perspective, that the lists of possible missions from Vision and Voyages for New Frontiers 4 and 5 be combined for the 2016 NF4 Announcement of Opportunity.***

7. The Next Decadal Survey (a)

- **Ice Giant Mission Study.** OPAG was very pleased to note the announcement of studies for Ice Giant orbiter missions. OPAG thanks NASA PSD for initiating this effort, which is consistent with the recommendations of the past two decadal surveys for planetary science. OPAG is particularly pleased to hear that the science community will be engaged in this process from the outset. OPAG notes that finding a means for international collaboration for ice giant mission studies would be advantageous, given the broad interest in these bodies as evidenced by meetings and mission proposals abroad.

- We believe that additional studies are also needed to inform the next Decadal Survey which will likely recommend missions to Titan, follow-on to the Europa Mission, Enceladus plume investigations, etc.

- ***OPAG finding: OPAG endorses PSD's direction that the next-in-line flagship priority of the 2013 Decadal (Uranus orbiter with probe) be used now to convene an ice-giant Science Definition Team (SDT) to steer a comprehensive mission concept study. OPAG urges other Decadal Survey preparatory studies and commits to supporting NASA in developing and documenting credible mission concepts to inform the next Decadal Survey.***

7. The Next Decadal Survey (b)

- **Future Decadal Survey Structure.** A number of structural/process decisions had an impact on outer solar system mission recommendations in the Decadal Survey, including (but not limited to) putting all outer solar system moons in one panel, and requiring that preliminary mission concepts be fully costed (thus limiting the innovative nature of a competitive process). Although the NRC recently completed a Survey of Surveys, these were high-level general results. OPAG feels that lessons learned at the deeper PSD level could be collected from the planetary community to feed forward to the next planetary Decadal Survey. We will pursue this at our next meeting.

- ***OPAG finding: We suggest that a query go out to the planetary science community to solicit feedback with regard to how the next Decadal Survey is structured.***

8. Earth-based observations for missions

- **Earth-based observations for mission support**. Earth-based, telescopic observations of planetary objects being studied by spacecraft enable greater science return than the mission itself can provide. These assets provide context to the spacecraft observations, and assist in targeting observations to optimize science return from the mission. The Galileo, Cassini, and New Horizons missions have demonstrably benefitted from Earth-based observations that helped target their remote observations (such as the satellite flux tube footprints) and yielded contextual information on Io's volcanoes and Titan's and Jupiter's clouds, for example.

- Some of the key elements for such support are Earth-orbiting spacecraft that are Astrophysics division assets, such as HST, Spitzer, Kepler, and JWST. Recent observations by HST have enabled detection of several dozen KBOs, two of which are possible targets for the New Horizons extended mission. The giant planet atmospheres are dynamic places, and our understanding of them requires frequent monitoring. We are pleased that HST and Kepler support such monitoring programs.

- ***OPAG finding: To leverage greater science return from active missions, OPAG continues to encourage NASA to support Earth-based observations in general, as well as observations with Earth-orbiting facilities operated by the Astrophysics Division.***

9. Research & Analysis programs

- R&A plays an essential role in maximizing science return from NASA's missions, and was recognized by the 2013 Decadal Survey as an essential part of a balanced program of planetary exploration. While almost all "Excellent" proposals are getting funding, innovative but less familiar proposals could be passed over in favor of the more conventional fare. Many "Very good" proposals would yield "Excellent" science results if given the opportunity. The looming decade-long gap in outer solar system missions means that many scientists with that expertise will have to be funded largely or even purely through R&A. We are concerned that we will lose vital skills and knowledge as many outer solar system scientists may be forced to leave the field or seek alternative subjects to study. The Cassini mission has not only been the primary source of support for Cassini data analysis, but a substantial support for the Outer Solar System science community overall, i.e. Cassini's end of mission will raise the pressure on R&A across the board. We are pleased that the National Research Council has accepted the charge to evaluate the re-structured R&A program and we urge that looking at the challenges the outer planets community will face in the coming decade be part of their task.

7. Research & Analysis programs (cont.)

- ***OPAG finding: OPAG finds that increased funding to the R&A programs would improve selection rates and allow more excellent peer-reviewed planetary science and data analysis to proceed. We note the looming pressure on R&A as science mission support for scientists comes to a close.***

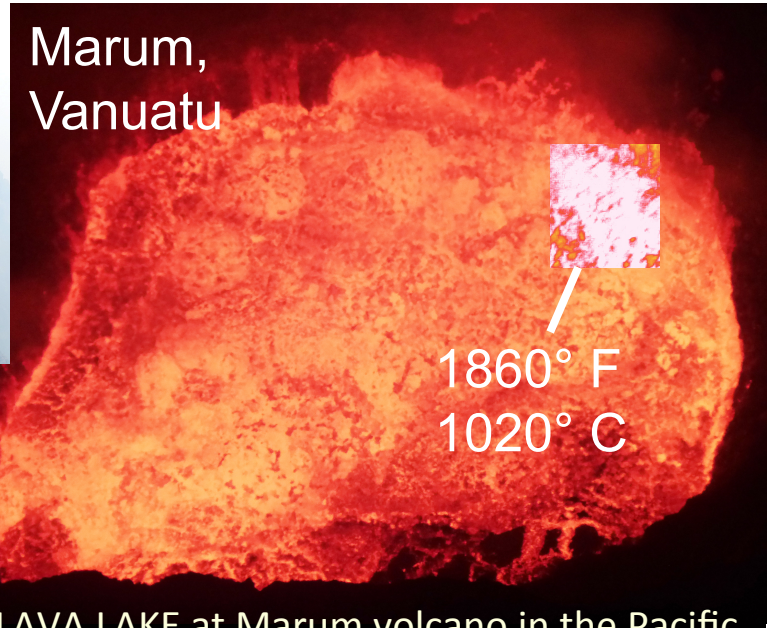
SCIENCE NUGGETS

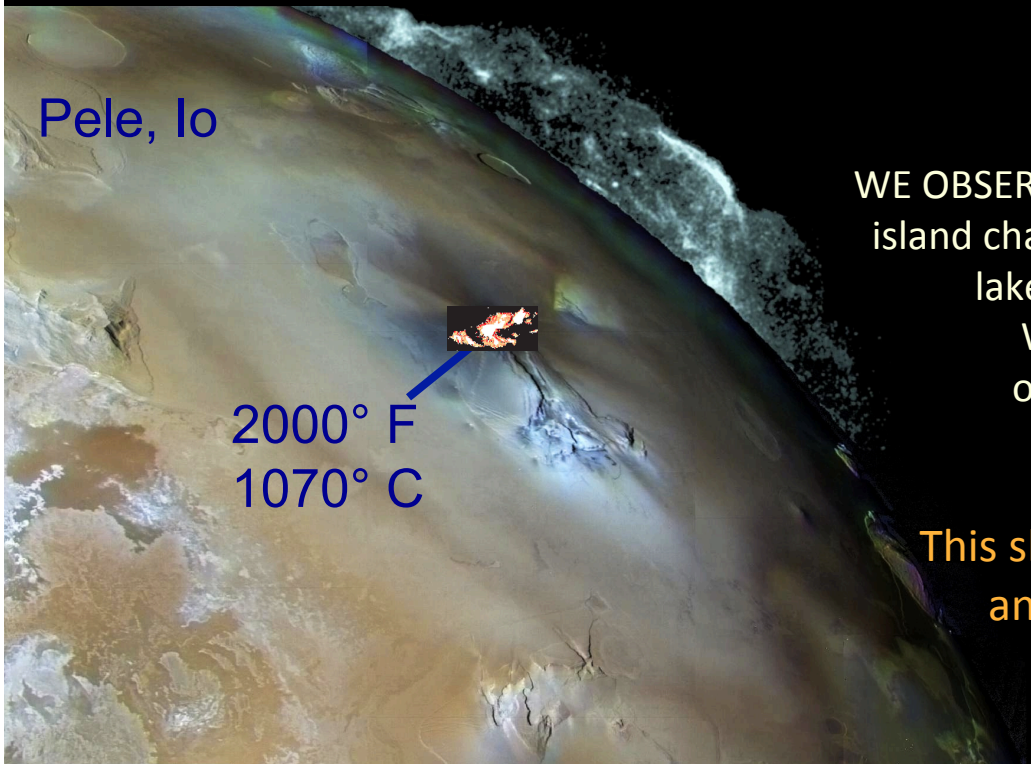
When we reach the end of funding for current flight missions as they complete their missions, the outer planets science community will rely on R&A funding alone to continue data analysis and pursuit of new hypotheses. *The health of the R&A program is an ongoing concern, and we discussed **our own responsibilities** to help it thrive.* With this motivation, we held a "science nuggets" workshop to teach everyone how to craft a science nugget on their own research, and thereby promote outer solar system research.

Active Lava Lakes on Io from the Field

ERUPTING VOLCANOES ON JUPITER'S MOON IO reveal the makeup of the crust and how heat is released.

DO THE TEMPERATURES measured from distant spacecraft represent the actual heat from eruptions on Io?





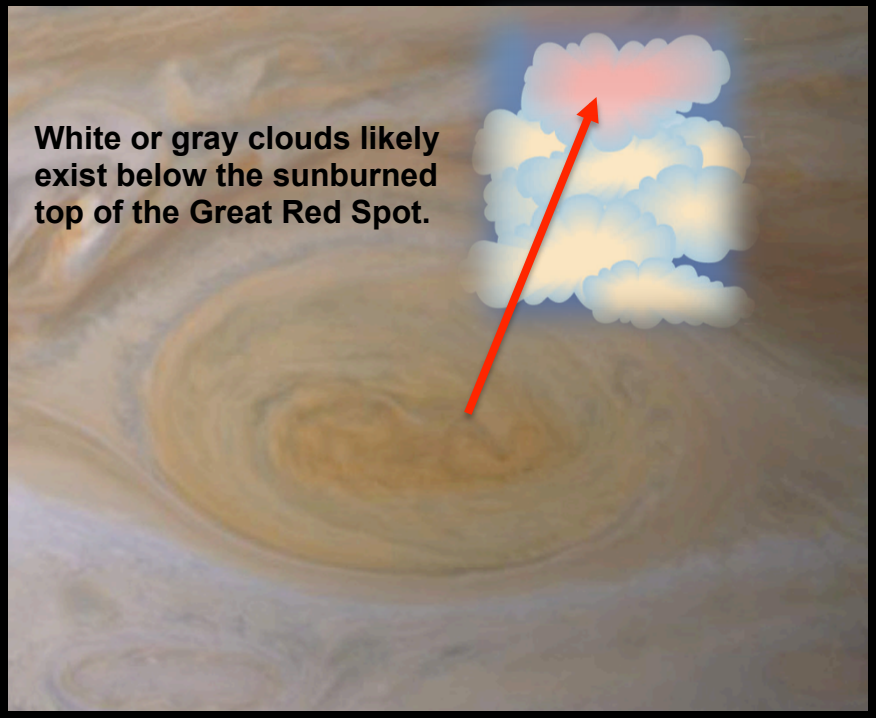
WE OBSERVED A LAVA LAKE at Marum volcano in the Pacific island chain of Vanuatu, an analog for Io's most active lava lake, Pele (named for the Polynesian goddess of fire). We measured accurate temperatures and changes over time from handheld instruments like those on spacecraft that visited Io.

This shows LAVAS ARE SIMILAR ON EARTH AND IO and internal energy is released in similar ways.

Jani Radebaugh, R. Lopes, R. Howell, R. Lorenz, E. Turtle. Jour. of Volcanology and Geothermal Research, In review

Sunburn Colors Jupiter's Red Spot

Just like a human who spends too long in the sun, Jupiter's Great Red Spot gets its ruddy color from overexposure to ultraviolet light from the sun, according to new laboratory analysis by Cassini researchers.



- Ultraviolet light breaks down ammonia and acetylene, producing the Great Red Spot's characteristic hue. Analysis suggests that beneath the sunburned top of the storm are bland, pale clouds of ammonia and hydrocarbons still unexposed to sunlight.
- These new results contradict the other leading theory for the origin of the spot's striking color – that reddish chemicals are churned up from beneath Jupiter's clouds. If upwelling of reddish chemicals were the cause, the red spot would be even redder.
- Determining the chemistry responsible for Jupiter's colorful clouds provides insights into the composition of the giant planet and clues to the original ingredients that made up our solar system.

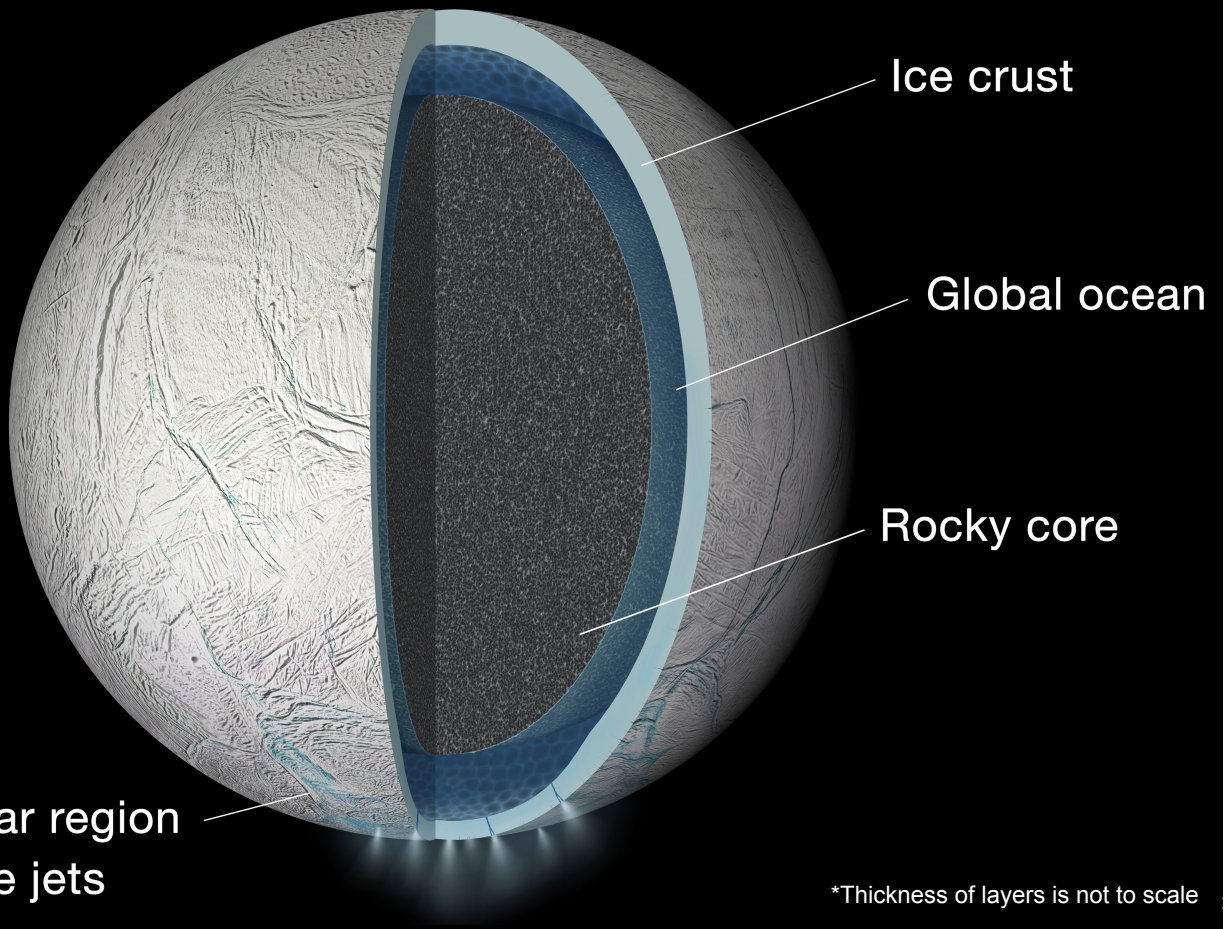
"Why is the Great Red Spot Red? The Exogenic, Photolytic Origin of the UV/Blue-Absorbing Chromophores of Jupiter's Great Red Spot as Determined by Spectral Analysis of Cassini/VIMS Observations using New Laboratory Optical Coefficients," K.H. Baines, R.W. Carson, T. W. Momary, American Astronomical Society, DPS meeting #46, #511.05, 2014

Press Release - http://go.nasa.gov/1DVgMFM

Global Ocean Inside Enceladus

- Cassini imaging observations of Enceladus' rotation and its wobble (libration) as it orbits Saturn revealed the presence of a global ocean[1].
- Explaining the magnitude of the wobble requires a global ocean separating the outer ice shell from the interior. It rules out a completely frozen interior.
- A global ocean may mean that tidal flexing by Saturn's gravity generates much more heat inside Enceladus than previously thought.
- This discovery, together with this year's discovery of seafloor hydrothermal activity[2,3], indicates that ocean could be long-lived. Enceladus, the "ocean world," invites exploration.

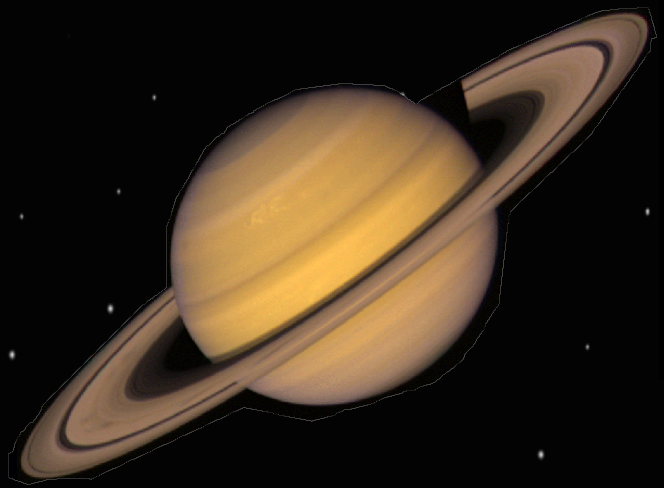
Press Release - http://1.usa.gov/1NDHVlV

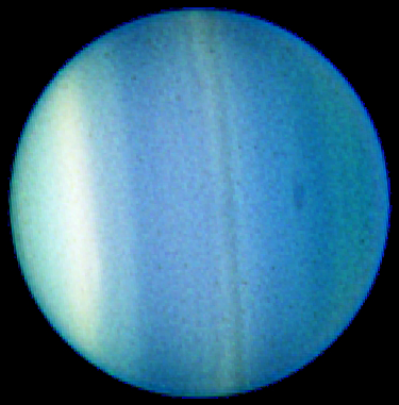


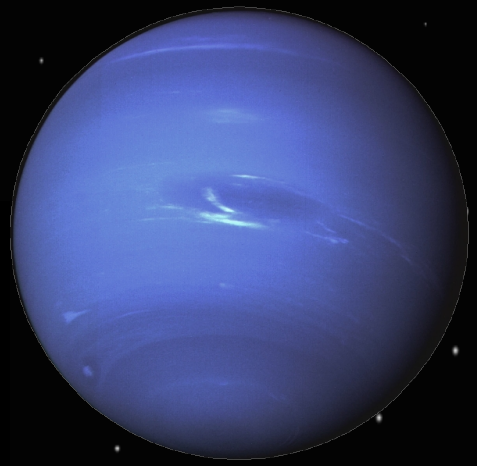
*Thickness of layers is not to scale

[1]*"Enceladus's measured physical libration requires a global subsurface ocean," P.C. Thomas, et al., 2015. doi:10.1016/j.icarus.2015.08.037*
[2]*"Ongoing hydrothermal activities within Enceladus," Hsu et al., Nature, 519, 207-210, 2015.*
[3]*"Possible evidence for a methane source in Enceladus' ocean ," Bouquet et al., Geophysical Research Letters, 42, 1334-1339, 2015.*

Outer Solar System Exploration







Worth the journey

BACKUP CHARTS

OTHER OPAG BUSINESS

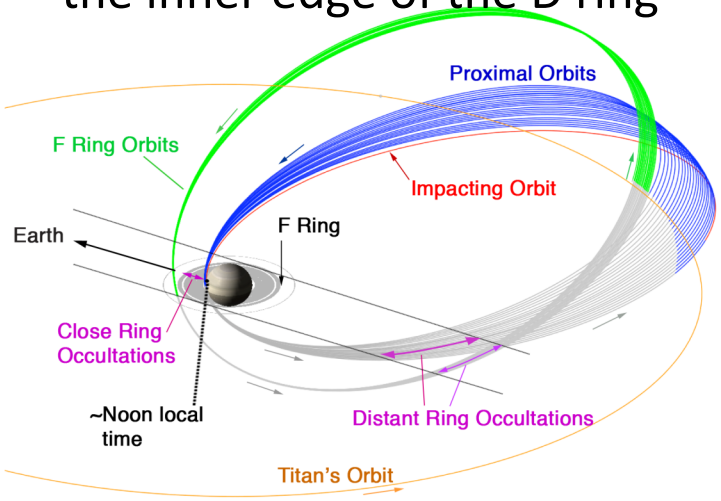
NEW SCIENCE GOALS DOCUMENT

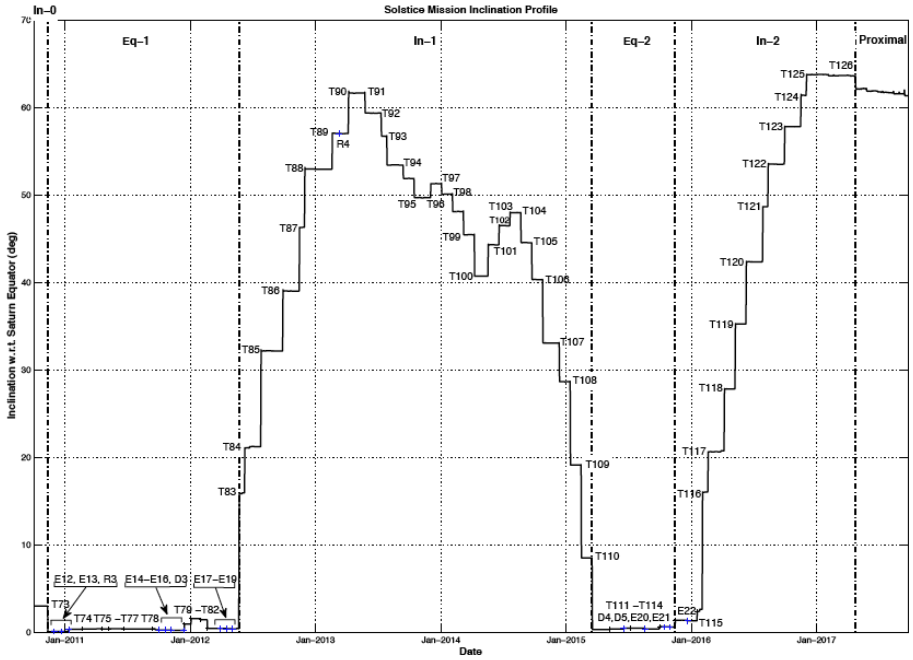
UPCOMING EVENTS

The Grand Finale of the Cassini Mission

- Cassini is starting its Eq-2 phase, the last time the orbit inclination will be in Saturn's equatorial plane

- After that the inclination will be pumped up to begin the F ring orbits, followed by the Proximal orbits that plunge between the top of Saturn's atmosphere and the inner edge of the D ring

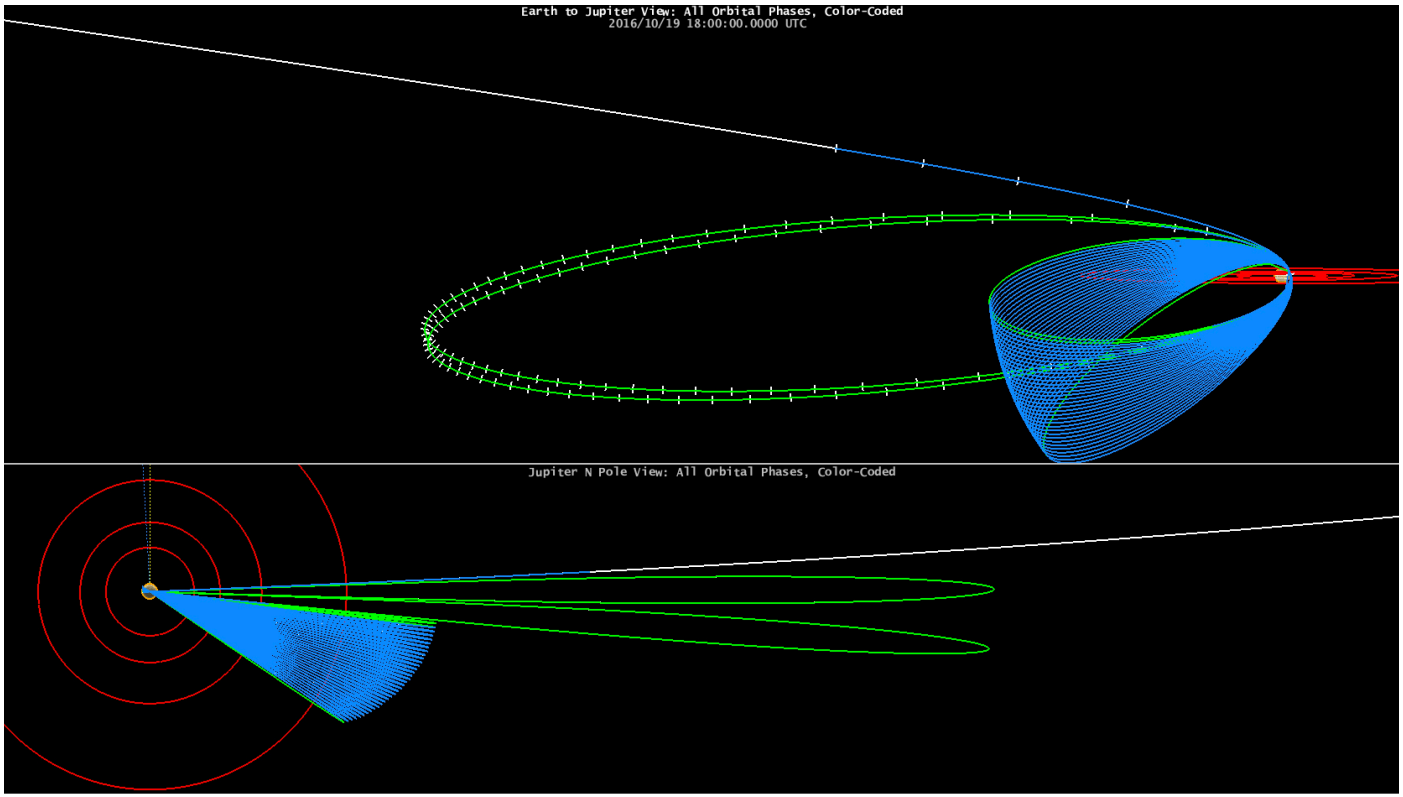




- After a long successful mission at Saturn the Cassini End-of-Mission is planned for Sept. 2017 when the spacecraft runs out of fuel and spirals into Saturn's atmosphere

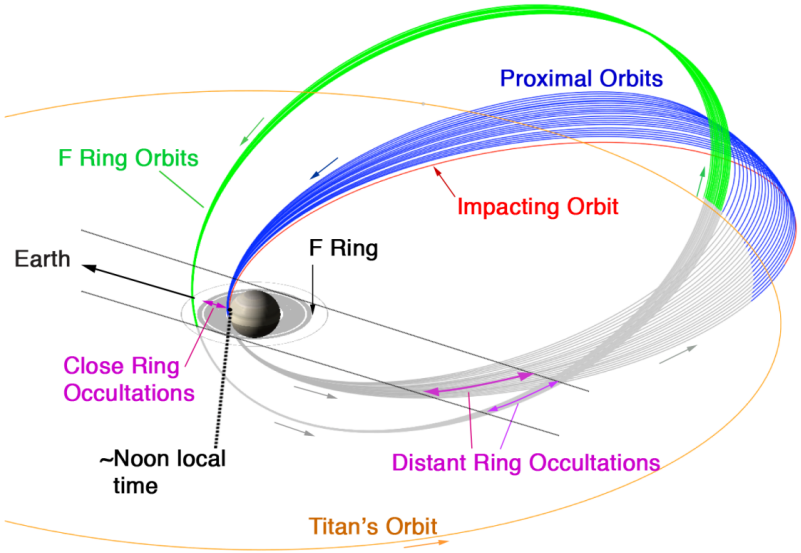
Juno Mission Update

- The Juno project recently made two important changes to its mission plan:
  - The 107 day capture orbit has been replaced by two 53.5 day orbits, allowing the first perijove after orbit insertion to be dedicated to characterization of the environment and observations needed for optimization of instrument configurations for the prime mission
  - The prime mission orbits' period will be 14 days rather than 11 days

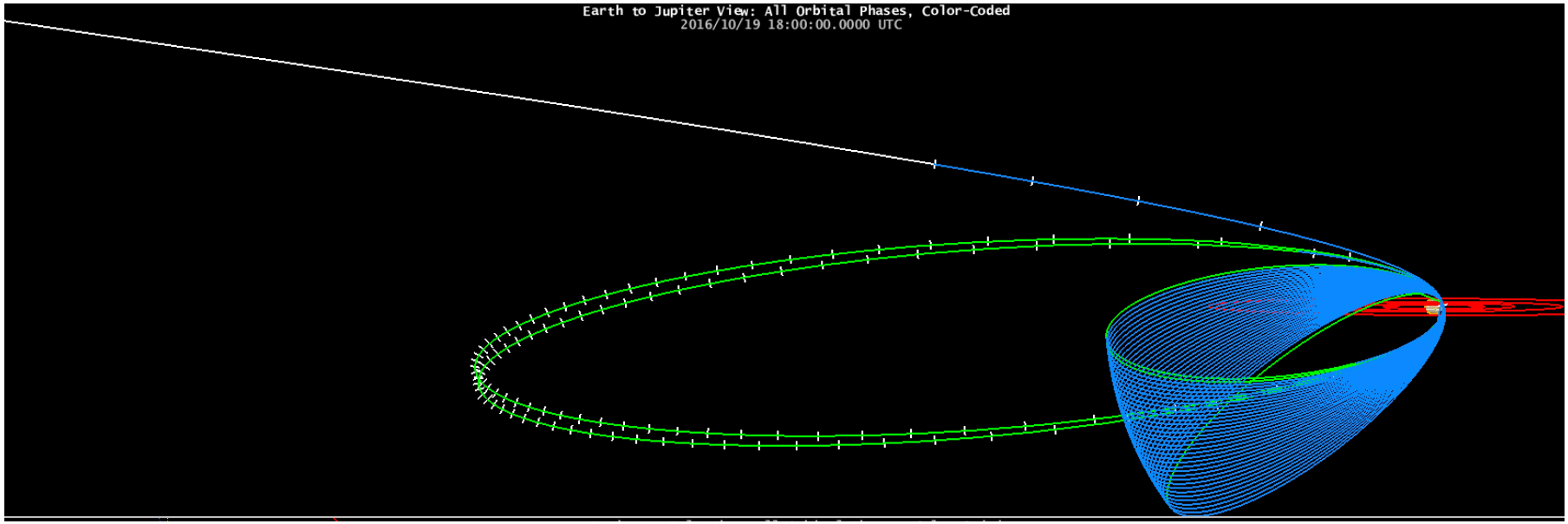


Juno Jupiter Orbit Insertion will take place July 4, 2016

Juno and the final stages of the Cassini mission



- Similar orbits offer comparable science objectives – giant planet interior structure, gravity field, auroral studies, magnetospheric physics



Why should we explore the Outer Solar System?

Why not just focus on Mars? (Mars is *a fascinating* planet, certainly worthy of exploration, but…)

- Understanding *atmospheric circulation* – the giant outer planets have entirely different atmospheres than the terrestrial planets – understanding them means developing advanced fluid dynamics models (that have been applied for example to ocean currents)
- *Weather* more akin to earth: Earth is at the mercy of processes today that are taken to extremes on Saturn's moon Titan: a thick greenhouse atmosphere with violent rainstorms, desertification, and seas with coastline erosion and climate impact.
- *Atmospheric chemistry and astrobiology* - The reducing atmospheres in the outer solar system are home to a vigorous organic chemistry that does not occur in the inner solar system in the present day, providing an opportunity to study natural production of biological building blocks.
- *Magnetospheres* – the variety of the outer solar system tests our models and understanding of how our own magnetosphere is structured
- *Materials' behavior* in extreme pressures and temperatures not natural on earth – for example ice behaves like rock at outer solar system temperatures, but interior to many moons may be liquid
- *Exoplanets* – most of the new planets discovered around other stars are similar to Uranus and Neptune – we have a very limited understanding of our own ice giants

Treasures in the Outer Solar System

- *The outer solar system is target-rich*. We'd like to learn more about volcanoes on Io, storms on Titan, the rings around Uranus and whether Ariel is a frozen version of Enceladus. We'd like to study geysers on Triton, the plumes of Enceladus, and the magnetosphere of Neptune. And of course the highest priority of all is to learn more about Europa, a moon that could conceivably have life today in a subsurface ocean.
- We send our robotic emissaries to places too dangerous for humans – that doesn't make those places less worthy of exploration
- Destinations recommended in the Decadal Survey "Vision and Voyages" for the upcoming decade:
  - Europa, to learn more about the subsurface ocean and how to access it in the future
  - Uranus orbiter, to study an ice giant in our own solar system analogous to many exoplanets being discovered
  - Saturn probe, to study the layers under the cloudtops
  - Io volcano observer, to learn the secrets of the most volcanically active place in the solar system

What do we need to do to achieve a healthy program of outer solar system exploration

A. Maintain support for current missions and data analysis
B. Support the Decadal-Survey-responsive Europa Multiple Flyby mission
C. Invest in power sources appropriate for the outer solar system
D. Make sure that outer solar system missions have a home in Discovery and New Frontiers
E. Go after other opportunities with international collaboration
F. There will be a gap in data for >10 years; how do we maintain a knowledgeable outer solar system community of scientists?
   - Keep that gap as short as possible
   - CDAP extension

OPAG: Outer Solar System Vision

Draft threads

- Study origin and evolution of our solar system
  - With major complementarity with exoplanets
- Investigate habitability of icy worlds
  - To gain insight into the origin of life on earth
- Understand the dynamic nature of processes in our solar system
  - importance of time domain

What's next? Baby steps toward implementation; strategic multi-decadal plan