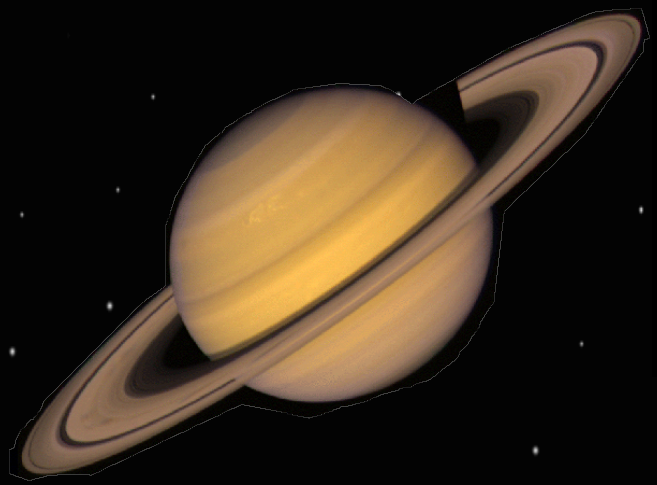
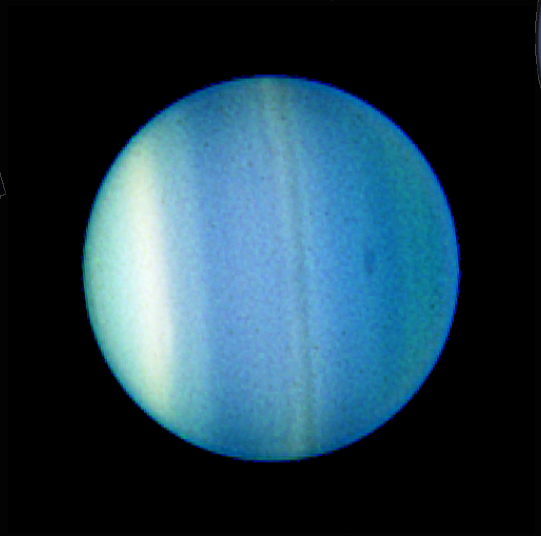
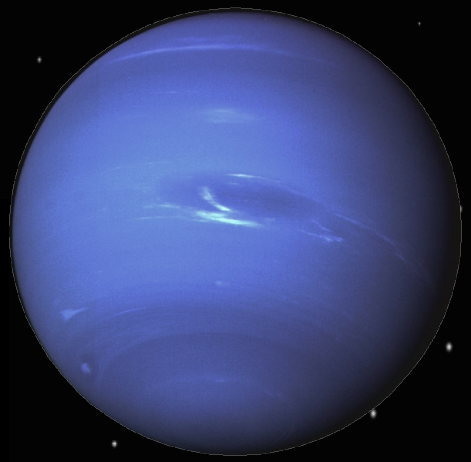
Outer Solar System Exploration







Outer Planets Assessment Group (OPAG) Report
October 2013

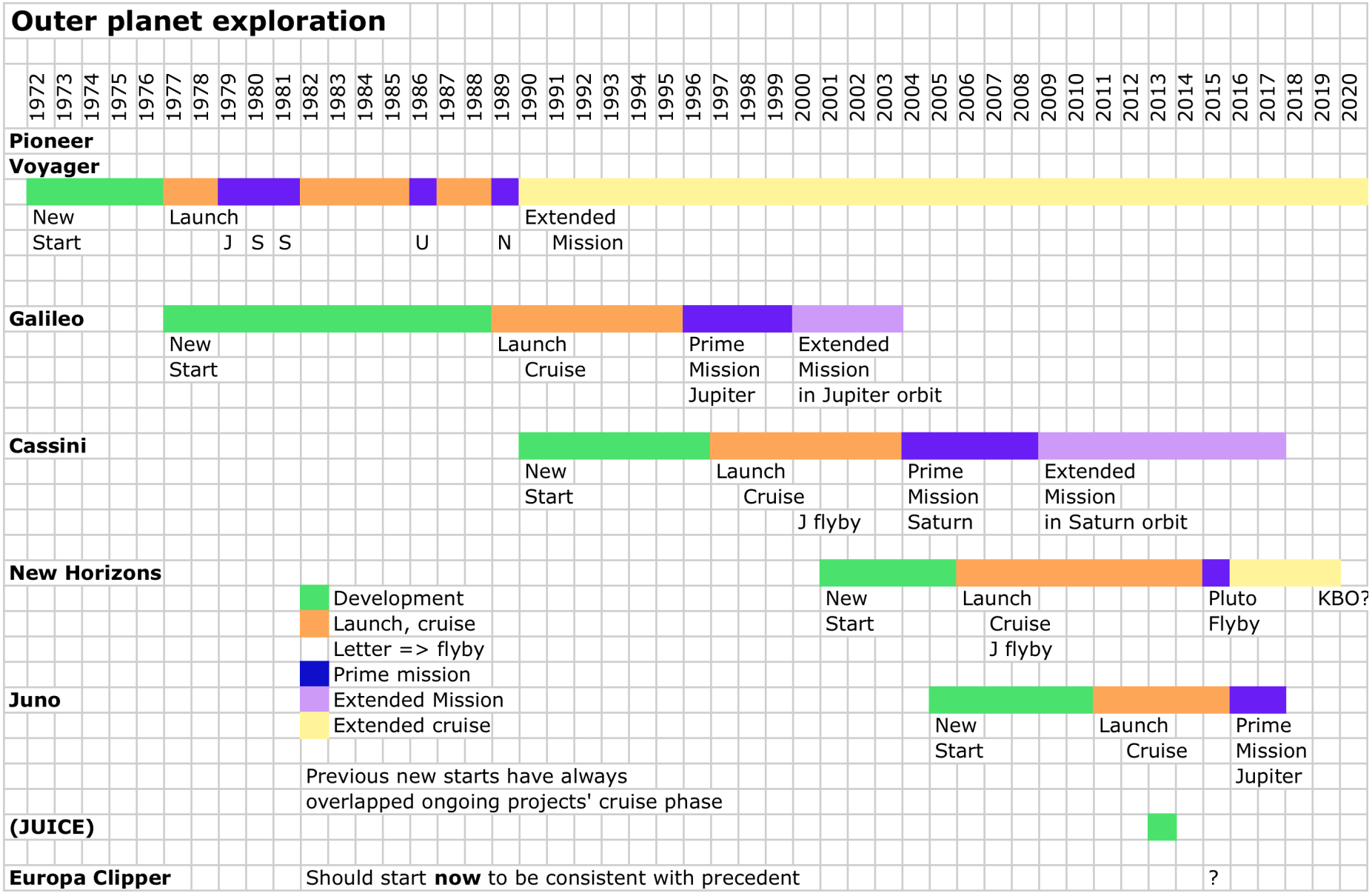
OPAG Assessment: Mind the Gap

- 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.
  - >500 people have signed up on OPAG website with indication of interest
  - Most recent OPAG meeting was 15-16 July 2014

- ***Our biggest concern remains the looming gap in missions to the outer solar system***

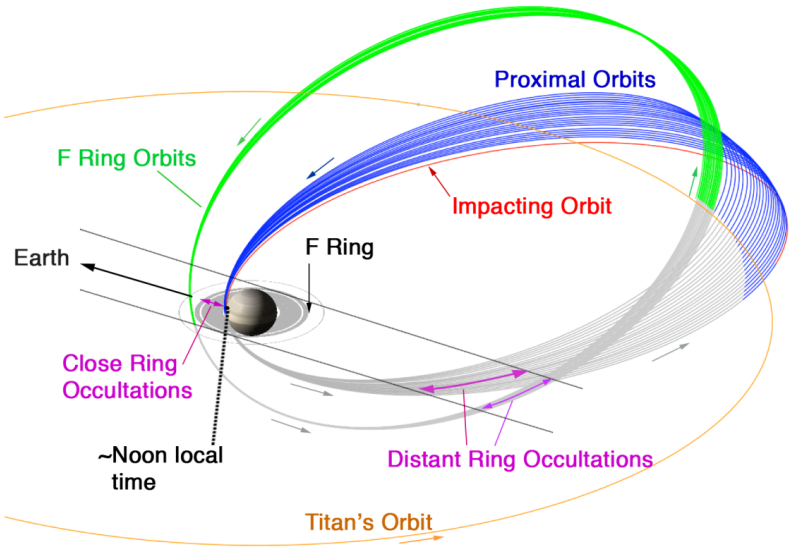
- The near-term future is bright
  - Juno at Jupiter
  - Cassini at Saturn
  - New Horizons flyby of Pluto

- After that we have only
  - Limited participation in JUICE
  - Possible New Horizons flyby of a KBO

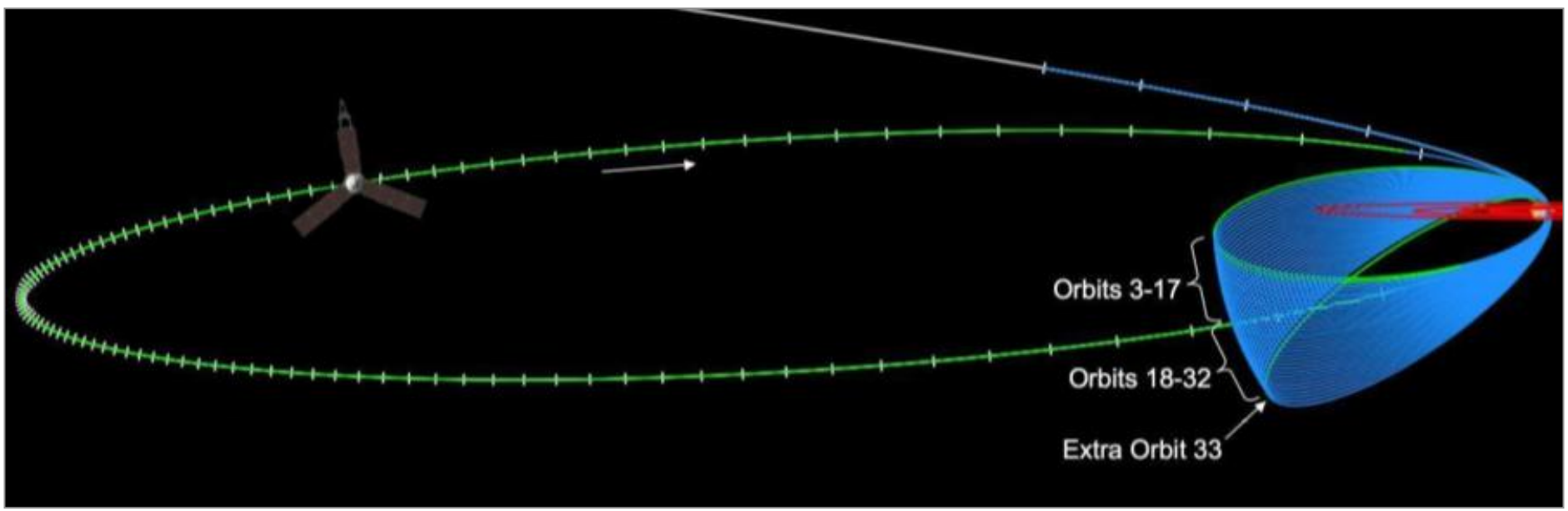


The lights go out in 2018 with no new US-led missions in development

Juno and the final stages of the Cassini mission



- After a long successful mission at Saturn the Cassini End-of-Mission is planned for Sept. 2017 when the spacecraft runs out of fuel
- Juno End-of-Mission at Jupiter is predicted as October 2017 with expected radiation damage
- Comparable science objectives – giant planet interior structure, gravity field, auroral studies, magnetospheric physics



Threat to Cassini's final years?

- NASA's notional budget for the outyears no longer includes funding for Cassini in the outer planets line
- The final three years of the Cassini mission promise entirely new discoveries as the orbit of the spacecraft is cranked to high inclination and periapse is brought inside the rings. *This geometry enables acquisition of new data on Saturn's interior and magnetosphere*, as well as a new perspective for viewing its rings, that continue the Cassini legacy of ground-breaking new scientific discoveries in the Saturnian system

- ***OPAG finding:*** *NASA should explicitly show a notional budget for the Cassini Solstice Mission in 2015, 2016, and 2017. OPAG asserts that the unique science return from the Cassini end-of-mission observations strongly warrants full funding of the final three years of the mission.*

- ***OPAG finding****: OPAG seeks clarification from NASA PSD on the details of the senior review process as well as a better understanding of the ground rules for these reviews. In addition OPAG suggests NASA PSD should consider returning to senior reviews focused solely on the merit of individual extended missions.*

Under budgetary threat; also no science in proximal orbits

From Jim Green's report to OPAG in January 2013

Planetary Science Division	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017
Planetary Research	$174,087	$188,546	$222,544	$233,377	$231,683	$230,339
Lunar Quest	$139,972	$61,469	$6,167	$0	$0	$0
Discovery	$172,637	$189,556	$242,162	$235,643	$193,771	$134,335
New Frontiers	$143,749	$174,967	$269,802	$279,598	$259,912	$155,085
Mars Exploration	$587,041	$360,804	$227,722	$188,671	$266,885	$503,086
Technology	$161,899	$132,902	$84,557	$85,867	$90,915	$99,624
Outer Planets	$122,054	$84,041	$80,782	$78,796	$76,238	$76,314
	$1,501,439	**$1,192,285**	**$1,133,736**	**$1,101,952**	**$1,119,404**	**$1,198,783**

From Jim Green's report to OPAG in July 2013

* Notional

Planetary Science Division	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018
Planetary Research	$174,087		$220,600	* $233,300	$229,100	$230,400	$232,200
Lunar Quest	$139,972		$17,700	$0	$0	$0	
Discovery	$172,637	TBD	$257,900	$268,200	$242,300	$187,500	$215,000
New Frontiers	$143,749		$257,500	$297,200	$266,500	$151,000	$126,200
Mars Exploration	$587,041		$234,000	$227,700	$318,400	$504,700	$513,200
Technology	$161,899		$150,900	$142,800	$144,700	$154,400	$140,000
Outer Planets	$122,054		$79,000	$45,600	$24,400	$26,400	$26,000
	$1,501,439		**$1,217,600**	**$1,214,800**	**$1,225,400**	**$1,254,400**	**$1,252,600**

Europa Clipper

- We are pleased that the US Congress has partially restored funding for NASA's planetary science division in its FY14 request, including specific funding for the Europa Clipper Study.
- We continue to support the Europa Clipper as a scientifically compelling, technologically feasible and fiscally responsible approach to exploration of Europa. The Clipper will accomplish flagship-worthy science by investigating access to Europa's subsurface ocean, a potential habitable zone.

- ***OPAG finding:*** *We are enthusiastic that NASA is funding studies of a potential Europa mission and that NASA has allocated a significant fraction of the funds to instrument maturation. It is important that the outer planets community be kept up-to-date on the goals, balance, and progress of these studies, such as via frequent regular reports to the Europa Science Advisory Group and OPAG. We request that the next such report to OPAG include a notional schedule (perhaps expressed in relative time) for moving the Clipper from a study to the launchpad.*

Europa Clipper Concept Summary

Objectives:

- **Ocean:** Existence, extent, salinity
- **Ice Shell:** Water within or beneath; nature of surface-ice-ocean exchange
- **Composition:** Key compounds; links to ocean composition
- **Geology:** Surface feature formation; sites of recent or current activity
- **Reconnaisance:** Surface characteristics at lander scales

Model Payload:

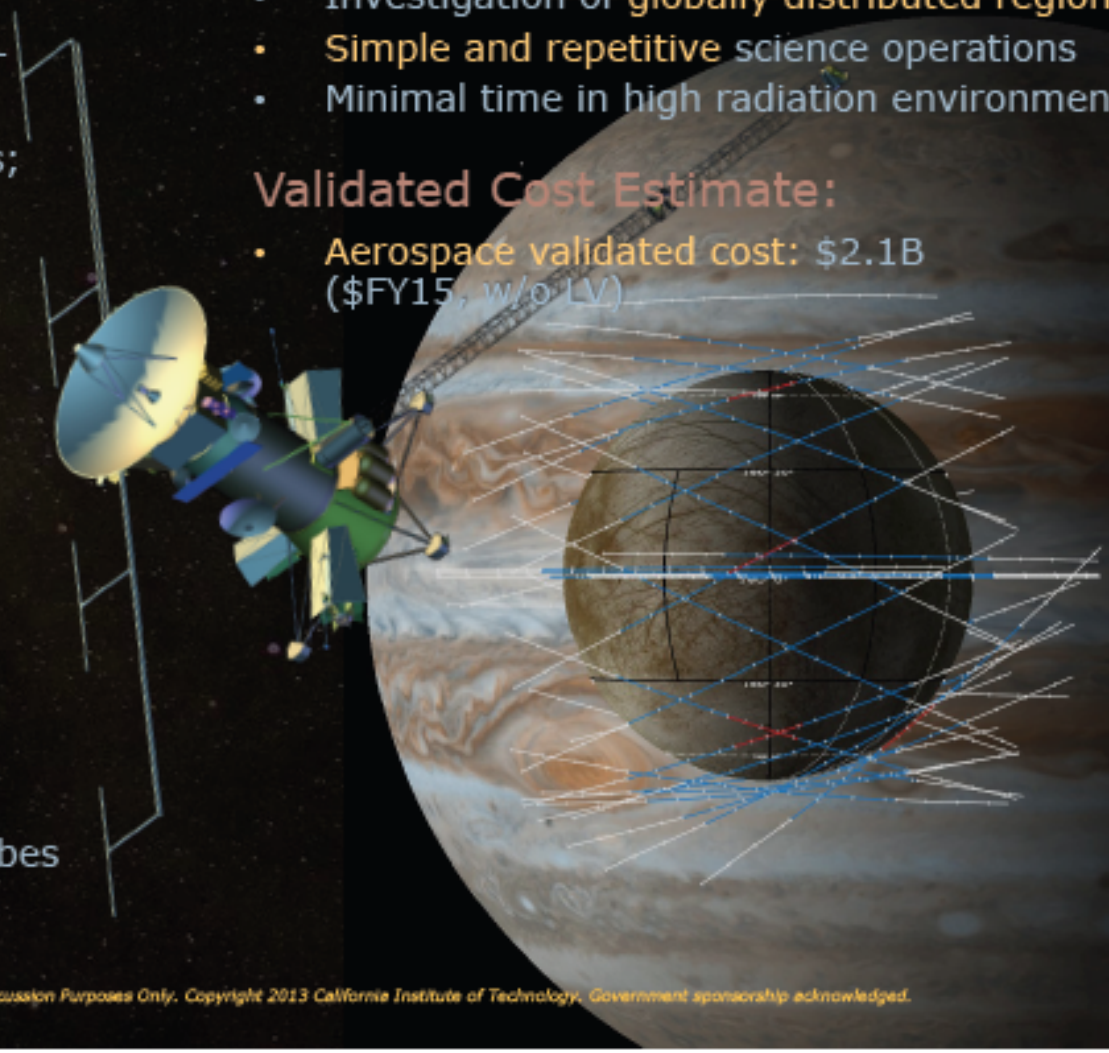
- Ice-Penetrating Radar
- Topographical Imager
- Infrared Spectrometer
- Neutral Mass Spectrometer
- Gravity Science Antenna
- Magnetometer & Langmuir Probes
- Reconnaissance Camera
- Thermal Imager

Operations Concept:

- 45 low-altitude flybys from Jupiter orbit
- Investigation of globally distributed regions
- Simple and repetitive science operations
- Minimal time in high radiation environment

Validated Cost Estimate:

- Aerospace validated cost: $2.1B ($FY15, w/o LV)



Pu238

- OPAG wishes to express its deep gratitude to NASA for persisting and now succeeding in the quest to re-start domestic production of Pu238. Without the availability of this fuel, access to the outer solar system would be severely curtailed if not terminated, as exemplified by the exclusion of missions requiring a nuclear power system in the New Frontiers 3 Announcement of Opportunity. In addition to its importance to exploration of the outer solar system OPAG notes that Pu238 also enables some missions in the inner solar system.

- ***OPAG finding****: The re-start of domestic production of Pu238 is a huge achievement and enables our continued exploration of the outer solar system.*

JUICE Co-I Funding

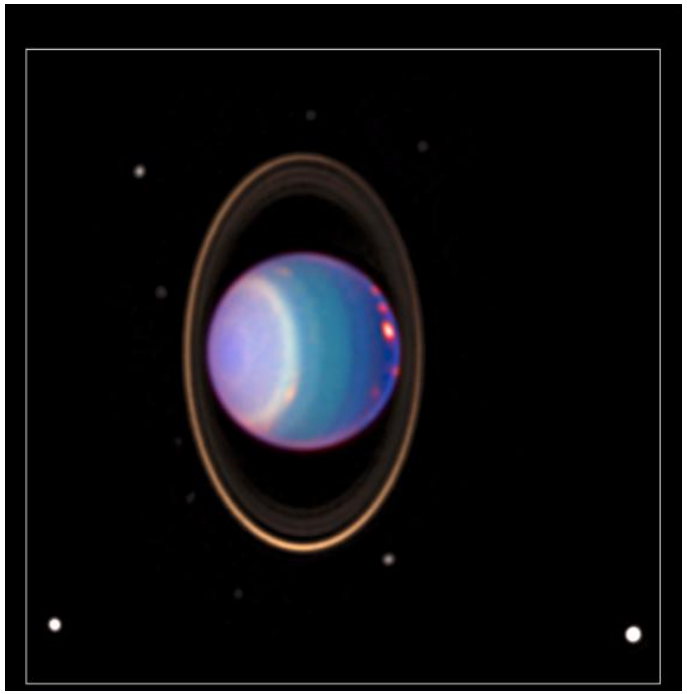
- Strong international collaborations extend the capabilities and reach of any individual space-faring institution
- The ESA JUpiter ICy moons Explorer (JUICE) flagship-class mission is a logical successor to the fruitful Cassini- Huygens partnership. As in previous assessments, OPAG lauds NASA's commitment of $100M (total lifecycle) to enable U.S. participation.
- OPAG is, however, concerned about the NASA announcement that it will not be able to fund US Co-Is on selected European instruments if they were not directly associated with selected hardware, because of the excess costs above the $100M allocation that this would require.
- We recognize that in times of tight budgets every investment must be carefully considered. OPAG therefore requests that NASA continue the dialogue with ESA to better understand critical scientific needs.
- ***OPAG finding:*** *OPAG is concerned that not funding US JUICE Co-I's damages JUICE science as well as international relations, and reduces the yield from NASA's JUICE investment. A lack of international scientific cross-fertilization risks the isolation of outer solar system scientific communities in Europe and the US. The collaborative international framework built by Cassini-Huygens represents years of effort and investment, and is a benefit to science that should be nurtured.*

Thermal Protection Systems

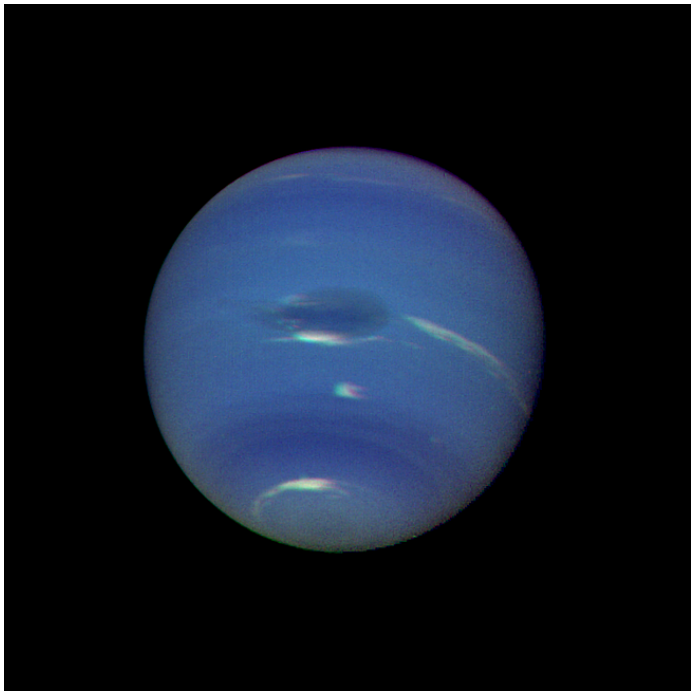
- OPAG heard reports on a variety of technological developments - OPAG is pleased that a study of probe entry technologies applicable to Uranus is being undertaken as part of the program at Ames Research Center, because it provides an actual point design.

- Thermal protection systems (TPS) are key to probe missions and aerocapture missions – it is essential to make timely progress on bringing the technology to the level of technical readiness required

- ***OPAG finding****: OPAG is concerned about the consistency of the thermal protection system (TPS) development with the likely schedule for NF- 4. It is not clear that TPS required for a Decadal-Survey-recommended Saturn Probe mission will be at an appropriate TRL level by the time the NF-4 AO comes out. OPAG would also like to receive, as part of the current Uranus probe study, a report on missions possible with current technology and what would be enabled by new technology.*



Ice Giants Knowledge Gap



- OPAG also notes that to enable future probe missions, refined knowledge of the upper atmospheres of the Ice giants is needed, as well as an analysis of the spacecraft hazards posed by ring particles on trajectories suitable for probe delivery.

- ***OPAG finding:*** *OPAG highlights the lack of knowledge in the outer solar system that brings risk to future missions to the ice giants. OPAG will establish a subcommittee to assess how some of the knowledge gaps can be filled.*

Concern about proposed changes in Education and Public Outreach at NASA

- In the FY14 budget, the Office of Management and Budget (OMB) proposed to consolidate 90 Science, Technology, Engineering and Math (STEM) programs and to realign ongoing STEM education activities "to improve the delivery, impact, and visibility of these efforts."

- For NASA, this reorganization affects not only the NASA Office of Education, but more importantly the individual Education and Public Outreach (EPO) programs carried out within the Science Mission Directorate (SMD).

- ***OPAG Finding:*** *OPAG is concerned that the elimination of EPO from NASA science missions such as Cassini, Juno, and New Horizons removes a major opportunity for the science community to maintain their competitiveness and communicate their relevance to broader societal goals. Further, if EPO science mission partnerships with diverse communities can no longer be included in mission proposals, this would disenfranchise constituencies who would contribute to a future, more diverse scientific community.*

OTHER OPAG BUSINESS

OPAG Tasks in Progress

1. NASA RFI for AO recommendations: Lessons Learned from Recent Planetary Science Division Announcements of Opportunity

- Formed a subcommittee to draft recommendations, report back to the steering committee
- At least 12 responses to the RFI are being formulated
  - Some are OPAG specific, aimed at leveling the playing field for outer planet missions within Discovery constraints
  - Working with VEXAG and SBAG to coordinate responses that are more general

2. Career paths for young scientists

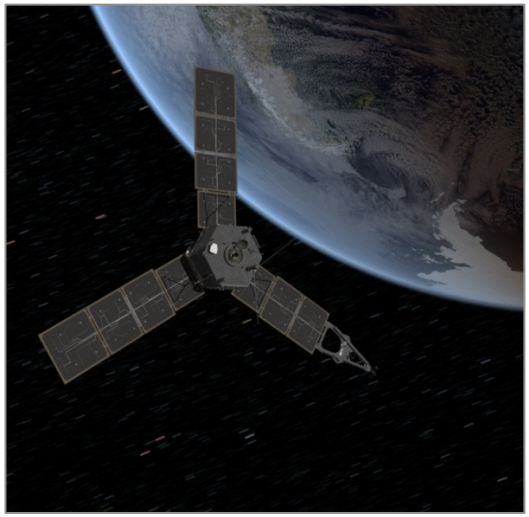
- Draft of recommendations formulated within OPAG
- Sent to SBAG and VEXAG to broaden scope
- Plan is to submit a joint-AG finding to PSS

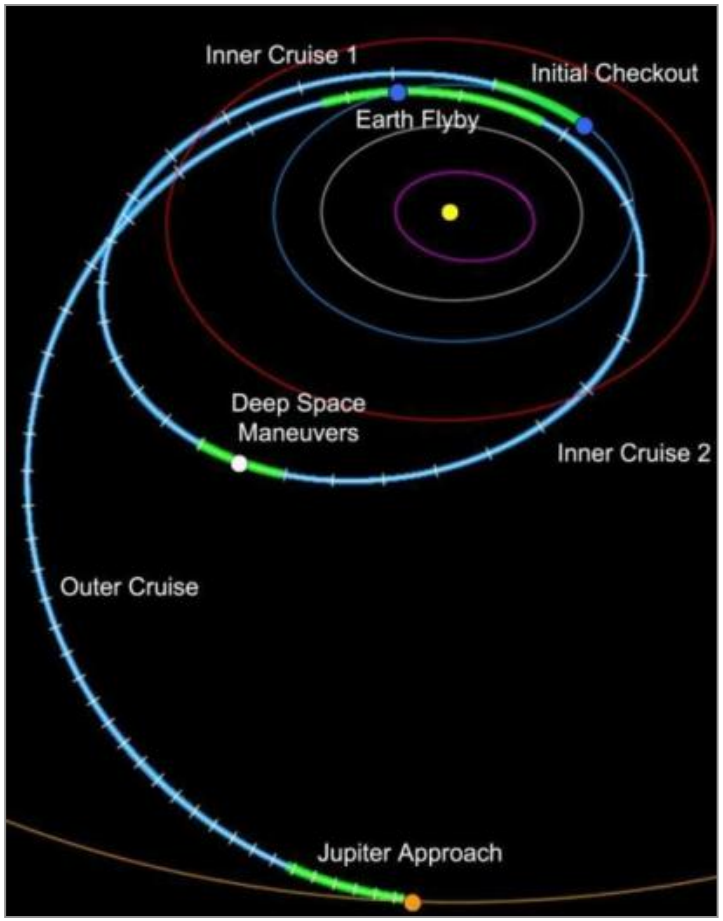
3. Update the OPAG goals document – last version was 2006

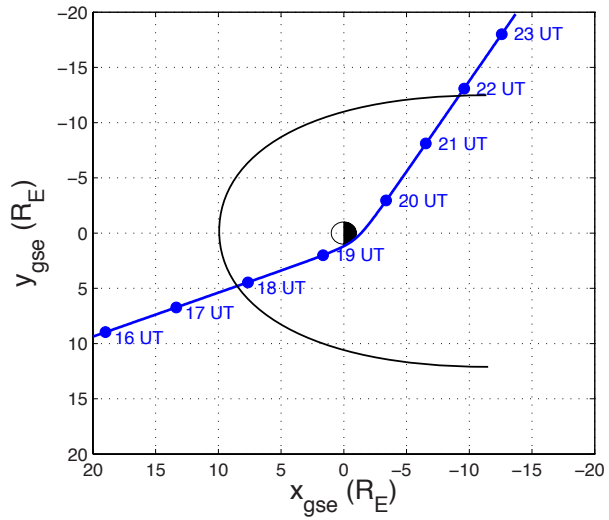
NEAR TERM EVENTS

Juno at Earth

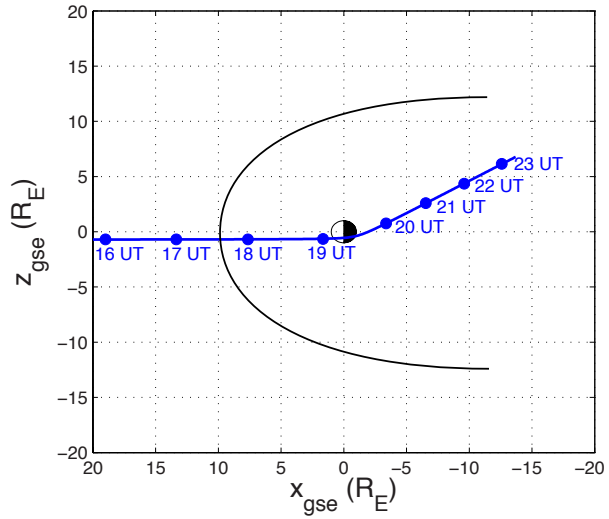
9 October 2013



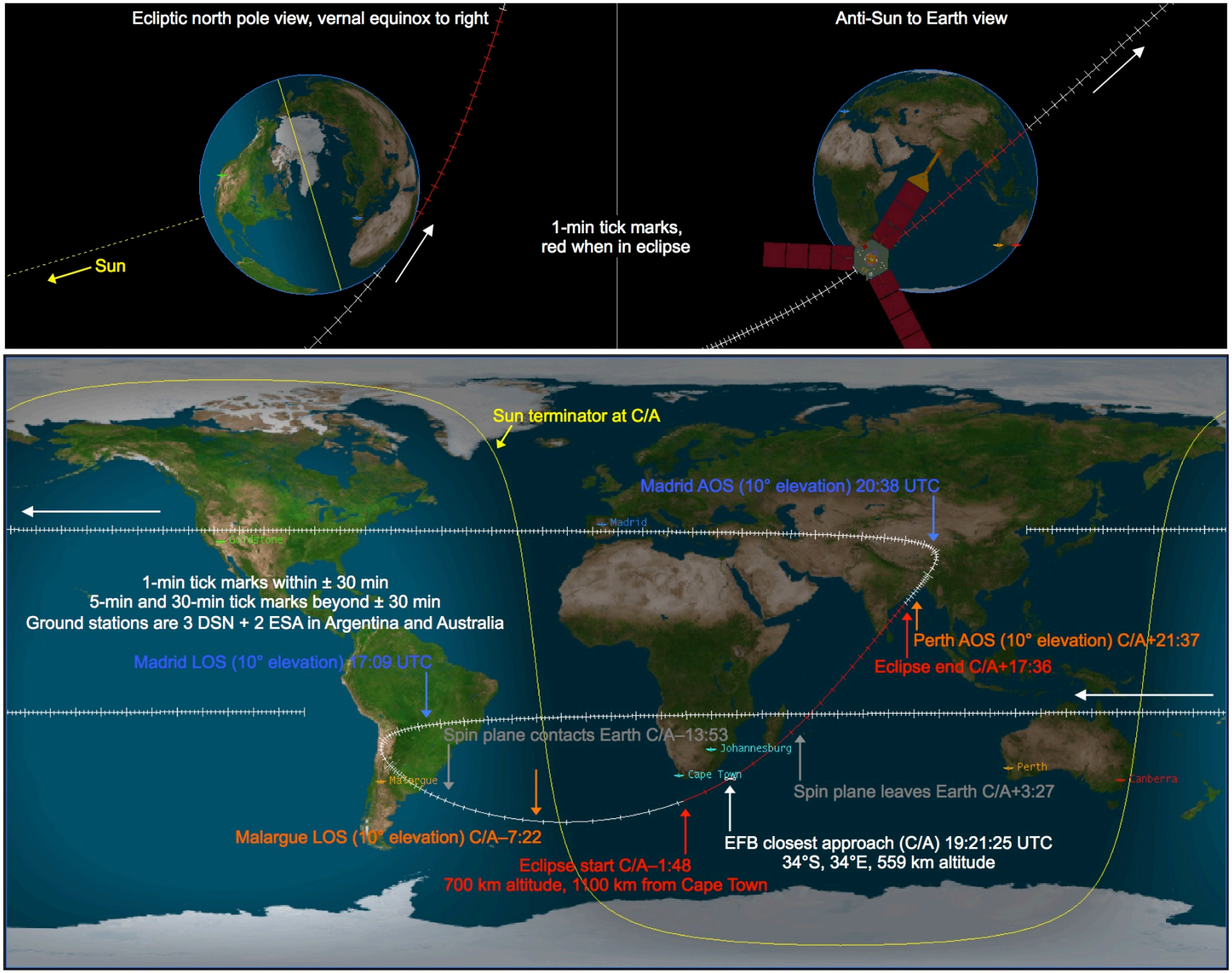




Earth's Magnetosphere



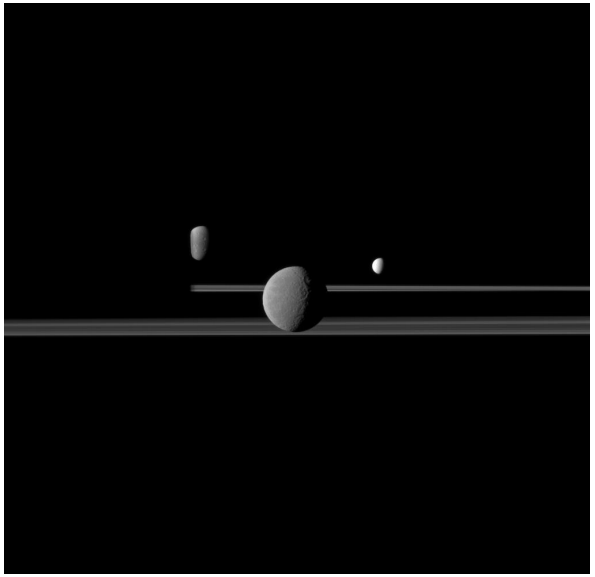
- Opportunity to cross-calibrate Juno instruments with earth orbiters in a well-understood magnetosphere
- Put spacecraft through its paces in manner similar to that planned for Jupiter


Ecliptic north pole view, vernal equinox to right
Sun
1-min tick marks,
red when in eclipse
Anti-Sun to Earth view
Sun terminator at C/A
Madrid AOS (10° elevation) 20:38 UTC
Madrid
Goldstone
1-min tick marks within ± 30 min
5-min and 30-min tick marks beyond ± 30 min
Ground stations are 3 DSN + 2 ESA in Argentina and Australia
Madrid LOS (10° elevation) 17:09 UTC
Perth AOS (10° elevation) C/A+21:37
Eclipse end C/A+17:36
Spin plane contacts Earth C/A–13:53
Johannesburg
Cape Town
Malargue
Perth
Canberra
Spin plane leaves Earth C/A+3:27
Malargue LOS (10° elevation) C/A–7:22
EFB closest approach (C/A) 19:21:25 UTC
34°S, 34°E, 559 km altitude
Eclipse start C/A–1:48
700 km altitude, 1100 km from Cape Town

NUGGETS

Cold, Old Preserve of the Solar System

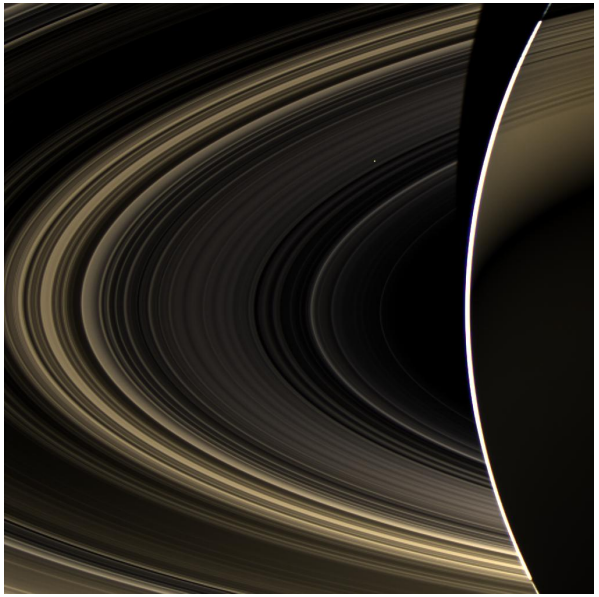
Some of Saturn's rings and moons are rusty, dusty, sunburned or polluted, but scratch their surfaces and its apparent they are artifacts that preserve the original chemistry that was present at the birth of the planets.



•Continuing study of the Saturnian system by NASA's Cassini mission is providing clues to the chemical and physical evolution of our solar system.

•New analysis* of Cassini data shows that for the most part, the differences between the surfaces of the moons and rings of Saturn are only skin deep.

•Beneath their sometimes colorful surfaces, the materials tend to be the gently worn geochemical specimens from the primordial era of our solar system when planetary bodies began to form out the cloud of material that orbited the sun after its ignition as a star. Saturn system formed in a region well beyond the "snow line" of the solar system, currently placed some 250 million miles from the sun. In this deep freeze zone, water and volatiles condense in ices and little change occurs.

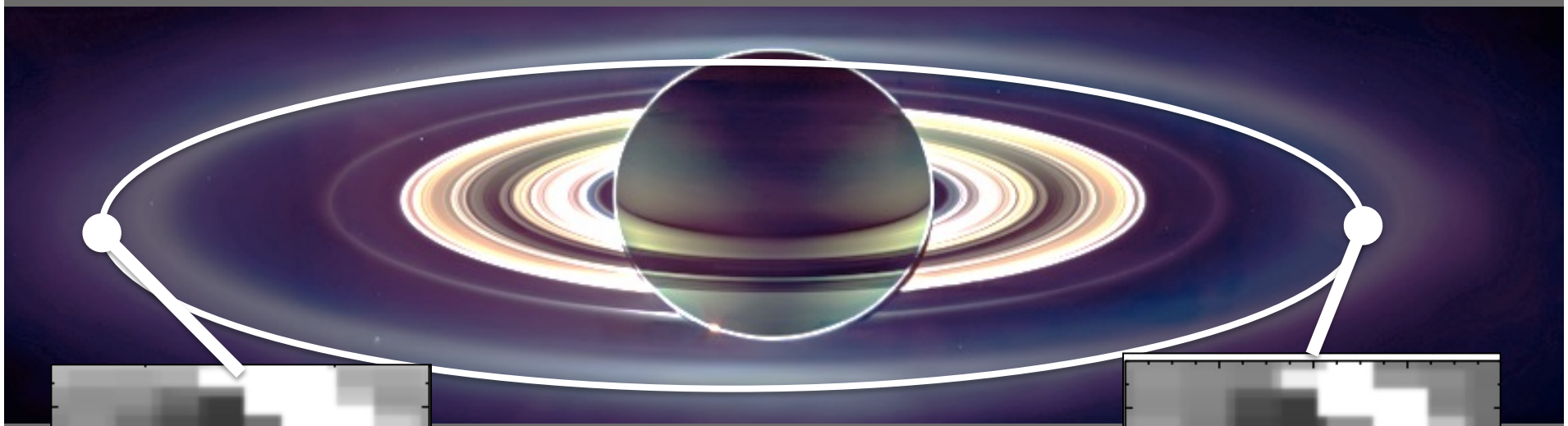


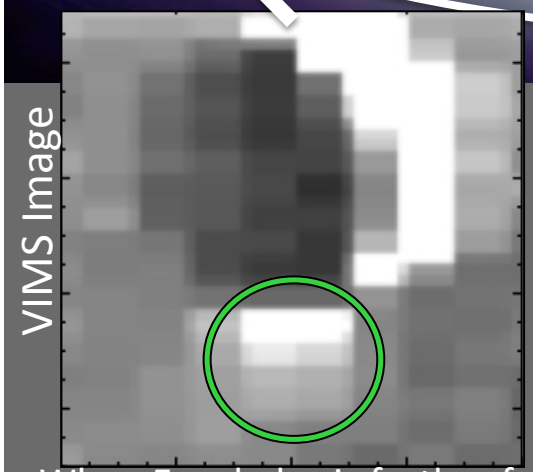
•The colored patina on the ring particles and moons roughly corresponds to local pollution sources in their vicinity. For Saturn's inner ring particles and moons, water-ice spray from the geyser moon Enceladus has a whitewashing effect. Farther out, Phoebe, a moon thought to originate in the far-off Kuiper Belt, seems to be shedding reddish dust that rouges the faces of its neighboring moons.

G. Filacchione et al.,"The Radial Distribution of Water Ice and Chromospheres across Saturn's System"
Astrophysical Journal and ArXiv

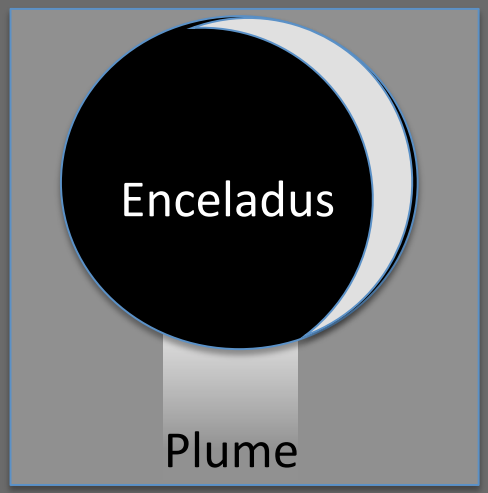
Cassini Finds Tidal Forces Controlling Enceladus' Jets

Enceladus' geological activity varies systematically as moon moves around its elliptical orbit

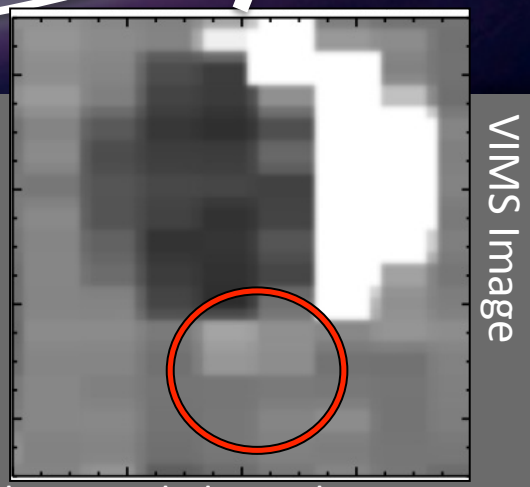




When Enceladus is further from Saturn, fissures might be pulled open and more material appears to escape from the moon



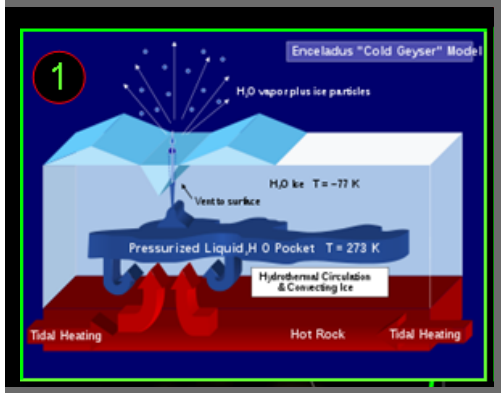
Interperative drawing

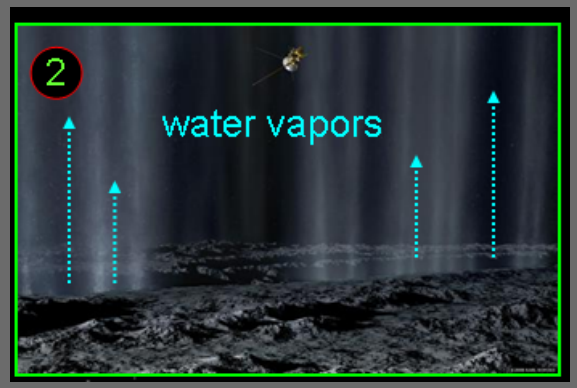


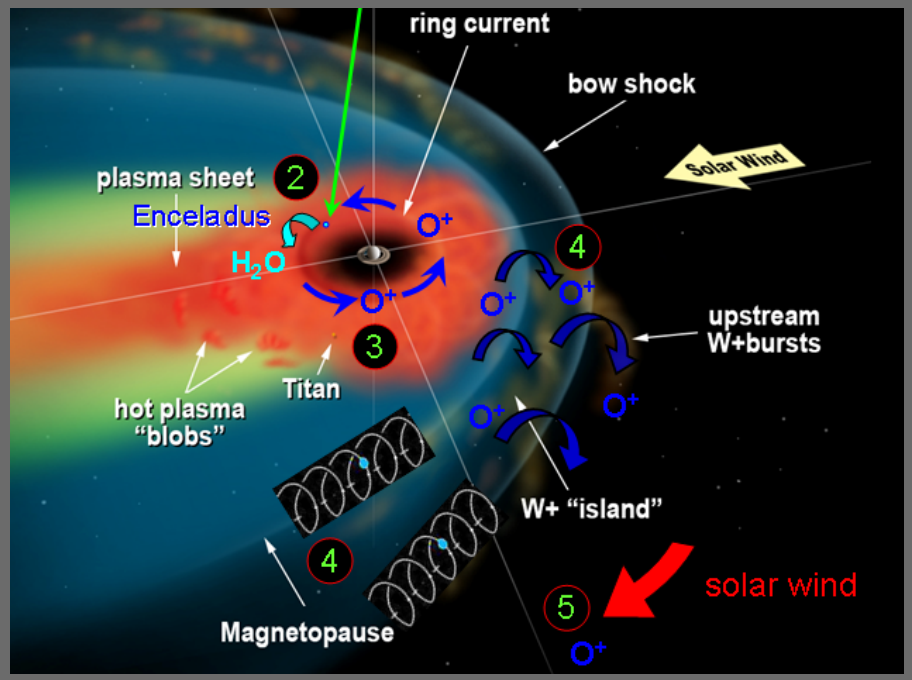
When Enceladus is closer to Saturn, fissures might be pushed shut and less material appears to escape from the moon

Hedman, et al. An observed correlation between plume activity and tidal stresses on Enceladus (Nature 2013)

From a subsurface ocean to outer space: The adventure of an oxygen particle from Enceladus







1 Enceladus, a small, icy moon of Saturn, possesses a sub-surface water "ocean" and tectonic activity due to tidal forces exerted by Saturn.

2 Water vapor and ice are being ejected from surface cracks at a rate of around 200 kg/s

3 Water atoms soon become ions and form a "ring current" composed primarily of protons and singly ionized oxygen ions (O^+) that nearly corotate with the planet.

4 The hottest of the heavy O^+ ions gyrate in circular orbits of enormous radii due to the very low magnetic field, Defying the physical boundaries around Saturn, the Magnetopause and the Bow Shock, they find their way upstream into the nearby solar wind where they are captured by the INCA camera of Cassini

5 Once in the solar wind and free from their magnetic 'prison' the hot O+ ions become a strange 'guest' in the solar wind and eventually they get convected to its flow and travel toward the limits of our solar system.

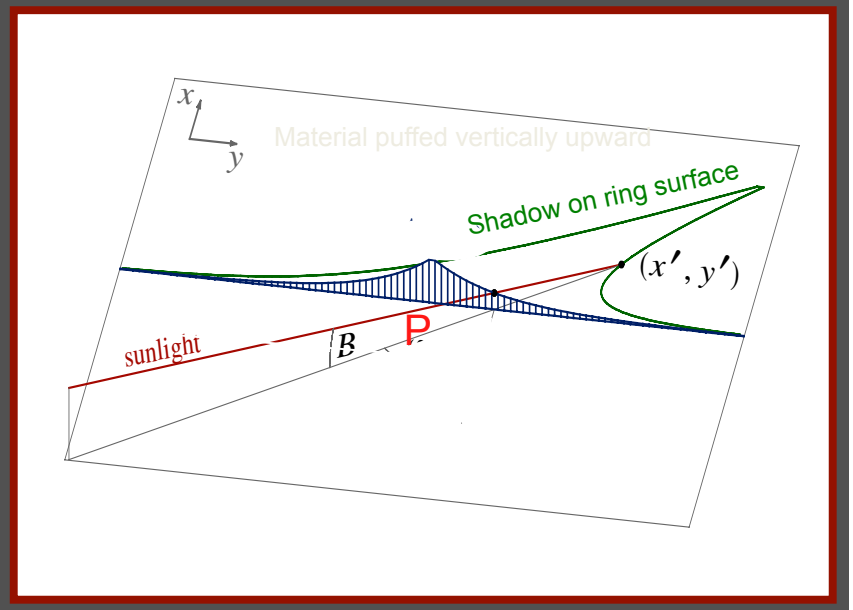
Sergis et al., Islands of hot magnetospheric W^+ in the magnetosheath of Saturn, JGR, in press

The Shadow Knows

Cassini scientists estimate small, hundred-meter-size moonlets in the millions could be embedded in Saturn's Rings. Elongated, propeller-shaped features in the rings are actually clearings in the rings created by these moonlets. Now, the geometry of the shadows cast in Saturn's rings reveals how these unseen moonlets puff up the surrounding ring particles.

The bright spot below is a cloud of particles scattered upwards by the half-mile tall moonlet, Earhart, embedded in the rings. When the sun illuminated the rings edge-on near equinox, the cloud casts a shadow approximately 185 miles long.

The moonlets scatter smaller particles into puffy clouds that are much larger than the moonlets themselves. In the case of half-mile-wide Earhart, the scattered material puffs up into an 850-foot tall, 37 mile-wide cloud that casts a low mountain-shaped shadow on the rings. The empty ring space around the moonlets (not seen here) often creates propeller-shaped clearings.

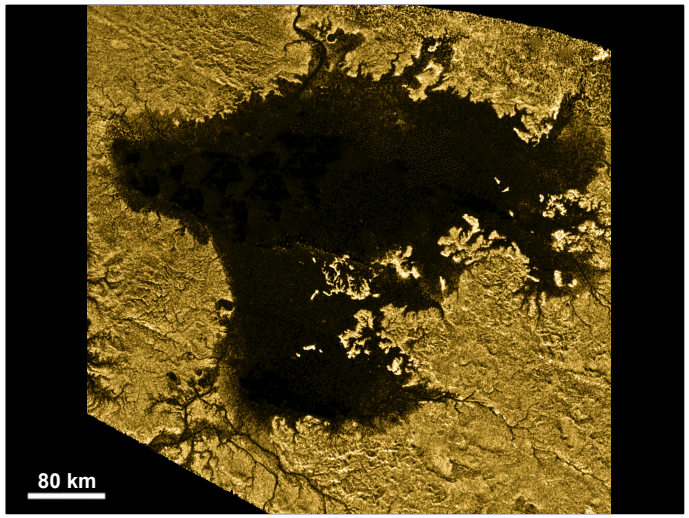


A new light-scattering model allows for gravitational scattering and collisional damping of ring particles by a "propeller" (P), predicting the shape of its shadow.

The new model explains why the puffed up, 850 foot-tall "cloud" of ring particles is much shorter along the orbit direction than the usual channel cleared out by the object and others like it.

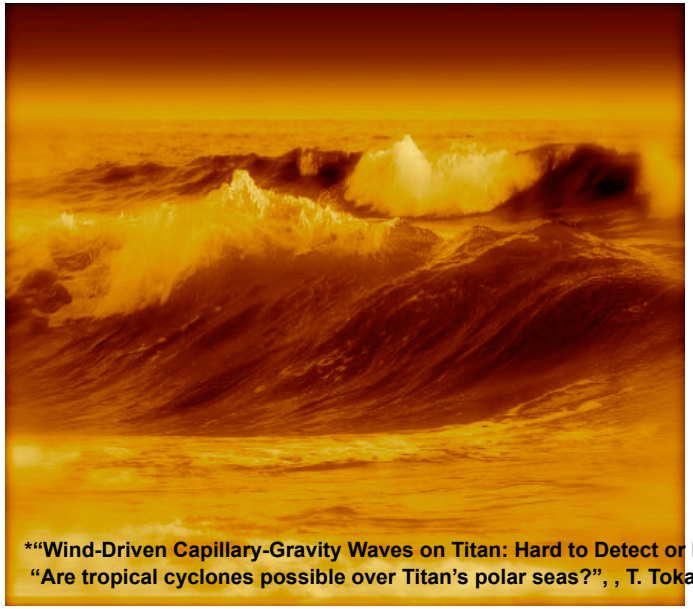
"Vertical structures induced by embedded moonlets in Saturn's rings: the gap region," Holger Hoffmann, Frank Spahn, Martin Seiß, August 2013; Source: arXiv

Gnarly Surf & Cyclones for Saturn's Moon Titan?



(Top) Ligeia Mare, one of the hydrocarbon seas of Titan.

(Bottom) Artists's concept of potential wild weather on Titan.



Wind-whipped waves and cyclones could occur on Saturn's moon Titan as summer arrives in the north toward the end of Cassini's mission. Two new research papers* describe the possibilities for wild weather on the only other body in the solar system besides Earth with stable liquid on its surface.

- Cassini observations of waves, or no waves, during this time will provide valuable clues about the composition of Titan's lakes and seas, and help determine the accuracy of the Global Circulation Model for Titan.
- Some of Titan's hydrocarbon lakes and seas are as large as the Great Lakes or Caspian Sea. Titan has a denser atmosphere than Earth's and less gravity. Its lakes and seas of ethane and methane have a lower surface tension than the equivalent bodies of liquid on Earth. These and other factors mean that even a light wind of one mile an hour could potentially whip up waves on Titan's lakes and seas.
- Winds are predicted to exceed the threshold for wild weather as Titan approaches summer solstice in 2017. Even tropical cyclones could also conceivably occur over Titan's polar hydrocarbon seas as summer warms the northern hemisphere.

*"Wind-Driven Capillary-Gravity Waves on Titan: Hard to Detect or Non-Existent?" A. G. Hayes et al., Icarus, in press, May 2013.
"Are tropical cyclones possible over Titan's polar seas?", , T. Tokano, *Icarus* 223 (2013) 766–774

Is Titan's Methane Cycle Temporary?

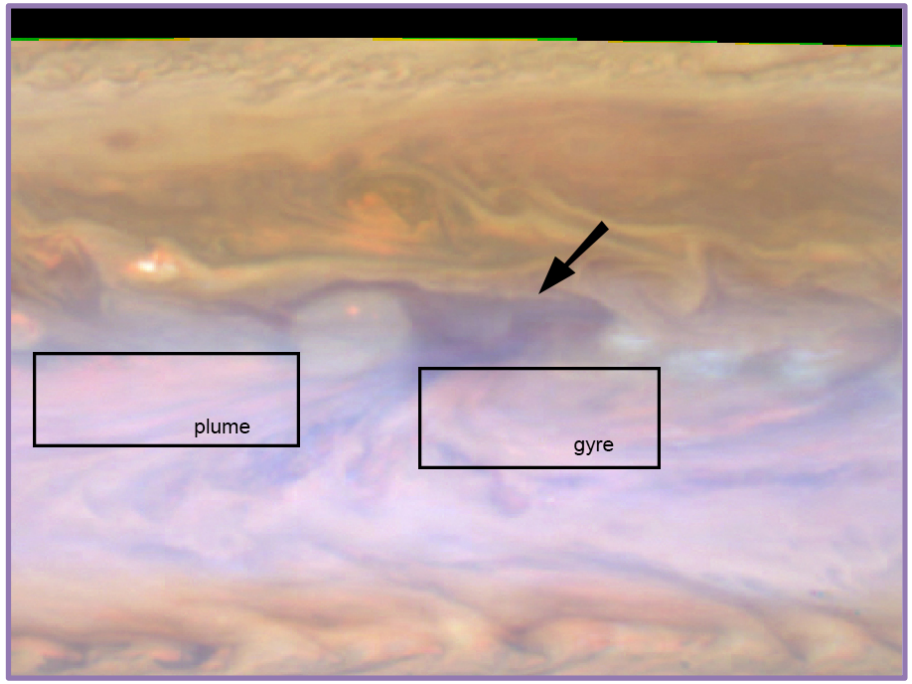
Titan's fascinating methane chemistry, its lakes, rain and hydrocarbon dunes, may be just a temporary anomaly, geologically speaking.

- A gigantic outburst of methane may have been released eons ago, possibly after a huge impact. This would have led to Titan's current global smog haze and its continent-size hydrocarbon sand dunes, according to a new model* based on data from NASA's Cassini mission.
    - A comet impact or global resurfacing by cryovolcanic activity could have caused such a release.
- The new model indicates that methane is not being replaced fast enough to sustain Titan's methane cycle. In Earth's water cycle, water continuously migrates from the surface to the atmosphere and back again. But it appears that Titan's methane rises into the atmosphere on a one-way trip to destruction.
    - Sunlight is destroying Titan's methane, and the data indicate it's not being replaced, so Titan's "methane era" may one day draw to a close.
- Over time, the destruction of methane by sunlight will reduce the overall amount of methane in Titan's environment while sand, seas and lakes derived from its destruction will continue to accumulate on the surface.

"Observations of Titan's Northern lakes at 5 microns: Implications for the organic cycle and geology," C. Sotin et al., Icarus, 2012

“Hot Spots” Offer Windows into Jupiter

Cloudless patches called “hot spots” occasionally form in Jupiter’s cloudy atmosphere. These events provide windows on activity in normally unseen deeper layers of Jupiter's atmosphere. Why these special areas occur, and why they are only near the equator, are enduring questions.

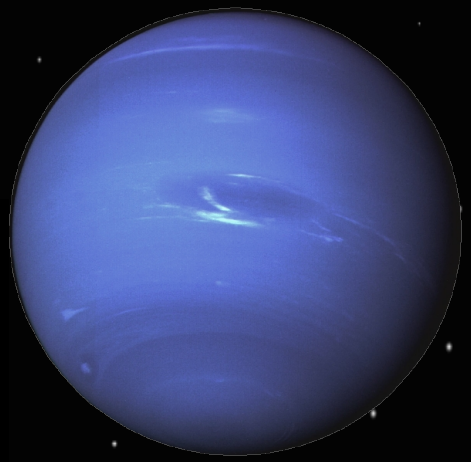


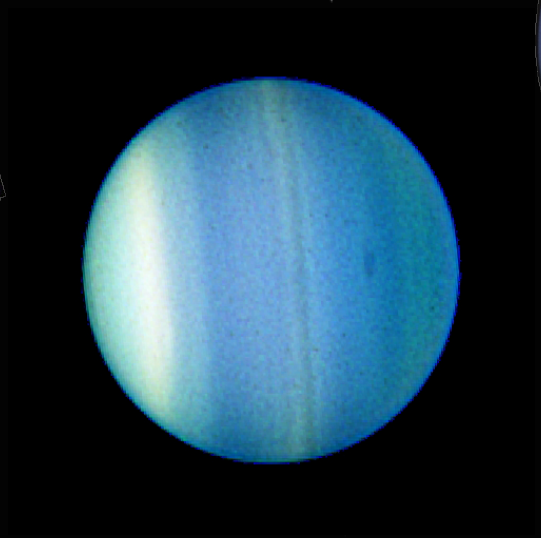
This false-color image from Cassini is a window deep into Jupiter's atmosphere. The arrow points to the dark hot spot. The bluish clouds to the right are in the upper troposphere, or perhaps higher still, in the stratosphere. The reddish gyre under the hot spot to the right and the large reddish plume at its lower left are in the lower troposphere.

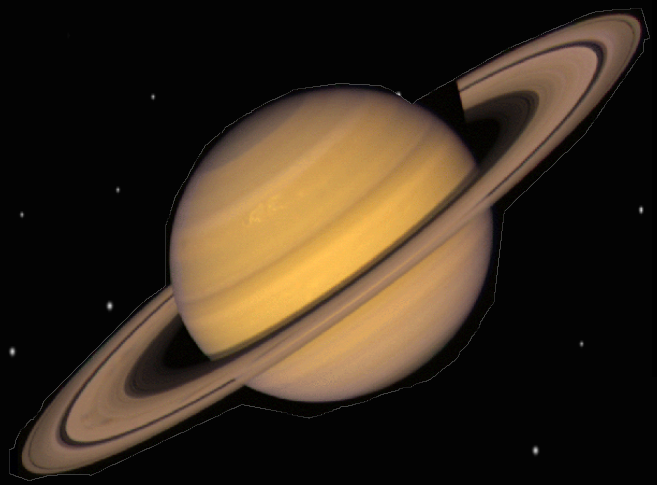
* “Meteorology of Jupiter’s equatorial hot spots and plumes from Cassini,” David S. Choi et al., *Icarus*, 2013

- Time-lapse imagery compiled during Cassini’s approach and flyby of Jupiter in 2000 enabled unique analysis of flow around a hot spot as well as its interactions with other atmospheric systems. http://saturn.jpl.nasa.gov/news/cassinifeatures/feature20130314/
- A team of scientists has published new evidence* that the hot spots are created by a Rossby wave, which on Earth plays a major role in weather (e.g. when a blast of frigid Arctic air suddenly dips down and freezes Florida's crops, a Rossby wave has nudged the polar jet stream off course.)
- The team found the Rossby wave flows in Jupiter’s atmosphere east to west as on Earth, but instead of wandering north and south, it glides up and down in altitude like a carousel horse, about 15 to 30 miles (24 to 50 kilometers) in altitude.
- Small "scooter" clouds, similar to cirrus clouds on Earth, were also tracked and helped provide what may be the first direct measurement of the true wind speed of Jupiter’s equatorial jet stream – about 300 to 450 mph (500 to 700 kph), much faster than anyone previously thought. The hot spots amble at a more leisurely pace of about 225 mph (400 kph).
- These observations help atmospheric modelers constrain properties of Jupiter's atmosphere that are difficult to observe directly.

Outer Solar System Exploration







Worth the journey

BACKUP CHARTS

Decline in NASA Planetary Launches

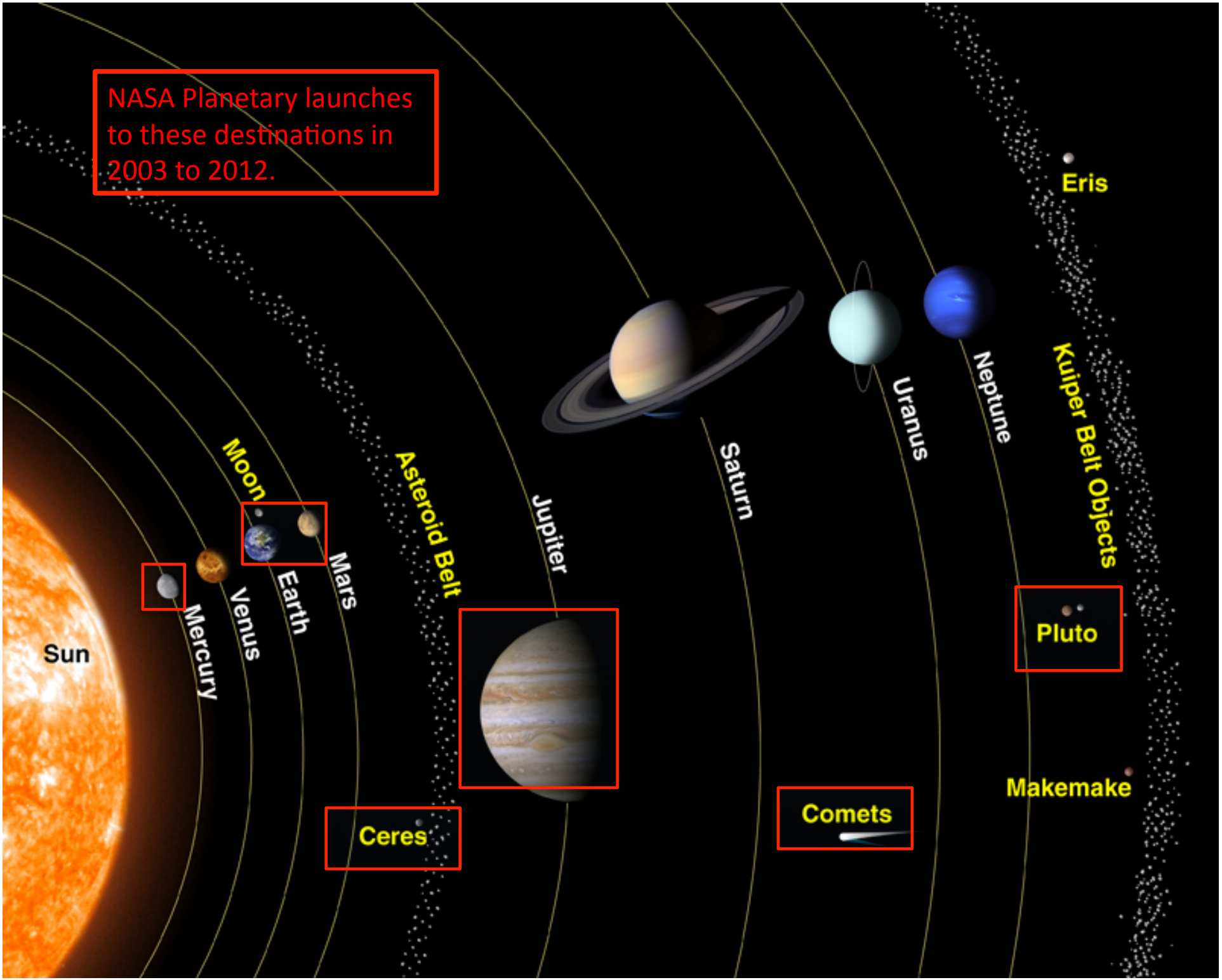
- 2003-2012:
  - MESSENGER – Mercury
  - GRAIL -- Moon
  - Lunar Reconnaissance Orbiter
  - MER-Opportunity
  - MER-Spirit
  - Mars Reconnaissance Orbiter
  - Phoenix – Mars lander
  - Mars Science Laboratory
  - Dawn – Vesta and Ceres
  - Juno – Jupiter
  - Deep Impact – comets
  - New Horizons – Pluto

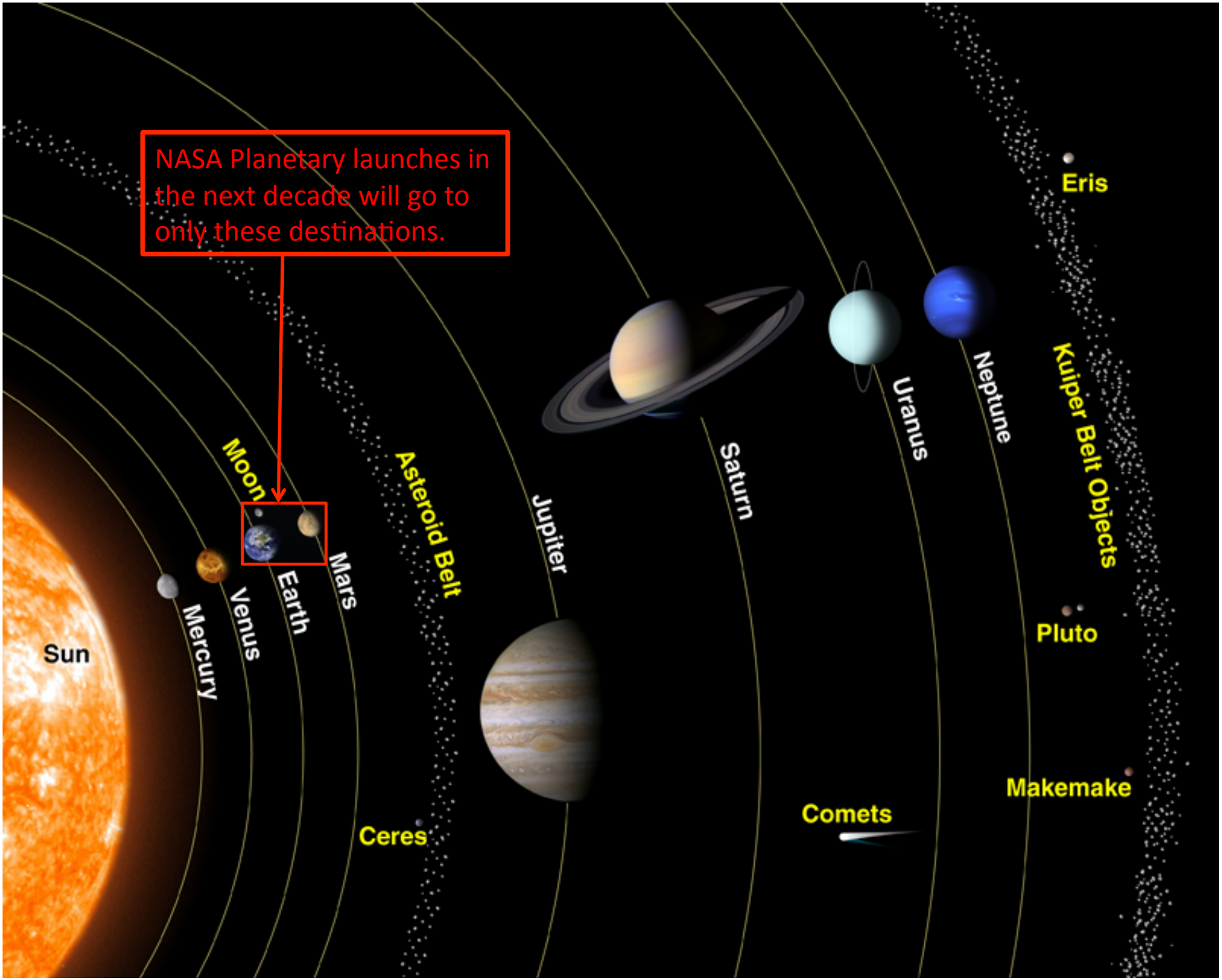
  - **Total: 12 missions, from Mercury to Pluto, all successful**

- 2013-2022:
  - LADEE – Moon
  - MAVEN – Mars orbiter
  - InSight – Mars Lander
  - OSIRIS-Rex – near-Earth asteroid sample return
  - 2020 Mars rover
  - New Discovery mission?

  - **Total: 5 or 6 missions**

  - It is already too late to increase the number of launches over the next decade, except for one Discovery mission if the planetary budget is restored soon.


NASA Planetary launches to these destinations in 2003 to 2012.
Sun
Mercury
Venus
Earth
Moon
Mars
Asteroid Belt
Ceres
Jupiter
Saturn
Uranus
Neptune
Kuiper Belt Objects
Eris
Pluto
Makemake
Comets


NASA Planetary launches in the next decade will go to only these destinations.
Sun
Mercury
Venus
Earth
Moon
Mars
Asteroid Belt
Ceres
Jupiter
Saturn
Uranus
Neptune
Kuiper Belt Objects
Eris
Pluto
Makemake
Comets

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

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 "Visions 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