NEPTUNE-ODYSSEY: Mission to Neptune-Triton System

"Neptune's moons were normal until Triton came crashing in."
New Scientist

PI Abigail Rymer
Large team including: Kirby Runyon (Project Scientist), Robin Vaughan (Project Engineer) and Co-Is and collaborators from 17 national and international institutions.

"There is only one planet-type left to orbit – an Ice Giant, and we propose that NASA continue their voyage of excellence in planetary exploration and leadership by scheduling a Flagship-class mission to the Neptune-Triton system."

[Rymer et al., 2019 PMCS proposal]

Support for Ice Giant Mission

'Top and only priority for a new flagship mission is the Uranus Orbiter and Probe.'

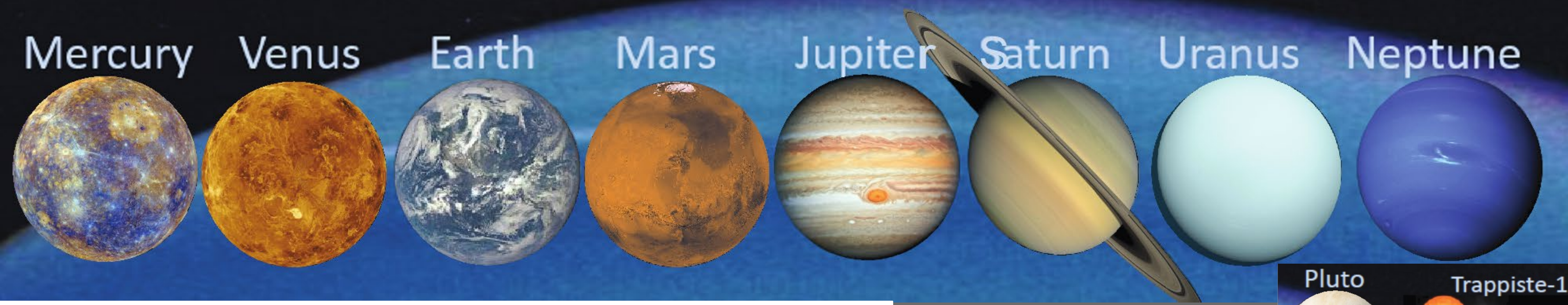
[Vision and Voyages for Planetary Science in the Decade 2013-2022]

This changes in the coming decade and the Outer Planets Assessment Group (OPAG) support **Neptune** for a flagship mission.

'…owing to Triton, a captured dwarf planet itself and also a high priority Ocean World target'

[OPAG Scientific Goals for Exploration of the Outer Solar System]

‘It Takes a Village.’ Collaborative Outer Planet Missions.



WHITE PAPER FOR THE
HELIOPHYSICS SCIENCE DECADAL SURVEY, 2013-2023.

The Case for Exploring Uranus’ Magnetosphere.

This White Paper is endorsed by 66 scientists (listed at the end) from the USA and Europ
of whom are early career scientists representing the driving force of the heliophysics con
in the decades to come.

WHITE PAPER FOR EXOPLANET SCIENCE STRATEGY 2018

Solar System Ice Giants: Exoplanets in our Backyard.

(Cover page)

Co-authors and endorsers:

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Kathleen Mandt[1], Dana Hurley[1], Carey Lisse[1], Noam Izenberg[1], H.Todd Smith[1], Joseph Westlake[1], Emma Bunce[2], Christopher Arridge[3], Adam Masters[4], Mark Hofstadter[5], Amy

Advancing Space Science Requires NASA Support for Coordination Between the Science Mission Directorate Communities

White paper submitted as a State of the Profession paper to the Astro2020 Decadal Survey. It will be submitted next to the Planetary and Heliophysics Decadal Surveys.

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Abigail Rymer[1], Jason Kalirai[1], Robert Allen[1], Alice Cocoros[1], Kevin Stevenson[2], Dana Hurley[1],

Using the Interstellar Probe to Decipher Exoplanet Signatures of Our Planets from the Very Local Interstellar Medium

Pontus C. Brandt, Ralph McNutt, Michael Paul, Carey Lisse, Kathleen Mandt, Abigail Rymer

VISION *and* VOYAGES

for Planetary Science in the Decade 2013-2022

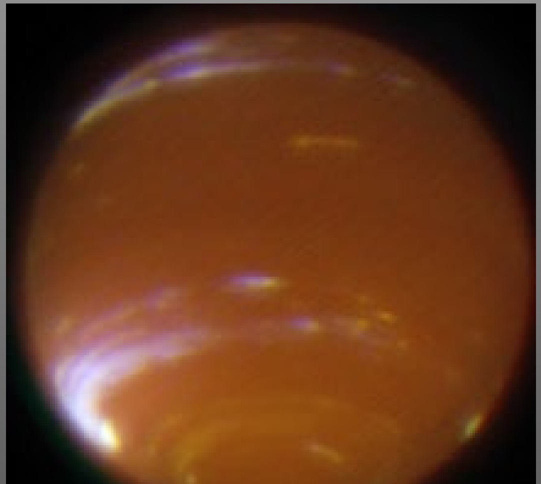
TABLE ES.3 Large-Class Missions (in priority order)

Mission Recommendation	Science Objectives	Key Challenges	Decision Rules	Chapter
Mars Astrobiology Explorer-Cacher descope =MARS 2020	• Perform in situ science on Mars samples to look for evidence of ancient life or prebiotic chemistry Collect, document, and package samples for future collection and return to Earth	• Keeping within Mars Science Laboratory design constraints • Sample handling, encapsulation, and containerization • Increased rover traverse speed over Mars Science Laboratory and Mars Exploration Rover	Should be flown only if it can be conducted for a cost to NASA of no more than approximately $2.5 billion (FY2015 dollars)	6
Jupiter Europa Orbiter descope =Europa Clipper	Explore Europa to investigate its habitability	• Radiation • Mass • Power • Instruments	Should be flown only if changes to both the mission design and the NASA planetary budget make it affordable without eliminating any other recommended missions	8
Uranus Orbiter and Probe (no solar-electric propulsion stage) =Neptune-Triton?	• Investigate the interior structure, atmosphere, and composition of Uranus • Observe the Uranus satellite and ring systems	• Demanding entry probe mission • Long life (15.4 years) for orbiter • High magnetic cleanliness for orbiter • System mass and power	Should be initiated even if both MAX-C and JEO take place	7

ODYSSEY: Mission to Neptune-Triton System

- Ice Giant Orbiter and Probe mission: In Top 3 Decadal Priorities
- Comparative planetology of Kuiper Belt Dwarf Planets (Triton)
    - Ocean Worlds, heliophysics, and exoplanet objectives
        - “Neptune’s moons were normal until Triton came crashing in.” (New Scientist)
- Neptune > Uranus due to captured dwarf planet Triton

- Structure and characteristics of the dynamo and overall interior.
- Bulk composition (V&V; IG predecadal study report 2017)
- Dwarf planet comparative planetology (Simon et al. 2018 WP)



Near IR (I. de Pater) all
Moussis et al. 2018

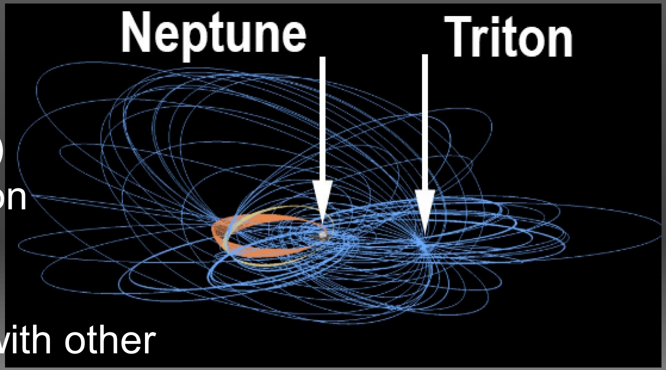
Required Measurements:

- Magnetic field
- Gravitational harmonics
- Spectroscopy
- Visible imager
- Ions and electrons
- Neutral mass spectrometry
- Dust

Candidate Architectures: **Cassini-Huygens, New Horizons, Juno, LCross**

Development

- Cost/technical evaluation
- Cassini-like tour, using Triton
- Long-lived RPS (eMMRTGs?)
- Atmospheric thermal protection
- Engage ESA, NASA/Helio
- Optical Comm?
- **Flagship Class**. Cost share with other agencies and NASA divisions?



Why this proposal?

At least 7 Ice Giant mission proposals were submitted to the PMCS call:

“Given the high science priority of the Ice Giants, a number of studies have been performed of dedicated orbital missions. However, previous NASA-led studies have lacked a strong Triton element.” Rymer PMCS proposal.

‘Neptune-Triton Mission: a flagship for everyone’ Carol Paty, OPAG 2019.

Major strength 1 –
A flagship for everyone

The science objectives of the proposed Flagship-class mission to Neptune-Triton system are high-priority, broadly multi-disciplinary and would impact virtually the entire planetary science community. These science objectives have been developed and vetted by the community via the previous Planetary Decadal Survey, OPAG strategy documents, as well as NASA objectives in Planetary Science, Exoplanets and Heliophysics. The results obtained from a Neptune-Triton mission would provide ground truth data from an ice giant planet and a dwarf planet / ocean world. The results would affect the entire planetary science community in a manner that parallels the Cassini-Huygens mission to Saturn.

Major strength 2 – New approach the gives equal weight to system science, especially Triton.

The proposed mission concept study is timely and distinct from previous studies of Neptune missions and takes into account revised science objectives for ice giant, dwarf planet and ocean world exploration. The proposed study is unique in that it offers equal emphasis on developing the science objectives and mission strategies to explore Triton as an 'ocean world' and dwarf planet in conjunction with the numerous science objectives associated with the Neptune system (e.g., the rings, atmospheres, interiors, atmospheres, magnetospheres, ...etc). This approach leverages recent advances in understanding the Kuiper Belt, dwarf planets and ocean worlds, and the prevalence of ice giants among exoplanets.

Major strength 3 – Great team

The study team's combination of excellence, breadth in multi-disciplinary science, international collaborations, and mission experience (e.g., Voyager, Galileo, Cassini and New Horizons) is ideally equipped to complete the proposed study and provide useful input to the next Planetary Decadal Survey. The study team consists of recognized leaders from many areas in planetary science. The study team remains open to new members and reflects the disciplinary and generational diversity of the community.

Minor strength 1 – Robust approach

The proposal describes a clear and reasonable plan for linking the specific instrumentation and trajectory requirements directly to the science goals. As appropriate for a Flagship-class mission a broad range of science objectives and instruments will be studied and a mission concept developed.

Minor strength 2 – Professional approach to addresses human challenges is given as much weight as engineering challenges

The proposed study would include clear strategies to address human aspects of managing a complex mission over a multi-decade span. The proposed study includes thoughtful strategies to address challenges in data stewardship. The approach to address long-term planning for mission leadership, inclusive team membership and turnover is well-conceived and clear.

Minor weakness 1 – We can’t be ready by 2030, can we?

The Project Summary in Section VII of the proposal cover pages states that ‘the launch window to Neptune using chemical propulsion only is optimal from 2029 to 2030’. This raised concern among the panelists about the availability of the necessary lead time to adequately develop the mission and the ‘viability’ of meeting this launch window as well as the implications of failing to do so. The panel noted that this issue may be addressed during the proposed study by identifying new trajectories and/or strategies for rapid mission development.

‘This study will provide a practical ‘shovel ready’ concept that is quickly executable in the coming decade.’

[Rymer et al., 2019 PMCS proposal]

Minor weakness 2 – should not have ditched the Triton trade study

The Project Summary in Section VII of the proposal cover pages states the study will consider a Triton lander. However, pages 14-15 describe that the option of a Triton lander has been discarded as 'too high risk', despite the science return potential. Panelists were concerned about how the omission of considering a lander would affect the science return. The panel noted that this minor issue might be addressed by identifying the risk/return aspects of a lander in the mission concept study.

'Two elements (a Triton lander and aerocapture) that we have determined do not provide sufficient benefit compared to added risk to include in our proposed …A Triton lander would enable unprecedented science discovery … similar arguments arise here as with the Europa lander concept: that the nature of the surface of Triton is not sufficiently well characterized causing the team to consider inclusion of this element on our first orbiting mission to Neptune of too high risk despite the enormous potential science return.' **[Rymer et al., 2019 PMCS proposal]**

Table of Work Effort

Team member	Affiliation	Role	Funded (hours)	Unfunded (hours)	Total funded effort (hrs)
Abigail Rymer	JHUAPL	PI	120	0	120
Ralph McNutt	JHUAPL	Co-I	0	24	24
Kathleen Mandt	JHUAPL	Co-I	0	24	24
Kirby Runyon	JHUAPL	Co-I	76	0	76
Noam Izenberg	JHUAPL	Co-I	15	0	15
Elizabeth Turtle	JHUAPL	Co-I	15	0	15
Elena Provornikova	JHUAPL	Co-I	15	0	15
Mark Hofstadter	JPL	Co-I	36	0	36
Amy Simon	NASA-GSFC	Co-I	27	0	27
Imke de Pater	Uni. of CA, Berkeley	Co-I	0	24	24
Kunio Sayanagi	Hampton University	Co-I	51	0	51
Janet Vertesi	Princeton University	Co-I	0	24	24
Candice Hansen	Planetary Science Institute	Co-I	30	0	30
Lynnae Quick	NASA-GSFC	Co-I	54	0	54
Tracy Becker	SwRI	Co-I	36	0	36
Alan Stern	SwRI	Co-I	0	24	24
Carol Paty	University of Oregon	Co-I	0	24	24
Krista Soderlund	University of Texas at Austin	Co-I	36	0	36
Thomas Spilker	Self	Co-I	35	0	35
Frank Crary	LASP	Co-I	0	24	24
Corey Cochrane	JPL	Co-I	0	24	24
Jonathan Fortney	JPL	Co-I	0	24	24
Dana Hurley	JHUAPL	Co-I	0	15	15
Ronald Vervack	JHUAPL	Co-I	0	15	15
Marzia Parisi	JPL	Coll	0	8	8
James Roberts	JHUAPL	Coll	0	8	8
Ian Cohen	JHUAPL	Coll	0	8	8
Olivier Mousis	Besancon Observatory, Fr	Coll	0	8	8
Tom Stallard	Uni. of Leicester, UK	Coll	0	8	8
Adam Masters	Imperial College,UK	Coll	0	8	8
Leigh Fletcher	Uni. of Leicester, UK	Coll	0	8	8
Ravit Helled	Uni. of Zurich, CH	Coll	0	8	8
Victoria Meadows	University of Washington	Coll	0	8	8

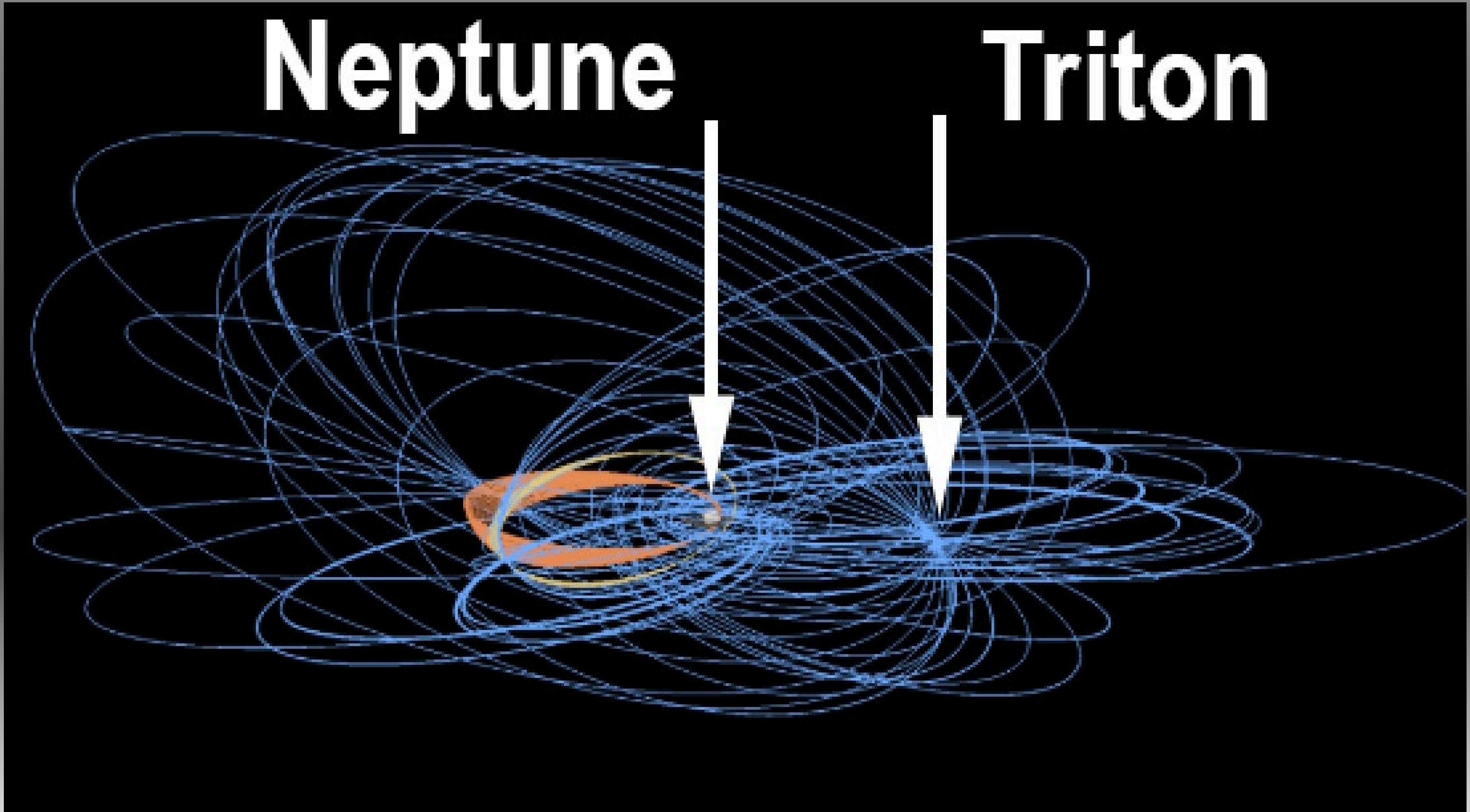
38 total
17 women, including PI and 3/8 Working Group leads
Also include Princeton sociologist Janet Vertesi

+ Jonathan Fortney
Todd Smith
George Hospodarsky
Emily Martin
Alex Patthoff

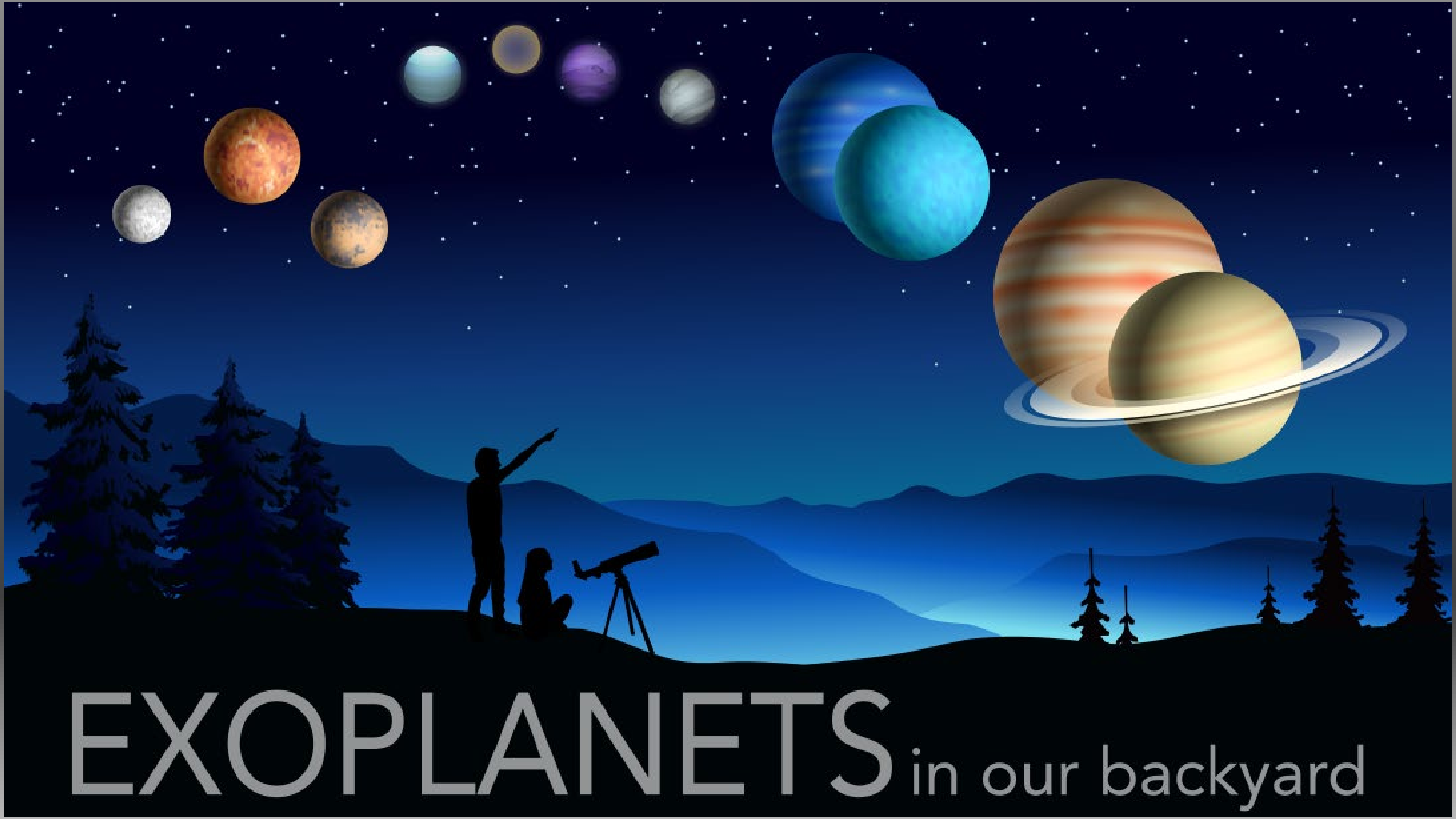
Working groups

	Neptune	Aurora/Magnetosphere/ Solar Wind	Icy sats and rings	Triton	Exoplanets
Co-Lead	Mark Hofstadter	Ian Cohen	Tracy Becker	Alan Stern	Jonathan Fortney
Co-Lead	Krista Soderlund	Frank Crary		Lynnae Quick	
	Jonathan Fortney	Corey Cochrane	Noam Izenberg	Frank Crary	Leigh Fletcher
	Corey Cochrane	Elena Provornikova	Imke de Pater	Noam Izenberg	Alan Stern
	Imke de Pater	Adam Masters	Kirby Runyon	Corey Cochrane	Noam Izenberg
	Kunio Sayanagi	Krista Soderlund	Zibi Turtle	Kirby Runyon	Lynnae Quick
	Leigh Fletcher	George Hospodarsky	James Roberts	Candy Hansen	Kathy Mandt
	Adam Masters	H. Todd Smith	Matt Hedman	Kathy Mandt	Ian Cohen
	Kathy Mandt			Zibi Turtle	Kevin Stevenson
	Amy Simon			James Roberts	
				H. Todd Smith	

Tour design and instrumentation to explore Tritons surface and sub-surface.



Exoplanets – a rear view camera to explore the ‘exoplanets on our own back yard.

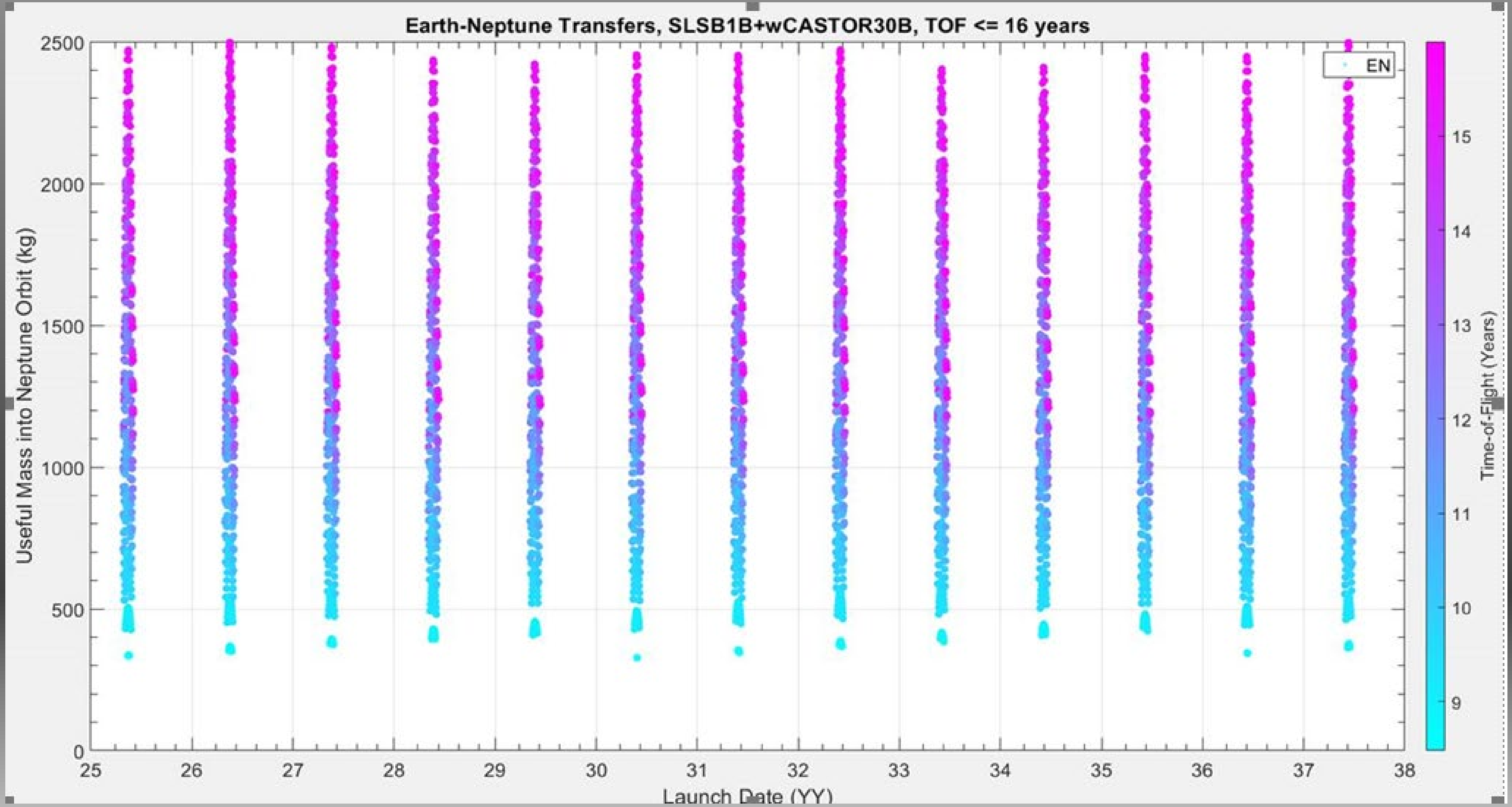


STM framework

Draft Science Traceability Matrix - Neptune Odyssey TRITON Group - Template

Objective	Science questions	Measurement Objectives	Required measurements	Potential Instrumentation	Notes and Comments	Costing c
Overall goals	*Specific questions that animate the measurement objectives. Prepopulated from top level questions in the proposal; your group may divide up as appropriate.*	*Specific measurements that must take place in order to answer the science question*	*Here lay out the precise required measurements essential to achieve objectives*	*Here suggest which potential instruments would achieve these objectives and which parameters they would need to incorporate (i.e. wavelength ranges etc). This will be taken up in more detail in the instrumentation phase.*	*Here include comments on scientific considerations raised in discussion to qualify measurements and instrument suggestions so we can better situate our proposed measurements and consider instrumentation.*	*Here include instruments data require matrix but i the outset.*
Interior	*Has Triton differentiated? What is Triton's interior structure? Does Triton have an intrinsic or crustal magnetic field? Is there an ocean present, and if so, what is its depth and salinity? How thick is the ice shell? What generates the plumes? What is the orgin of the plumes?*	Measure Triton's induced and intrinsic magnetic field.	**Corey,** Carol, Frank. Measure Neptune's magnetic field upstream/local to Triton, and fully characterize the time dependent variability (14 & 141 hr periodicity signals). At the closest approach to Triton measure the amplitude ratio of the secondary (induced field) to the primary field. Measure the	Fluxgate magnetometer (rather than SVH due to robustness and mission length), faraday cups (Frank?), potentially radio occultations of Triton's ionosphere depending on encounter geometry and closest approach altitude	Lots of considerations regarding the upstream variability both in the magnetic field periodicities (14 hr & 141 hr) as well as plasma varibility and Triton's ionosphere	
		Determine Triton's 3D shape to 1 km accuracy per axis.	**Kirby.Kirby. Image Triton's Sun-illuminated disc at <90° phase angle in visible or NIR wavelengths (~0.4-1 µm) from at >3 sub-spacecraft lon/lat on Triton at 1-10 km/pixel, SNR**	Panchromatic Imaging. E.g., LORRI, DRACO, EIS. Framing or TDI imaging modes. Mass ~8.6 kg (LORRI), Power ~15 W (LORRI), bit rate 1000-3000 bps (Variable; based on Ralph).	The Europa Clipper EIS camera combines mutlispectral TDI imaging and panchromatic framing in one focal	
		Measure libration tides	**James.** Measure libration amplitude to < 50 m to determine whether ice shell is decoupled from the interior. Panchromatic imaging, radio orbit determination of the Orbiter. Attitude	Panchromatic imaging (e.g., ISS, EIS), Geodetic camera (i.e., star tracker)	To confirm ice shell is decoupled from interior. Req'd image resolution depends on libration amplitude;	
		Image Triton's plumes, detect changes since Voyager, determine their composition, determine the composition of deposits on the	**Candy, Alan.** Image southern hemisphere at resolutions equivalent to Voyager (1 - 5 km) in order to look for changes in plume existence, size and/or location. If/when plumes are	Multispectral imager. E.g., Ralph, EIS. Framing or TDI imaging modes. IR spectroscopy. Mass ~8.6 kg (LORRI), Power ~15 W (LORRI), bit rate 1000-3000 bps (Variable;	The Europa Clipper EIS camera combines mutlispectral TDI imaging and panchromatic framing in one focal	
		Measure Triton's low degree static gravity coefficients to determine the ice shell thickness to ±20% and to determine whether the ice shell is in hydrostatic equilibrium.	**James. Radio Science:** Two-way coherent Doppler tracking (< 0.01 mm/s for 60-s count time) when SEP > 10°	Radio science subsystem (X / Ka-bands, Cassini, Clipper; Possibly S-band, Cassini) Only HGA likely to close the link at Neptune's distance Need Pt/N0 > 4 dB-Hz		
	What are the geologic processes responsible for Triton's unique surface features? What does the composition of the surface units tell us about their origin? What is the global range of 3D geologic experession on Triton? What is the global range of surface composition on Triton? What is the global range of colors and surface	Map Triton's surface, surface color variegation, photometric properties, surface topography, and surface composition.	**Alan,** Kirby, Noam. Color camera (1 km resolution, 4 color across 0.4-0.9 microns, dynamic range >=100:1). Panchromatic imaging (1 km resolution, SNR>100, Dynamic Range>100, >=2 stereo amgles)/IR surface mapping (3 km resolution, 1.25-2,.5	Imaging, IR spectroscopy, laser altimeter?Imaging: LORR-like camera; color camera and IR spectroscopy: Ralph-like. LOLA-like laser altimeter.		
		Measure changes in surface geologic and composition propertiies.	**Alan,** Kirby, Noam. Same as D9 above but no laser altimater needed..	Imaging, IR spectroscopy, laser altimeter? Same as D9 above but no laser altimeter needed.		

Extending launch window to Neptune with SLS +upper stage *preliminary*



Partnering

- NASA/Langley indicated they have additional money to help with lander and Neptune entry probe concepts during the study.

Outreach

- Website in prep, www.NeptuneOdyssey.jhuapl.edu
- Presentation
  - OPAG 4 Feb 2020
  - LPSC, Sunday 15 March 2020
- What more should we be doing?

Key milestones

- Bi-weekly full team telecons (all recorded)
  - Tom Spilker: ‘Aerocapture’
  - Noam Izenberg: ‘Triton Hopper’
  - Mark Hofstadter: ‘Trajectory’
  - Ralph McNutt: ‘Power’
  - Dana Hurley: ‘L-cross mission design’
  - (next time) Amy Simon: ‘If Ice Giant formation is difficult then why are they so common?’
- ~Weekly WG telecoms
- WG deliver STMs by Feb 7
- In person meeting at APL 25-27 March 2020
- Design Lab at APL 4-9 May 2020
- Report due to NASA 30 June 2020

Summary and Musings

- Focus on ‘system science’ and I am hearing that echoing back to us a lot, I think we have really captured the zeitgeist of planetary science with this mission target and concept and approach.
- NASA’s selection of *this* Ice Giants PMCS shows that satellite science is a driving consideration in ice giant exploration.
- New Horizons’ exploration of Pluto, Charon and Arrokoth captures the imagination for Kuiper belt science and a Triton-centric Neptune tour is an excellent opportunity to enhance the science from the New Horizons mission
- Provide an unashamedly large flagship mission that excites the broader community and the nation.
- Worried about the late start. We’d be worried even without the late start! But excited to have the chance to do this and the science team and broader support have been fantastic.

Back up slides

Neptune planetary science

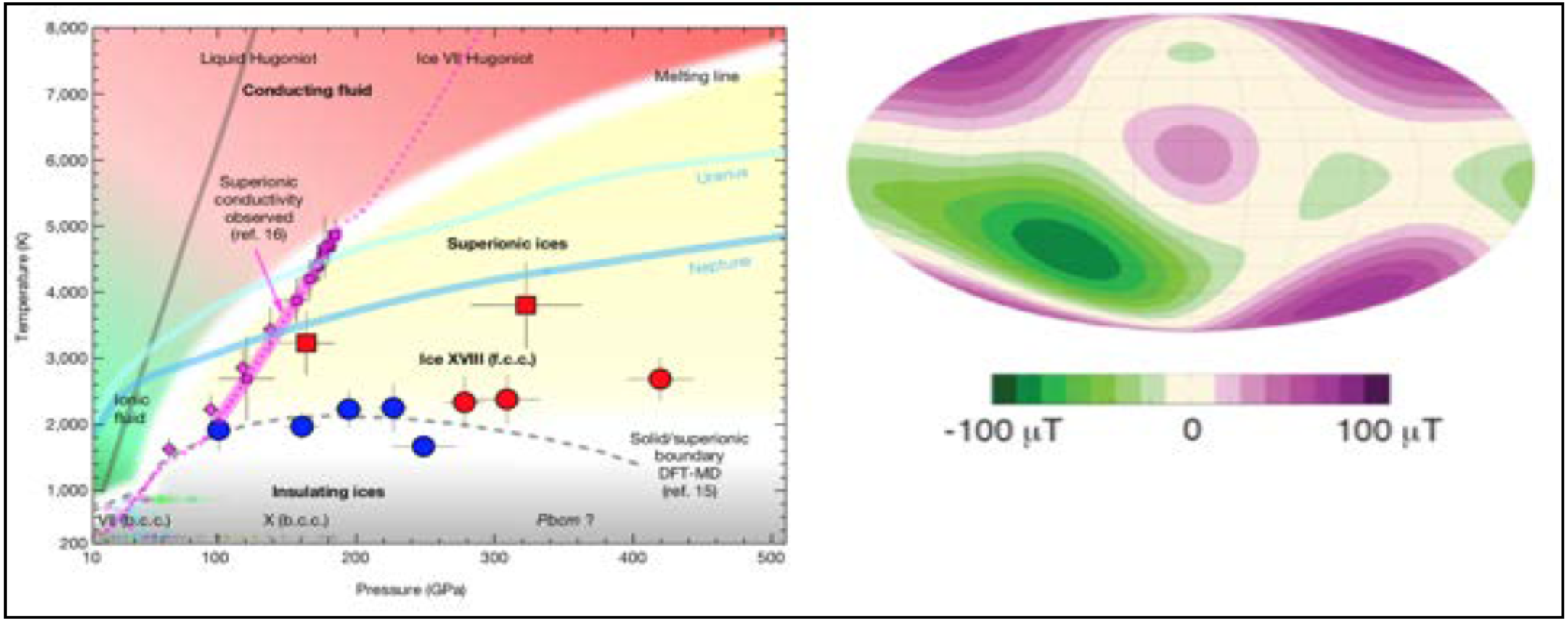


Figure 2. Left: Phase diagram of water showing hypothesized interior conditions for the ice giants (Millot et al. 2019); magnetic fields are likely generated in the shallow ionic fluid region. Right: Radial magnetic field at the 1 bar pressure level as measured by Voyager 2, including the dipole, quadrupole, and octupole components (Holme & Bloxham, 1996). Color represents field intensity with purple (green) denoting outward (inward) directed fields.

Neptune-Odyssey: A Large Strategic Class Mission Study for the Exploration of the Neptune-Triton System.

Proposal to NASA Solicitation Number: NNH18ZDA001N-PMCS

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Planetary Science Institute
Southwest Research Institute, San Antonio
Southwest Research Institute, Boulder
University of Washington
University of Texas at Austin
Princeton University
Besancon Observatory, France
University of Leicester, UK
University of Zurich, Switzerland

Neptune-Triton "Odyssey" timeline

November ……..	December ..2020….	……February………	…… …… April……… …	May……………………	… 30 June 2020
Begin regular team and sub-team telecons	Trajectory outline	In-person Science team meeting #1	Define Science Detailed trajectory Strawman payload	Design Lab In-person Science team meeting #2	Deliver "shovel ready" mission concept to NASA

Outbrief at LPSC March 2020

- Triton lander element opportunities:
  - L-cross mission impactor science – Dana Hurley
- Reflections on outreach, importance of and how-to – Alan Stern?
- Induction analysis for given trajectories – Corey Cochrane and Frank Crary

Work so far

- Tom Spilker presentation on aerocapture (see recording)
- Noam Izenberg presentation on ‘Triton Hopper’ concept
    - Revisit in response to review minor weakness 1:

> The Project Summary in Section VII of the proposal cover pages states the study will consider a Triton lander. However, pages 14-15 describe that the option of a Triton lander has been discarded as ‘too high risk’, despite the science return potential. Panelists were concerned about how the omission of considering a lander would affect the science return. The panel noted that this minor issue might be addressed by identifying the risk/return aspects of a lander in the mission concept study.

Design lab schedule…

- Trajectory design – review minor weakness 2:

The Project Summary in Section VII of the proposal cover pages states that ‘the launch window to Neptune using chemical propulsion only is optimal from 2029 to 2030’. This raised concern among the panelists about the availability of the necessary lead time to adequately develop the mission and the ‘viability’ of meeting this launch window as well as the implications of failing to do so. The panel noted that this issue may be addressed during the proposed study by identifying new trajectories and/or strategies for rapid mission development.