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# Uranus and Neptune Missions: A Study in Advance of the Next Planetary Science Decadal Survey

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**Figures:**

- Figures 1, 2, and 4 should be printed in color.
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- We recommend all figures be at least 1.5 columns wide.

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1 **Abstract**

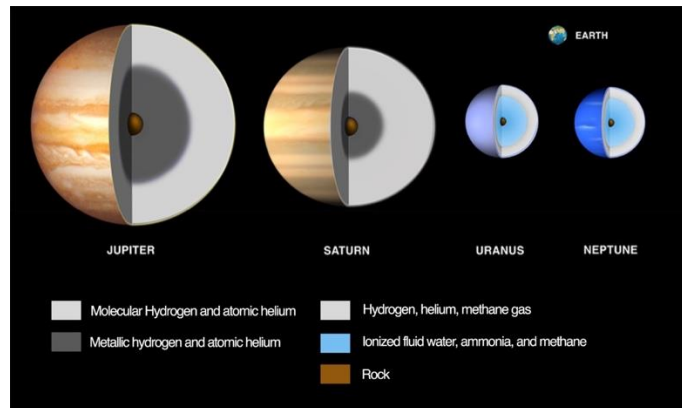
2 The ice giant planets, Uranus and Neptune, represent an important and relatively  
3 unexplored class of planet. Most of our detailed information about them comes from  
4 fleeting looks by the Voyager 2 spacecraft in the 1980s. Voyager, and ground-based work  
5 since then, found that these planets, their satellites, rings, and magnetospheres, challenge  
6 our understanding of the formation and evolution of planetary systems. We also now know  
7 that Uranus-Neptune size planets are common around other stars. These are some of the  
8 reasons ice giant exploration was a high priority in NASA’s most recent Planetary Science  
9 Decadal Survey. In preparation for the next Decadal Survey, NASA, with ESA participation,  
10 conducted a broad study of possible ice giant missions in the 2024 – 2037 timeframe. This  
11 paper summarizes the key results of the study, and addresses questions that have been  
12 raised by the science community and in a recent NASA review. Foremost amongst these  
13 are questions about the science objectives, the science payload, and the importance of an  
14 atmospheric probe. The conclusions of the NASA/ESA study remain valid. In particular, it  
15 is a high priority to send an orbiter and atmospheric probe to at least one of the ice giants,  
16 with instrumentation to study all components of an ice giant system. Uranus and Neptune  
17 are found to be equally compelling as science targets. The two planets are not equivalent,  
18 however, and each system has things to teach us the other cannot. An additional mission  
19 study is needed to refine plans for future exploration of these worlds.

20  
21  
22 **Keywords:** Uranus, Neptune, Ice Giant, Mission  
23  
24

25 **1.0 INTRODUCTION**

26 Uranus and Neptune are collectively known as the ice giant planets. They are  
27 fundamentally different from the better known terrestrial and gas giant planets, and  
28 formed and evolved in different ways (Guillot 2005; Frelikh and Murray-Clay 2017). The  
29 term “ice giants” reflects the consensus that, by mass, they are predominantly made of  
30 water and other so-called “ices,” such as methane and ammonia. Those species were likely  
31 in a solid (ice) phase during the early stages of solar system formation. Today, however,  
32 virtually all of the water in an ice giant is thought to be in fluid phases (Fig. 1). The ice  
33 giants are the least understood of the three planetary types found in our solar system  
34 (Guillot 2005). Terrestrial planets, such as the Earth, are almost entirely made of rocky  
35 material. The gas giants, Jupiter and Saturn, are predominantly made of hydrogen and  
36 helium.

37



38

39 **Fig. 1** Illustration of compositional and structural differences among the giant planets and their relative sizes.  
40 Earth is shown for comparison. Jupiter and Saturn are primarily made of hydrogen and helium, the terrestrial  
41 planets are almost pure rock, while Uranus and Neptune are thought to be largely supercritical water

42

43 Ice giants are important because they challenge our models of planet formation and  
44 evolution, and because they, along with their rings, moons, and magnetospheres, exhibit  
45 structures not yet understood. This is discussed more fully in Hofstadter et al. (2017)  
46 (hereafter referred to as the IG Study). An example of the challenge they present is that  
47 solar system formation models do not create ice giants unless restrictive timing, location,  
48 or nebular conditions are invoked (e.g. Frelikh and Murray-Clay 2017). The venerable  
49 Voyager 2 spacecraft gave us our only close-in look at these objects during its brief dash  
50 through the Uranus system in 1986 and through Neptune's in 1989. Those tantalizing  
51 glimpses answered some basic questions, but also revealed that each is a unique planetary  
52 system containing unexpected phenomena.

53  
54 Understanding the mysteries of the ice giants has implications beyond our solar system.  
55 The flood of exoplanets discovered around other stars has revealed that ice giants are  
56 common in our galaxy. Among all planets known today (see <https://exoplanets.nasa.gov/>  
57 for an up-to-date list), there are more ice giant sized planets as opposed to gas-giant or  
58 even terrestrial planets. (As of early May 2019, of the 3,940 confirmed and categorized  
59 exoplanets listed on the referenced website, 34% are “Neptune-like” and 31% are  
60 intermediate in size between Earth and Neptune; most of these so-called Super-Earth’s are  
61 thought to be more Neptune-like than Earth-like. Those numbers are to be compared to  
62 the 31% categorized as Gas-Giants, and 4% as Terrestrial. Given selection effects in  
63 exoplanet surveys, however, we cannot say with confidence whether or not ice giants are  
64 more abundant than gas giants.) Untangling the mysteries surrounding the ice giants in

65 our solar system will lead to fundamental insights into the formation and evolution of  
66 planetary systems in general.

67

### 68 *The Purpose of the Mission Study and this Paper*

69 The above discussion explains why the 2011 Planetary Science Decadal Survey, titled *Vision*  
70 *and Voyages* (National Research Council 2011, hereafter V&V) ranked a Flagship mission to  
71 an ice giant as a high priority, to be flown after a Mars sample cache and Europa mission.  
72 Now that work on those first two missions is underway, it is consistent with NASA's  
73 strategic plans to reconsider what an ice giant mission might look like. Recognizing that  
74 such a mission is likely to slip into the period governed by the next Decadal Survey, in  
75 August 2015 the Director of NASA's Planetary Science Directorate announced a "Pre-  
76 Decadal Survey" study of missions likely to be considered by the next Survey, starting with  
77 the ice giants. The ice giant study goal was to "Assess science priorities and affordable  
78 mission concepts and options in preparation for the next Decadal Survey" (Green 2015). In  
79 regards to mission science objectives, NASA directed that they be based on V&V but  
80 "revised with recent developments in science and technology." The full report of that study  
81 is available (the IG Study).

82

83 This paper, authored by all members of the IG Study Science Definition Team (SDT) and key  
84 members of the engineering teams, summarizes the report to make it as accessible as  
85 possible to the science community. We also clarify the discussion of science goals and  
86 potential science payloads to correct common misunderstandings that became evident  
87 since the IG Study's release in community discussions and in the recently completed

88 National Academies mid-term review of progress implementing the V&V Decadal Survey  
89 (National Academies 2018, hereafter referred to as the Mid-Term Review). Section 2  
90 highlights some of the study methodology relevant for later discussions. Section 3  
91 describes the priority science goals identified by the SDT. At the end of that section we  
92 discuss how the science to be done at Uranus is equally important to (but different from)  
93 the science to be done at Neptune, and the value of being able to compare the two planets.  
94 Section 4 discusses possible instruments to address the science goals, and presents the  
95 model payloads that were used for designing potential missions. Section 5 presents high-  
96 level conclusions regarding trajectories to the ice giants, and Section 6 summarizes the  
97 team's prioritization of possible mission architectures. Section 7 highlights relevant recent  
98 discoveries and their relation to differences among V&V, the IG Study, and the Mid-Term  
99 Review. Section 8 discusses the study's conclusions and recommendations in light of those  
100 advances.

101

102

## 103 **2.0 STUDY APPROACH**

104 For details of how the IG Study was formulated and carried out, see the full report. There  
105 are a few aspects worth highlighting, however, as they will impact later discussions. First it  
106 should be noted that the IG Study is intended to be a broad survey sampling a wide range of  
107 missions and mission types. This allows it to guide high-level decision making, but also  
108 prevents it from extensively exploring what ultimately is the recommended mission  
109 architecture (an orbiter with probe).

110



111 The IG Study operated under a specific set of ground rules. For example, we were directed  
112 to reassess the science priorities of V&V in light of discoveries since V&V's publication.  
113 Therefore, the prioritization in the IG Study is different from that in V&V. This also allowed  
114 for a more detailed look at broad system science than was possibly during the rapid V&V  
115 study. Similarly, we were tasked with identifying new technologies that could have a  
116 significant impact on an ice giant mission. In line with this directive, our study identifies  
117 items such as a Doppler Imager instrument which—while not necessary for a mission—are  
118 worthy of further study. There were also two important cost-related ground rules. First,  
119 launch vehicle costs were not included in our mission cost estimates. Second, there was  
120 some evolution of how to treat the cost target for the missions. While asked to study a  
121 range of mission costs, the initial cost target was identified as \$2B (in FY15 dollars). Our  
122 preliminary reports therefore referred to our recommended mission as one with a  
123 relatively small (50 kg) payload which meets the \$2B target. It was recognized, however,  
124 that a larger payload is needed to address all priority ice giant system science goals. In  
125 subsequent discussions with NASA and ESA, it was clarified that our recommended mission  
126 should be the one the science team believes should be flown, even if it exceeds the cost  
127 target by a moderate amount. We therefore ultimately recommend a 150 kg science  
128 payload for an ice-giant Flagship orbiter.

129

130 It should also be noted that, while this was a NASA study performed at the Jet Propulsion  
131 Laboratory/California Institute of Technology, many organizations were involved. The  
132 science team reflects a mix of NASA, academic, and private institutions. ESA is a full  
133 partner, having helped plan the study and contributing personnel and expertise. Purdue

134 University, Ames Research Center, Langley Research Center, and the Aerospace  
135 Corporation all made significant technical contributions, described in the full report.

136

137

### 138 **3.0 SCIENCE OBJECTIVES**

#### 139 **3.1 Science Objectives and Priorities**

140 The ice giants and their systems are a natural laboratory to challenge our understanding of  
141 fundamental processes in planetary formation, evolution, and structure. Following a  
142 process described in the full IG Study report, and starting with the comprehensive science  
143 output of a community workshop held in 2014 in Maryland, USA, the SDT identified 12  
144 high-priority science objectives for an ice giant flagship mission. The list is very similar to  
145 what is in V&V, though the final prioritization changed somewhat to reflect knowledge  
146 gained in the few years between V&V and the IG Study.

147

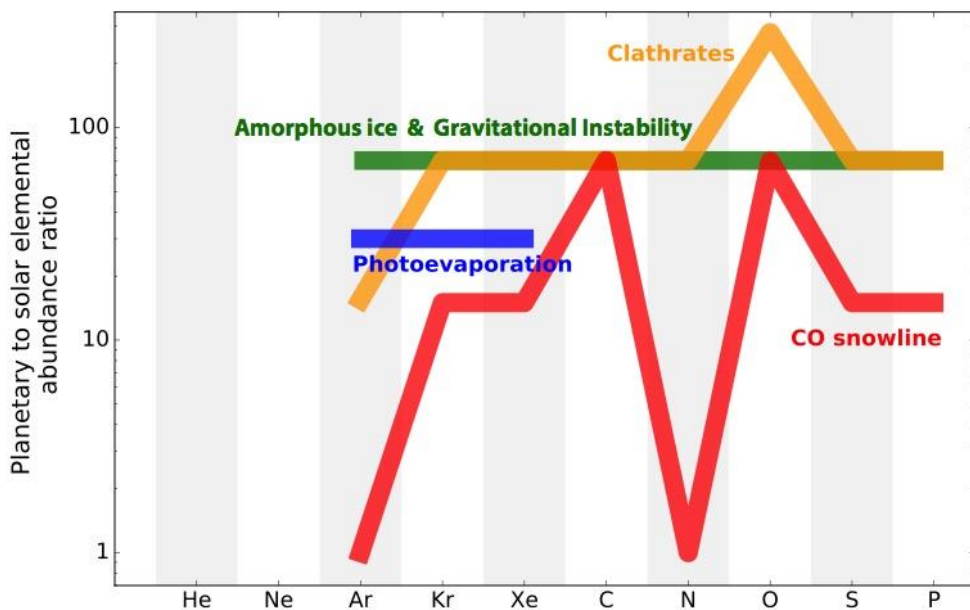
148 We find that the two highest-priority objectives for the next ice giant mission are to

- 149 • Constrain the structure and characteristics of the planet's interior, including  
150 layering, locations of convective and stable regions, and internal dynamics
- 151 • Determine the planet's bulk composition, including abundances and isotopes of  
152 heavy elements, He, and heavier noble gases

153 These two objectives are ranked most highly because they define what it means to be an ice  
154 giant planet and they provide the best evidence for how and where these planets formed.

155 These objectives must be addressed in order to understand ice giants as a type of planet,  
156 and they cannot be addressed by studying any of the other planets in our solar system.

157 Furthermore, a space mission with both remote sensing instruments and an in situ  
158 atmospheric probe is needed to fully address these items. Earth- or near-Earth-based  
159 instruments cannot do the job. (See the IG Study and Atreya et al. 2018 for a detailed  
160 discussion of the need for a probe, and the importance of measuring heavy noble gases and  
161 key isotopic ratios. Those abundances are not modified by atmospheric meteorology,  
162 dynamics, or chemistry, allowing a single entry probe to make definitive measurements  
163 diagnostic of planetary formation models [Fig. 2].)  
164



165  
166 **Fig. 2** Qualitative differences among the enrichment of noble gases and volatile species predicted by different  
167 Uranus and Neptune formation scenarios. Abundances are normalized to the carbon abundance. Figure is  
168 updated from Mousis et al. 2018 (Olivier Mousis, personal communication)  
169

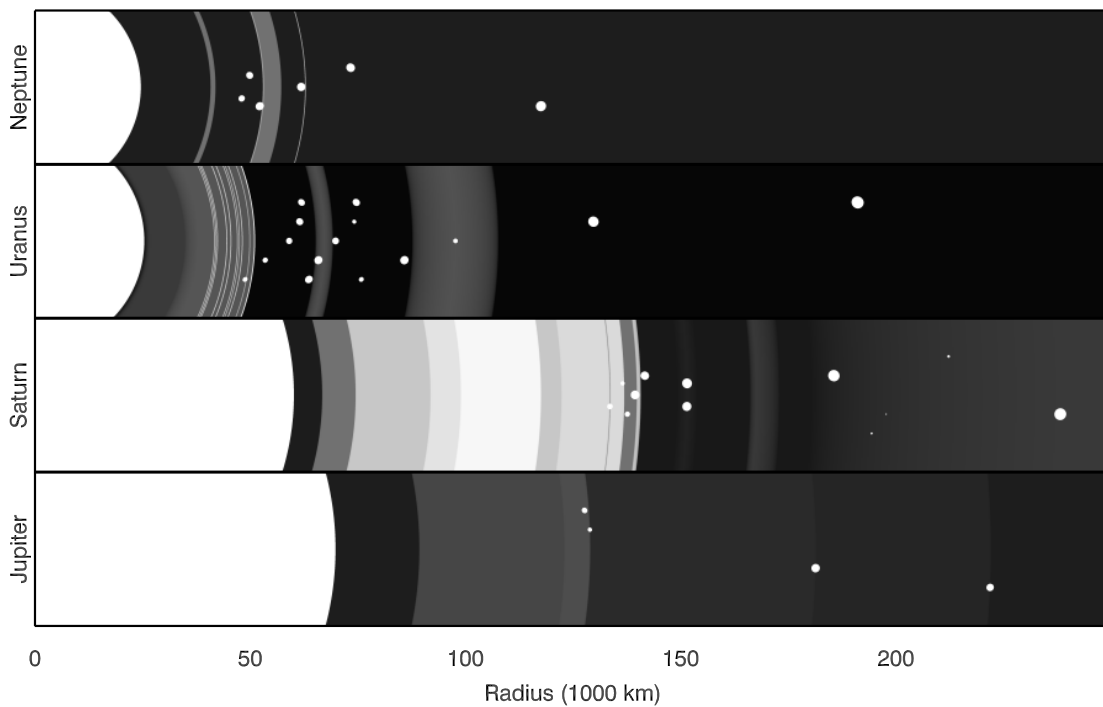
170 The V&V Decadal Survey includes the above objectives (e.g. for interior structure see V&V  
171 Table ES.3; for references to noble gases and isotopic ratios, see the first paragraph on page  
172 7-11), but does not rank them as top priority due to concerns about our ability to make the  
173 necessary measurements (V&V was limited to what could be accomplished based on  
174 current understanding and technology at the time, for a mission to launch before 2023).  
175 Our study makes use of recent technological advances and additional mission design work  
176 to mitigate those concerns (see Sections 5.2 and 7).

177

178 The remaining priority science objectives identified in the IG Study are all ranked of equal  
179 importance, and cover all aspects of the ice giant systems, from the interiors and  
180 atmospheres, rings and satellites (Fig. 3), and out to the magnetospheres and their  
181 interactions with the solar wind. They are (listed in order of distance from the planet's  
182 center):

- 183 • Characterize the planetary dynamo
- 184 • Determine the planet's atmospheric heat balance
- 185 • Measure the planet's tropospheric 3-D flow (zonal, meridional, vertical) including  
186 winds, waves, storms and their lifecycles, and deep convective activity
- 187 • Characterize the structures and temporal changes in the rings
- 188 • Obtain a complete inventory of small moons, including embedded source bodies in  
189 dusty rings and moons that could sculpt and shepherd dense rings
- 190 • Determine the surface composition of rings and moons, including organics; search  
191 for variations among moons, past and current modification, and evidence of long-  
192 term mass exchange / volatile transport

- 193 • Map the shape and surface geology of major and minor satellites
  - 194 • Determine the density, mass distribution, and internal structure of major satellites
  - 195 and, where possible, small inner satellites and irregular satellites
  - 196 • Determine the composition, density, structure, source, spatial and temporal
  - 197 variability, and dynamics of Triton's atmosphere
  - 198 • Investigate solar wind-magnetosphere-ionosphere interactions and constrain
  - 199 plasma transport in the magnetosphere
- 200 It should be noted that all the objectives, with the exception of the one regarding Triton,
- 201 apply to both Uranus and Neptune.



202

203 **Fig. 3** Diagram comparing the ring-inner moon systems of the giant planets. The extents of the various rings

204 are shown to scale, with greyscale levels indicating their relative optical depths. The locations of inner moons

205 are indicated by dots. At Neptune, the outermost satellite shown is Proteus, while at Uranus the two

206 outermost are (from right to left) Ariel and Miranda. The outermost Saturn and Jupiter satellites shown are

207 Enceladus and Thebe, respectively. These dots do not indicate the size of the moons relative to the rings,  
208 though the relative sizes of the satellites are approximately correct. Credit: Matthew Hedman

209

210 A detailed discussion of these science objectives, the associated measurements, and  
211 mission requirements can be found in the IG Study. Given our charter to utilize scientific  
212 and technological advances since V&V to reassess science goals (see Section 7), and our  
213 directive to explore a broader range of options than were presented in V&V, the  
214 prioritization and emphasis of science objectives in the IG Study is different than in V&V.  
215 The two studies are overall quite consistent, however, and no science objective in one is  
216 entirely missing from the other.

217

### 218 **3.2 Uranus-Neptune Comparative Planetology**

219 While Uranus and Neptune are equally compelling, the two planets are not equivalent.  
220 Each system has things to teach us the other cannot, and we cannot hope to truly  
221 understand “ice giants” as a class of planet without studying both examples in our solar  
222 system.

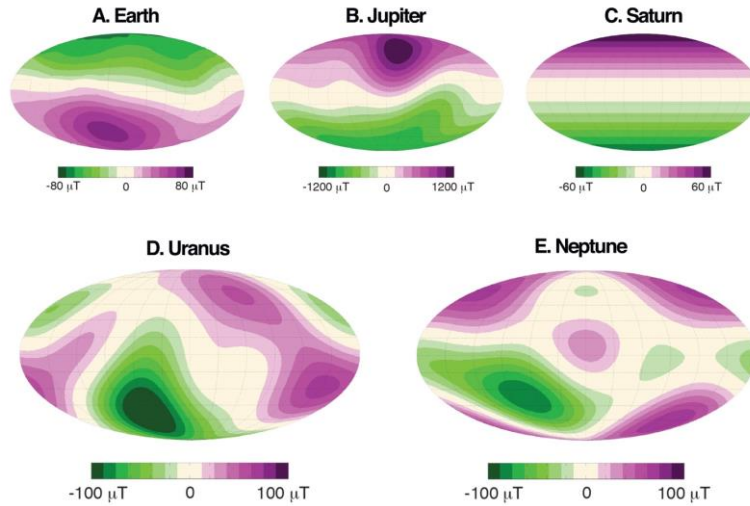
223

224 At the highest level, each planet is similar in size and gross composition, and is a potential  
225 archetype for the ice giant class of planets. Each planet has a system of rings and satellites  
226 with unusual features, evolving dynamically on decadal time scales. Each has a magnetic  
227 field with complexity unseen in the terrestrial and gas-giant planets (Fig. 4), and a  
228 magnetosphere that has unique diurnally and seasonally varying coupling to the solar wind.

229

230 In spite of these similarities, the brief Voyager flyby of each, along with Earth-based  
231 observations and modeling, have allowed us to see some fundamental ways in which the  
232 Uranus and Neptune systems differ. As an example, consider the satellites (Fig. 5). An  
233 orbiter at Neptune offers the opportunity for detailed exploration of Triton, a captured KBO  
234 which Voyager found to be active, with several “geysers” erupting (Soderblom et al. 1990).  
235 Triton is also a potential ocean world (Hendrix et al. 2018), and its exploration leverages  
236 the knowledge we are gaining from the recent New Horizons flyby of Pluto to better  
237 understand KBOs. But in the process of capturing Triton, Neptune appears to have lost its  
238 larger, native satellites, and perhaps fundamentally disrupted what a “normal” ice giant  
239 ring/moon system looks like (see Coradini et al. 2010, Mosqueira et al. 2010, Turrini et al.  
240 2014 and references therein). To explore a regular system of large ice giant satellites, one  
241 must go to Uranus (while its satellites may also have been influenced by the giant impact  
242 thought to have given Uranus its large inclination, Mobidelli et al. 2012 suggest such  
243 impacts and their aftermath may be the norm for ice giants). The Uranian moons Miranda  
244 and Ariel are particularly interesting given the evidence of geologic activity found in  
245 Voyager images. There is also a tremendous difference in the amount of internal heat being  
246 released by the two planets (a factor of 10!) and—presumably related to this—significant  
247 differences in their internal structures (Nettelmann et al. 2013, 2016).

248



249  
 250 **Fig. 4** Radial magnetic fields measured on (A) Earth, (B) Jupiter, and (C) Saturn are contrasted against those  
 251 measured on (D) Uranus and (E) Neptune. The colors represent field intensity where purple (green) indicates  
 252 outward (inward) directed fields. The measurements on Uranus and Neptune have the lowest spatial  
 253 resolution (to spherical harmonic degree 3), so all planets are shown with that resolution. This comparison  
 254 illustrates the ice giants' unique magnetic field morphologies. Adapted from Schubert and Soderlund (2011)

255  
 256 The SDT concludes that a mission to either ice giant system can fundamentally advance our  
 257 understanding of ice giants and processes at work in planetary systems, but the highest  
 258 science return will come from an exploration of both systems. Not only does each planet  
 259 provide information the other cannot, but by comparing the two we see how planets react  
 260 to differing physical inputs (e.g., sunlight vs. internal heat), and we get a better idea of what  
 261 properties might be common among ice giant exoplanets. Therefore, while the cost ground  
 262 rules of the IG Study lead us to recommend a mission to one planet, we also recommend  
 263 exploring ways to send missions to both. Since completion of V&V, we note several ideas  
 264 have been discussed to enable two-planet missions (e.g. Turrini et al. 2014; Simon et al.  
 265 2018).





267

268 **Fig. 5** Voyager 2 images of the 5 major satellites of Uranus (from the left, Miranda, Ariel, Umbriel, Titania,  
 269 and Oberon) and Neptune's Triton (far right). Satellites are shown with their approximate relative sizes.

270 Credit: NASA/JPL

271

272

## 273 4.0 INSTRUMENTS AND MODEL PAYLOAD

### 274 4.1 Introduction

275 An important area in which the original IG Study has been misunderstood is in its  
 276 discussion of instruments and payloads. It does not propose a specific payload for flight,  
 277 nor does it prioritize instruments, with the exception of a probe as a high priority payload  
 278 element. The IG Study, being a survey of alternative architectures and mission sizes, could  
 279 not reliably select instruments at this early stage. Instead, the model payload is intended to  
 280 be useful in assessing alternative architectures and in providing considerations to a future  
 281 science team who will take into account the latest advances and be constrained by the  
 282 resources (cost, mass, power, data volume) of their specific mission. Instead of  
 283 recommending a set of instruments, the IG Study recommends a payload size of 150 kg to  
 284 achieve all priority objectives based on current state-of-the-art instrumentation. It is

285 possible to address a diverse set of science objectives even with only a 50-kg payload.  
286 Criticisms of the instruments used in the IG Study model payloads as being too narrowly  
287 focused (like those found in the Mid-Term Review page S-4 and 3-20) therefore reflect  
288 misunderstandings of the IG study in this regard.

289  
290 Though the IG Study does not propose a specific set of instruments for flight, it is necessary  
291 to identify representative mass, volume, power, and data volumes needed by the science  
292 payload, so that alternative mission point designs (Section 6) can be tested for their ability  
293 to accommodate a reasonable payload, trajectories can be assessed for compatibility with  
294 representative needs of instruments, and to estimate mission costs. Therefore, the IG Study  
295 science team chose to consider three “model payloads” distinguished primarily by their  
296 total mass. Masses of 50, 90, and 150 kg were selected, as being likely to span what would  
297 be available to a future Flagship mission.

298  
299 Section 4.2 gives a very brief overview of instruments discussed during the course of the IG  
300 Study, and Section 4.3 presents the model payloads used in later mission point designs.

301

## 302 **4.2 Instruments**

303 Before converging on the 12 priority science questions presented in Section 3, the SDT  
304 began with an extensive, community-defined list of >90 questions and considered the  
305 instruments needed to address them (listed in Appendix F of the IG Study). The  
306 instruments discussed by the SDT are summarized in Table 1.

307

308 **Table 1.** Instruments considered for model payloads.

| Instrument   | Mass (kg) | Power (W) | Flight-Qualified Analog | Comments   |
|--|-----------|-----------|-------------------------|--|
| <b>In Situ Instruments on Main Spacecraft (flyby or orbiter)</b> |           |           |                         |  |
| Mass spectrometer  | 16        | 19        | DFMS/Rosetta            | Triton's atmosphere is a primary target.   |
| Magnetometer w/ 10 m boom  | 14        | 10        | MAG/Cassini             | Team-X used 10kg and 8 W based on Galileo.   |
| Radio and plasma waves   | 5.6       | 2.7       | LPW/MAVEN               | Combines an in-situ Langmuir probe with remote sensing of low-frequency plasma and radio waves.  |
| Plasma low-energy particles                                      | 3.3       | 2.3       | SWAP/NH                 |  |
| Plasma high-energy particles                                     | 1.5       | 2.5       | PEPPSI/NH               |  |
| Langmuir probe   | 1         | 0.1       | RPWS-LP/Cassini         | If LPW/MAVEN is used, this instrument is redundant.  |
| Energetic neutral atoms  | 6.9       | 3         | INCA/Cassini            |  |
| Dust detector  | 5         | 6.5       | SDC/NH                  |  |
| <b>In Situ Probe Instruments</b>                                 |           |           |                         |  |
| Mass spectrometer  | 17.4      | 66/50     | None                    | Specifications based on a proprietary proposal.  |
| Atmospheric pressure, temperature package (ASI)                  | 2.5       | 3.5       | Galileo Probe           | Team-X used 2.5 kg, 10 W power, which included accelerometer, other instruments, and a pitot tube extending 8 cm to reach beyond boundary layer. |
| Nephelometer   | 2.3       | 4.6       | Galileo Probe           | Team-X used 4.4 kg, 11 W avg which includes a boom extending beyond the boundary layer..   |
| H <sub>2</sub> ortho-para instrument                             | 1         | 3.5/1     | None                    | If required to be outside boundary layer, mount on nephelometer boom. Based on Banfield et al. 2005.   |
| Net-flux radiometer  | 2.3       | 4.6       | Galileo Probe           |  |
| Helium abundance   | 1.4       | 0.9       | Galileo Probe           |  |

309

310

311 **Table 1.** (Continued)

| <b>Instrument</b>                       | <b>Mass (kg)</b> | <b>Power<br/>(W)</b> | <b>Flight-Qualified<br/>Analog</b> | <b>Comments</b>   |
|---|------------------|----------------------|------------------------------------|---|
| <b>Imaging Spectrometers</b>            |                  |                      |                                    |   |
| Vis/NIR                                 | 16.5             | 8.8                  | OVIRS/O-Rex                        | Assumed imaging capability and longer IR wavelengths can be added to OVIRS.   |
| UV                                      | 7                | 10                   | UVS/Europa Clip                    | Specs intermediate to Alice/NH and UVS/Juno.  |
| Mid-IR                                  | 6.3              | 10.8                 | OTES/O-Rex                         | Used OTES for its longer wavelength coverage than the Ralph instrument on New Horizons.   |
| Doppler Imager                          | 20               | 20                   | None                               | Based on ECHOES proposal for JUICE mission to Jupiter, with mass increased by 6 kg to account for lower illumination levels and instrument maturity.  |
| <b>Cameras/Bolometers</b>               |                  |                      |                                    |   |
| Thermal-IR bolometer/Visible photometer | 12               | 25                   | DIVINER/LRO                        | The mass and power levels chosen are well above what a minimal bolometer/photometer instrument would need. DIVINER is an analog: eliminate its scan capability, add imaging. Desire longer wavelengths than ETHEMIS/Europa Clipper. |
| Narrow-angle camera                     | 12               | 16                   | EIS/Europa                         | LORRI/NH was considered as the analog, but the desire for filters and pushbroom capability drove us to use EIS (Turtle et al. 2016, LPSC).  |
| Wide-angle camera                       | 4                | 10                   | MDIS-Messenger                     | Overestimates mass and power because MDIS includes extra components.  |

312

313

314

315

316 **Table 1.** (Continued)

| <b>Instrument</b>                 | <b>Mass (kg)</b> | <b>Power<br/>(W)</b> | <b>Flight-Qualified<br/>Analog</b> | <b>Comments</b>                     |
|-----------------------------------|------------------|----------------------|------------------------------------|-------------------------------------|
| <b>Other</b>                      |                  |                      |                                    |                                     |
| Radar                             | 21               | 50                   | MARSIS/Mars<br>Express             |                                     |
| Ultra-Stable Oscillator (USO)     | 2                | 2                    | Many                               | Proposed JUICE USO is 2 kg and 6 W. |
| Microwave sounder                 | 42               | 33                   | MWR/Juno                           |                                     |
| <b>Additional Flight Elements</b> |                  |                      |                                    |                                     |
| Atmospheric Probe                 | ~220             | Variable             | Galileo                            | See discussion.                     |
| Smallsats/CubeSats                | 10+              | 10                   | None                               | See discussion in the IG Study.     |
| Lander(s)                         | 10+              | 10                   | None                               | See discussion in the IG Study.     |

317  
 318 In Table 1, when two powers are listed, the first is a peak value and the second represents  
 319 an average. The Flight Analog column is an instrument that has flown or is under  
 320 construction for flight, which the science team selected as most similar to what is desired.  
 321 Mass and power estimates reflect that analog, except as noted in the comments.

322  
 323 The full IG Study should be consulted for additional discussion of each instrument and the  
 324 measurement requirements they would satisfy. In the remainder of this section we  
 325 highlight a few items that seem most relevant to discussions in the community since  
 326 release of the report. We start with the Doppler Imager which is likely the least familiar  
 327 instrument and one that has never flown. It represents a family of instruments that could  
 328 be used to detect planetary-scale oscillations of an ice giant. Detection and  
 329 characterization of these motions would revolutionize our understanding of interior

330 structure. To date, there is a reported ground-based detection of Jupiter oscillations  
331 (Gaulme et al. 2011, 2015), and Saturn’s rings display density waves that are driven by  
332 similar planetary oscillations (Hedman and Nicholson 2013, 2014). The Saturn data,  
333 collected by the Cassini spacecraft, has led to new insights on Saturn's deep interior  
334 structure (Fuller 2014) and rotation rate (Mankovich et al. 2018). There is to date,  
335 however, no theoretical or observational evidence indicating that such oscillations have a  
336 detectable amplitude at Uranus or Neptune (e.g. Rowe et al. 2017). The reason the Doppler  
337 Imager appears on the list of potential instruments alongside proven technologies and  
338 techniques is three-fold: 1) Part of the IG Study’s charter was to assess important new  
339 technologies, and we wished to highlight the value of developing this technique; 2) A  
340 Doppler Imager or similar instrument is the best way to dramatically advance our  
341 understanding of the interior structure of ice giants; and 3) The Doppler Imager is a  
342 relatively massive, power-hungry device which generates a tremendous data volume  
343 (making full disk images on the order of every second for several weeks), so it can serve as  
344 a good stress-test of mission architectures. *Any mission capable of accommodating a*  
345 *Doppler Imager can easily accommodate two or more replacement instruments.*

346

347 The items on the “Additional Flight Elements” part of Table 1 deserve mention here. While  
348 not technically instruments, the SDT felt that the choice of whether or not to add them to  
349 the mission would ultimately come down to a trade-off between the science return of the  
350 new flight element against the total mass of instruments that could be carried on the main  
351 spacecraft. Hence, it made sense to place them on this list. The mass of the probe  
352 represents the total mass of the payload and entry system for a single probe (but does not

353 include any special communication or mounting structures required on the carrier  
354 spacecraft). Details of probe design and architectures that accommodate probes are  
355 discussed in the IG Study. For SmallSats/CubeSats and Landers, the 10 kg/10 W  
356 designation was a placeholder to use while discussing payloads. The SDT considered one  
357 or more small elements (e.g. releasing a dozen CubeSats with magnetometers) as well as  
358 larger options (such as a soft lander for an icy moon). During early science trade-off  
359 discussions, the SDT decided that instruments on-board the carrier spacecraft were a  
360 better investment than very small flight elements, and that an atmospheric probe was  
361 higher priority than a larger lander or free-flyer, so detailed designs of SmallSats, CubeSats,  
362 and Landers were not developed.

363

#### 364 **4.3 Model Payloads**

365 As discussed earlier, model payloads allow mission designs to be costed and tested for their  
366 ability to accommodate science instruments, including mass, power, data rates, and  
367 pointing requirements. The SDT chose to model three payload sizes: 50, 90, and 150 kg.  
368 An atmospheric probe was considered an option to add to each of those payload sizes. The  
369 smallest mass limit was judged to be the minimum one would expect a Flagship-class  
370 mission to carry (for comparison, the New Horizons spacecraft carries about 30 kg of  
371 instruments). The 150 kg limit was picked because it is large enough to let us carry all  
372 instruments which were identified as “primary” for achieving each of our 12 priority  
373 science goals, because it is large enough to allow a diverse payload able to make and  
374 follow-up on unplanned discoveries, and also because 150 kg is small enough to force some  
375 instruments to not be carried (responding to the cost targets assigned to our study). For

376 comparison, the Cassini orbiter carried about 270 kg of science instruments. The 90 kg  
377 limit was selected as an intermediate option.

378

379 We find that a 50 kg payload could achieve significant science and (depending on the  
380 instrument set chosen) could address a broad range of objectives. It could not, however,  
381 address all 12 of our priority science goals. For modeling purposes we chose the 50 kg  
382 payload to consist of:

- 383 • Doppler Imager
- 384 • Narrow Angle Camera
- 385 • Magnetometer

386 This model payload demonstrates the ability of our smallest mission to achieve significant  
387 science, to accommodate our highest data volume instrument (the Doppler Imager) as well  
388 as accommodate the strict pointing requirements of the camera and magnetic cleanliness  
389 requirements of the magnetometer. It also serves to highlight our recommendation that  
390 NASA explore instruments and techniques for studying planetary oscillations. As  
391 emphasized above, however, this is not intended to be interpreted as the selected payload.

392

393 We believe a 90 kg model payload would be capable of touching upon (but not fully  
394 addressing) all 12 of our priority science goals. For modeling purposes, we added to the  
395 50-kg case the following instruments:

- 396 • Vis/NIR imaging spectrometer
- 397 • Thermal IR/visible instrument
- 398 • Plasma suite (Radio, low-energy, and high-energy plasma instruments)



- 399
- Mid-IR spectrometer for Uranus, UV spectrometer for Neptune

400 The mid-IR and UV spectrometers are good candidate instruments for either planet, but to  
401 explore any differences in accommodation needs the SDT chose to specify one for Uranus  
402 and the other for Neptune. The atmosphere of Triton is a good target for UV studies, so the  
403 UV instrument was assigned to Neptune.

404

405 The large, 150 kg model payload would allow significant progress to be made in all 12 of  
406 our priority science objectives, and is diverse enough to make the type of unplanned  
407 discoveries and follow-up observations that made the Cassini mission at Saturn so  
408 productive. The SDT recommends a payload of this size for a future ice giant Flagship  
409 mission. The model 150 kg payload adds the following instruments to the 90 kg case:

- 410
- Wide-angle camera
  - 411 • Ultra-Stable Oscillator (USO)
  - 412 • Energetic Neutral Atoms (ENA)
  - 413 • Dust detector
  - 414 • Langmuir probe
  - 415 • Microwave sounder (Uranus), mass spectrometer (Neptune)

416 The microwave sounder appears on this payload list both because of its unique ability to  
417 explore composition, dynamics, and cloud formation in the deep atmospheres of giant  
418 planets (as demonstrated by the Juno mission, see Bolton et al. 2017), and because its long-  
419 wavelength antenna is relatively large and we wanted to explore the spacecraft's ability to  
420 accommodate it. It would certainly be a valuable instrument to fly to Neptune as well, but  
421 the SDT also wished to explore accommodating a mass spectrometer on the main

422 spacecraft which could—among other things—be used to sample the atmosphere of Triton.  
423 So, as with the medium-sized payload, we chose to model different payloads for the two  
424 planets.

425

426 For architectures with an atmospheric probe, the following probe payload was modeled:

- 427 • Mass spectrometer
- 428 • Atmospheric Structure Instrument (ASI) for temperature, pressure, density
- 429 • Nephelometer
- 430 • H<sub>2</sub> ortho-para sensor

431 Only the mass spectrometer and ASI are considered “must have” instruments (see the IG  
432 Study for a discussion). If a probe is flown which can accommodate more than those two  
433 instruments, any or all of the remaining 4 listed in Table 1 is a viable candidate. There is no  
434 special reason the SDT chose to carry a total of 4 instruments on the probe as opposed to 3  
435 or 5. Four seems like an intermediate number, which is more than a minimal probe but still  
436 small enough to require some science prioritization and compromises.

437

438 We wish to emphasize again that these model payloads are meant to be representative  
439 examples for the purpose of estimating cost and requirements placed on the carrier  
440 spacecraft. When the mission ultimately flies, its payload will be based on the latest  
441 available technology and science information, results from the Juno and Cassini missions,  
442 as well as programmatic considerations not available to the IG Study.

443

444

## 445 5.0 Trajectory Considerations

### 446 5.1 Getting to the Ice Giants

447 During the study, over 10,000 trajectories were explored to bring a spacecraft from Earth  
448 to either Uranus or Neptune in the 2024 to 2037 time frame. Three launch vehicles were  
449 considered (an Atlas 551, a Delta-IV Heavy, and current performance estimates for the  
450 Space Launch System, or SLS, under development), up to four gravity-assist flybys were  
451 allowed in each trajectory, and both chemical and solar-electric propulsion (SEP) options  
452 were modeled. Both flyby and orbiter spacecraft were considered. Details are in the IG  
453 Study report, particularly Appendix A. The main conclusions are:

- 454 • Launch options exist any year, but the most favorable trajectories are in the 2029 to  
455 2032 time frame, utilizing a Jupiter gravity assist
  - 456 – Mass delivered to Uranus is maximized in launches between 2030 and 2032.
  - 457 – Mass delivered to Neptune is maximized in launches between 2029 and 2030.
  - 458 – Uranus missions launched prior to 2029 utilize a Saturn gravity assist.
  - 459 – There are no desirable Saturn flyby trajectories to Neptune.
- 460 • Uranus and Neptune do not align, so a single spacecraft cannot visit both planets
- 461 • Weighing flight time, cost, and other considerations, chemical trajectories to Uranus  
462 are preferred while a Neptune mission would likely use SEP
  - 463 – Chemical propulsion trajectories allow Flagship-class orbiters (>1500 kg dry  
464 mass) to be inserted into Uranus orbit, with flight times of 8 to 12 years using  
465 Atlas or Delta IV launch vehicles. Flight times can be 6 years with SLS
  - 466 – A Flagship-class orbiter on a chemical trajectory to Neptune requires an SLS  
467 launch vehicle if it is to arrive within 13 years of launch. (The 13-year travel

468 time requirement is based on lifetime and reliability issues, primarily with  
469 radioisotope power systems, assuming a 2-year prime mission after arrival.)  
470 – A Flagship-class orbiter to Neptune can be flown on the Atlas V or Delta-IV  
471 Heavy utilizing SEP with flight times of 12 to 13 years. SLS enables flight  
472 times down to 8 years

- 473 • Flight times for flyby spacecraft can be less than indicated above, due to there being  
474 no need to slow down for capture into orbit
- 475 • To propulsively capture into orbit (as opposed to aerocapture, for example),  
476 relatively large orbit-insertion burns are needed
  - 477 - 1.5 to 2.5 km/s at Uranus
  - 478 - 2.3 to 3.5 km/s at Neptune
- 479 • In general, use of an SLS launch vehicle can increase delivered mass and/or reduce  
480 flight times in any launch year, compared to the Atlas or Delta-IV Heavy
- 481 • If it is desired to launch two spacecraft on a single launch vehicle, one going to  
482 Uranus and the other to Neptune, an SLS may be required. (Note that, scientifically,  
483 there is no need to launch both spacecraft simultaneously, but our study ground  
484 rules specified using only a single launch vehicle.)

485

## 486 **5.2 Periapse Altitude: Orbit Insertion and Field Measurements**

487 It is desirable to fly as close to the ice giant as possible. This is because high spatial  
488 resolution in situ measurements of the gravity and magnetic fields (key for understanding  
489 the interior) require proximity, and because the fuel needed for orbit insertion (referred to  
490 as the “delta-V”) is minimized by performing the burn close to the planet. During the

491 earlier V&V mission study, concerns were raised that the region between the upper  
492 atmosphere and the known rings of both Uranus and Neptune could contain a population of  
493 infalling ring particles dangerous to a spacecraft. This concern deserves further study, and  
494 it is incorporated into our final recommendations (Section 8). In Section A.4.5 of the IG  
495 Study we discuss several risk mitigation strategies, but for our mission designs we chose to  
496 target ring-plane crossing during orbit insertion to be in a region where the atmosphere is  
497 dense enough that there could not be a population of orbiting ring particles, but still thin  
498 enough to present no risk to the spacecraft and to allow us to maintain precise pointing  
499 control. We estimate this region to be about 1.08 to 1.1 planetary radii from Uranus, and  
500 slightly closer in at Neptune. Additional work is needed to confirm that our uncertain  
501 knowledge of upper atmospheric structure does not significantly change the target altitude  
502 range. Other approaches for mitigating the ring-crossing hazard include targeting periapse  
503 at a higher altitude (with a corresponding increase in fuel needed for orbit insertion and a  
504 degradation in some science measurements), or releasing a small “pathfinder” spacecraft  
505 on approach that tests the safety of the desired periapse altitude (it is possible for the  
506 pathfinder to arrive early enough to allow the main spacecraft to re-target its periapse).  
507 We find it encouraging that the Juno and Cassini spacecraft, flying close to Jupiter and  
508 Saturn, respectively, encountered far fewer ring particles than expected and found the  
509 targeted region safe to fly through (e.g. Ye et al. 2017). More work is needed to understand  
510 the implications of these findings for the Ice Giants.

511

512

513

514 **5.3 Radiation Considerations**

515 The radiation environment at Uranus and Neptune is relatively benign, as the ice giants do  
516 not have intense radiation fields. For the point designs studied to either planet, we  
517 estimate the total radiation dose to be under 30 krad (including a factor of 2 margin)  
518 behind 100 mil of Aluminum (0.254 mm). This dosage is not unusual for long-duration  
519 outer planet missions, with most of the exposure occurring in the inner solar system during  
520 gravity assists using Venus and the Earth. While our chosen trajectories have Jupiter flybys,  
521 the flyby distance is large enough (over 1 million km) that the Jupiter environment does  
522 not add a significant dose.

523

524 **5.4 Seasonal Considerations at Uranus**

525 Because of Uranus' extreme obliquity, when the Voyager spacecraft encountered the  
526 system in 1986, near southern solstice, only the southern halves of its satellites were  
527 illuminated for imaging, and only one satellite, innermost Miranda, was imaged in detail. A  
528 goal of the next mission to Uranus is to image the unseen hemispheres, get higher spatial  
529 resolution on all satellites, and explore the weather and magnetosphere of Uranus at a  
530 different season. This calls for an encounter at or before the next equinox in 2049 (each  
531 season lasting 21 years). We note that, given the approximately 10-year flight time  
532 required (Section 5.1), launching a mission near 2030 will satisfy these requirements,  
533 while delaying another decade will not. Each Neptune season lasts 41 years, so any mission  
534 launched in the next few decades will sample a different season than seen by Voyager, and  
535 will observe previously unilluminated regions of its major moon, Triton.

536

## 537 **5.5 Probe Entry and Relay**

538 There are several conflicting requirements which make delivering an atmospheric probe  
539 while placing a spacecraft into orbit challenging. From the point-of-view of the main  
540 spacecraft, it is desired to drop the probe off before the orbit insertion burn because  
541 (assuming you are using chemical propulsion for orbit insertion) the probe's mass requires  
542 burning a significant extra amount of fuel to carry it into orbit. From a probe design and  
543 science point-of-view, however, it is desirable to release it after entering orbit because this  
544 significantly reduces the demands on the probe's thermal protection system (due to much  
545 lower entry velocities), dropping it off from orbit increases the range of latitudes which can  
546 be targeted, and because it allows time for extensive orbiter remote sensing observations  
547 before targeting the entry point. There are also trade-offs related to getting the probe's  
548 data to Earth. At the distance of the ice giants, direct to Earth transmission of probe data is  
549 impractical, as this imposes antenna pointing requirements and transmitter power levels  
550 which a probe would find extremely difficult to maintain. An orbiter must therefore play  
551 the role of relay station. To maximize data volumes returned from the probe, and for the  
552 probe to send data back from a wide range of altitudes, it is desired that the orbiter point  
553 its main antenna at the probe for as long as possible, and for the probe relay to occur close  
554 to the planet. This can conflict with the spacecraft orientation needed for the orbit  
555 insertion burn, which is also desired to occur as close to the planet as possible. There are  
556 many similar trade-offs to be made which are discussed more fully in the full IG Study  
557 report (see IG Study sections 4.3, 4.5, 4.6, 4.7, and Appendix A, Section A.5). For flyby  
558 missions which drop a probe the situation is somewhat simpler because the relay  
559 spacecraft does not need to enter orbit. There are still significant science trade-offs to be

560 made, however, such as the time devoted to probe relay vs. time spent observing the rings  
561 and satellites.

562

563 For the mission point-designs discussed in Section 6, we made the following choices for  
564 orbiter missions incorporating a probe:

- 565 • Probe release and entry occur prior to orbit insertion
- 566 • The probe enters near-equatorial latitudes
- 567 • The orbiter relays probe data for approximately 1 hour
- 568 • The orbiter terminates probe relay approximately 1 hour prior to the orbit insertion  
569 burn, with the probe at a depth of approximately 10 bars

570 Note that the maximum depth from which probe data is returned is limited by the amount  
571 of time the main spacecraft allocates for data relay. The science team identified 10 bars as  
572 a good target depth because it is well below the altitudes needed for the highest-priority  
573 measurements of noble gases and isotopic ratios (for which pressures of 1 bar are more  
574 than sufficient), and it is deep enough to possibly provide useful information on some  
575 upper cloud layers and some condensable species (such as CH<sub>4</sub>, whose cloud is expected  
576 near 1 bar, and the H<sub>2</sub>S/NH<sub>3</sub> ratio above the water cloud, which is significant for models of  
577 the deep tropospheric chemistry).

578

## 579 **5.6 Satellite Encounters/Tours**

580 Our study did not map out a detailed satellite tour for Uranus orbiter missions. We did,  
581 however, confirm that spacecraft design, instrument capabilities, fuel, and trajectories were  
582 consistent with having at least two flybys of each of the major uranian satellites (Miranda,



583 Ariel, Umbriel, Titania, Oberon) at relative velocities less than 5 km/s. For a Neptune  
584 orbiter, we did develop a sample Triton tour (Section 4.5.4.3 of the IG Study) that includes  
585 32 flybys over a two-year period, typically at an altitude of 100 km, sampling all latitudes  
586 and a wide range of longitudes, with relative velocities under 4 km/s.

587

588 For flyby missions to the ice giants, we confirmed that data volume and observing time are  
589 available for at least one satellite flyby (presumably Triton at Neptune, with Miranda or  
590 Ariel being favored by the SDT at Uranus), and that trajectories exist which cross the orbit  
591 of satellite targets. We did not identify specific times and trajectories that place the  
592 spacecraft and satellite in proximity, nor look at relative velocities.

593

## 594 **5.7 Other Flyby Targets and Science During Cruise**

595 The science team noted that on the cruise to an ice giant and—for flyby missions—after the  
596 ice giant encounter, there is a wide range of valuable science that can be done. In addition  
597 to potential observations of astronomical, heliophysics, and inner solar system targets,  
598 flybys of asteroids, comets, Centaurs, and Kuiper-Belt Objects are possible. The SDT  
599 expects and encourages resources to be devoted to such opportunities. Our Study's charter,  
600 however, was to try and optimize the ice giant science to be done for a given cost, so we did  
601 not want to give any weight to these potential observations. For that reason, we did not  
602 explore any of these other opportunities, nor consider them when ranking the science  
603 value of mission architectures (discussed in the next section).

604

605

## 606 **6.0 Prioritized Mission Architectures and Cost**

### 607 **6.1 Architectures Considered and Prioritization**

608 Early in the mission study, the science team (SDT) and mission designers were brought  
609 together for a 3-day face-to-face meeting to brain-storm a wide range of feasible mission  
610 architectures. These include flyby missions, orbiters, multi-spacecraft options, multi-target  
611 options, probes, and landers. The SDT then considered its priority science goals (Section 3),  
612 and its model payloads (Section 4.3), and ranked each architecture/payload combination in  
613 terms of its science return. The process and results are discussed in detail in the full IG  
614 Study, but here and in Fig. 6 we summarize the conclusions.

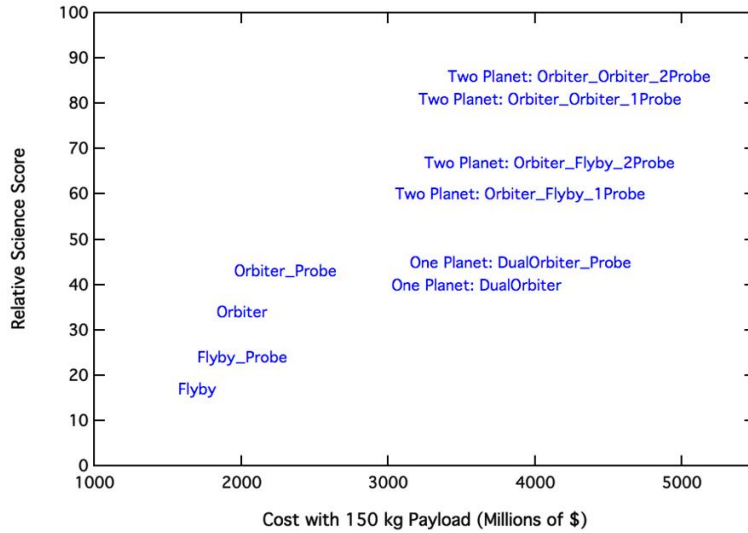
- 615 • For a given payload size, a flyby of a single ice giant has the lowest science return.  
616 Adding an atmospheric probe to the flyby provides a significant increase in science
- 617 • There is a larger jump in science value, however, in going from a flyby mission to an  
618 orbiter, even without a probe
- 619 • For an orbiter mission, there is a larger science return in adding a probe than in  
620 adding additional SmallSats or a second orbiter at the same planet
- 621 • The SDT finds that there is a large increase in science return when one moves from  
622 an orbiter at one planet to two-spacecraft, two-planet options which include at least  
623 one orbiter and one probe. (There are no trajectories in the next few decades that  
624 allow a single spacecraft to visit both Uranus and Neptune.)
- 625 • In general, moving to a higher-value architecture (flyby to orbiter to dual-planet  
626 mission) increases the science return more than moving to a larger science payload  
627 (50 to 90 to 150 kg)

- 628 • The SDT did not reach consensus on the relative value of two-spacecraft, two-planet  
629 missions that do not include at least one probe and one orbiter

630 The lack of consensus identified in the last bullet above hinged on differing opinions on the  
631 value of trading one of our highest priority goals (measuring noble gas abundances and  
632 isotopic ratios with a probe) for the opportunity to address secondary goals and do  
633 comparative planetology by visiting both ice giants. For example, we did not all agree on  
634 whether an orbiter with probe at one ice giant was scientifically more valuable than an  
635 orbiter at one ice giant with a flyby of the other, but neither having a probe. The team did  
636 agree, however, that a single orbiter is preferable to a two-flyby architecture. Recognizing  
637 that when an ice giant mission is ultimately chosen as a new start there will be more  
638 information on its science goals and the resources available, we felt it was not meaningful  
639 to fully explore two-planet, two-spacecraft architectures at this time. But an important  
640 conclusion for future missions is that, if one flies an orbiter and probe to one ice giant,  
641 there is significant science still to be done by sending any type of spacecraft to the other ice  
642 giant.

643  
644 Overall, the SDT determined that an ice giant orbiter with probe is the right baseline  
645 mission to target for the next ice giant flagship mission. The science payload on the orbiter  
646 should be 150 kg to address all 12 priority science goals (Section 3). We find a 50 kg  
647 payload is the lower limit to warrant a Flagship-level investment. Such a mission has the  
648 highest science return for an approximately \$2B cost (costs are discussed in the next  
649 section). It also lies on the left (least expensive side) of a “plateau” in Fig. 6. This means  
650 there are more expensive architectures that do not do significantly more science. To

651 significantly increase the science return above that achieved by an orbiter and probe, one  
 652 must go to two-planet, two-spacecraft architectures, with correspondingly higher costs.  
 653



654  
 655 **Fig. 6** Relative science value versus approximate cost for a subset of missions considered. Costs should be  
 656 read from the center of the mission label (e.g. the “i” in Orbiter), but note the factors discussed in the text that  
 657 can alter these numbers. For comparison purposes, all spacecraft plotted have a 150 kg science payload.  
 658 Smaller payloads will reduce the science ranking, but will also reduce single-spacecraft costs by up to \$600M  
 659 and dual-spacecraft costs by up to \$1100M. Single-planet missions are costed for Uranus; Neptune costs will  
 660 be about \$300M higher. Architectures are divided into three groups by their science value: flybys, single-  
 661 planet orbiters, and dual-planet missions. Note that the recommended mission, an orbiter with probe,  
 662 occupies a “plateau” in science value vs. cost, and is the least expensive option that achieves that level of  
 663 science. See the IG Study for additional discussion. This figure is an updated version of Fig. 3-17 of the IG  
 664 Study

665  
 666 **6.2 Mission Costs**

667 The full IG Study report should be consulted for a detailed discussion of costs. The cost  
 668 information contained in this document is of a budgetary and planning nature and is

669 intended for informational purposes only. It does not constitute a commitment on the part  
670 of JPL and/or Caltech.

671

672 During the study, we first developed rough cost estimates for a wide range of alternative  
673 mission architectures. We then selected 6 mission architectures for detailed point designs.  
674 The 6 selected were chosen to allow us to interpolate these refined cost estimates to the  
675 maximum number of architectures. It is important to recognize that the point designs do  
676 not include the mission we ultimately recommend (a Uranus orbiter with probe carrying a  
677 150 kg orbiter science payload). A subset of the 6 point designs costed at JPL were  
678 independently assessed by the Aerospace Corporation with close agreement.

679

680 The IG Study had these ground-rules related to cost:

- 681 • Cost is in FY2015 dollars
- 682 • The cost target for the Ice Giant Flagship is \$2B, but missions should be considered  
683 across a range of price points
- 684 • Assume a Class B mission (per NASA Procedural Requirements [NPR] 8705.4)  
685 [NASA has 4 categories of space missions, A through D, which are used to  
686 characterize the national importance, the cost, and the complexity of missions.  
687 Class-A missions are similar to the James Webb Space Telescope, and have stringent  
688 redundancy and risk-mitigation requirements which impose additional costs. Class-  
689 B missions are still high-priority, but have less stringent requirements. For  
690 comparison, the Mars Exploration Rovers were Class-B. Mission Class is formally  
691 selected near the time a mission is confirmed]

- 692 • Exclude launch vehicle from cost
- 693 • Include cost of Radioisotope Power System (RPS) (cost according to New Frontiers
- 694 4 guidelines as stated in the draft Announcement of Opportunity)
- 695 • Include cost of National Environmental Policy Act / launch approval process
- 696 • Include operations (full life cycle mission cost)
- 697 • Include Deep Space Network (DSN) costs as separate line item
- 698 • Include minimum 30% reserves (A–D), 15% (E–F)
- 699 – Reserves excluded on RPS and LV
- 700 – Provide risk-based rationale for reserves
- 701 • Exclude cost of technology development from the mission cost estimate
- 702 • Assume no foreign contributions to reduce costs but identify areas where such
- 703 contributions would be beneficial to NASA in terms of cost and interfaces

704

705 Some key cost trade-offs to consider are:

- 706 • A Neptune mission costs about \$300M more than a similar Uranus mission, driven
- 707 primarily by the cost of the SEP stage needed for Neptune
- 708 • The cost of adding an atmospheric probe to a mission is also about \$300 M
- 709 • The total mission cost of increasing an orbiter’s payload from 50 to 150 kg is
- 710 approximately \$600M
- 711 • A Uranus orbiter with a 50 kg science payload and an atmospheric probe fits within
- 712 the \$2B cost target by both JPL’s and Aerospace’s costing methods. A similar
- 713 Neptune mission fits the cost target by JPL’s estimate, but not by Aerospace’s. The

714 SDT considers such a mission a science floor, but recommends a larger orbiter  
715 payload

- 716 • A Uranus orbiter with a 150 kg science payload and an atmospheric probe is the  
717 SDT's preferred mission, and it is estimated to cost between \$2.3B (JPL) and \$2.6B  
718 (Aerospace). A similar Neptune mission would cost between \$2.6 and \$2.9B

719

720 The IG Study finds the following broad cost categories for the primary architectures  
721 considered (quoted ranges account for varying the payload size from 50 to 150 kg, and  
722 utilize JPL cost estimates. Aerospace cost estimates are 10-15% higher).

- 723 • A Uranus flyby mission with a probe would cost \$1.5 to \$2B
- 724 • A Uranus orbiter with a probe would cost between \$1.7B and \$2.3B
- 725 • A two-spacecraft, two-planet mission incorporating orbiters at both planets and a  
726 probe at one would cost \$2.5 – \$3.6B (assuming almost identical spacecraft built  
727 approximately the same time to realize savings in non-recurring engineering costs)

728 These results are reflected in Fig. 6, allowing a broad comparison of science value as a  
729 function of total mission cost.

730

731 Combining the science value, mission architectures, and cost estimates presented in  
732 Sections 3 through 6, the SDT developed a set of recommendations which are presented in  
733 Section 8 of this paper.

734

735

736

## 737 **7.0 Recent Scientific, Technological, and Programmatic Advances**

738 Before presenting the IG Study recommendations, we review some scientific and  
739 technological advances, as well as programmatic factors, that arose since the 2011 release  
740 of V&V and the 2017 release of the IG Study. These developments reaffirm the importance  
741 of an ice giant mission and have sharpened, but not fundamentally altered, the  
742 recommendations of both documents.

743

744 Four advances drive the IG Study to raise the priority of studying the internal structure of  
745 Uranus and Neptune above what was given in V&V. V&V listed this as a secondary  
746 objective (and therefore a descope option) due to concerns about the safety of the close-in  
747 orbits needed for high resolution gravity measurements. The first advance is mission  
748 design work performed as part of the IG Study which identified trajectories and mission  
749 architectures allowing safe, close orbits (Section 5.2). A second *potentially* mitigating  
750 advance is to use planetary oscillations to study internal structure, which does not require  
751 close orbits (Section 4.2). This technique does require development and validation,  
752 however. The third relevant advance, which occurred after the IG Study, is the knowledge  
753 gained by the Juno and Cassini missions during their close-in orbits of Jupiter and Saturn,  
754 respectively. Both orbiters found the region interior to the known rings to be relatively  
755 clear. In Saturn's case, surprisingly so (Ye et al. 2017). These factors together support the  
756 idea that interior structure is an achievable goal and should not be downgraded out of  
757 feasibility concerns at these early stages of mission planning. The fourth and final factor  
758 raising the priority of studying interior structure is continued modeling work showing the



759 available data require unexpected interior structures, and suggesting Uranus and  
760 Neptune’s interiors might be quite different (e.g. Nettelmann et al. 2013, 2016).

761

762 Several advances also call for the bulk abundance of the planet, particularly noble gases  
763 and isotopic ratios in the atmosphere, to be made high priority. As with interior structure,  
764 V&V felt this objective needed to be a descope option because it requires a probe and—in  
765 the limited time available to them—they did not find a fully consistent probe design and  
766 mission architecture. The IG Study, however, found architectures capable of carrying a  
767 scientifically capable probe and providing data relay during descent. We also note new  
768 predictions for the formation of ice giants (e.g. Lee and Chiang 2016; Frelikh and Murray-  
769 Clay 2017) and how they might be reflected in atmospheric composition (Mousis et al.  
770 2018 and reference therein), reinforcing the importance of noble gas and isotopic  
771 measurements (Fig. 2).

772

773 The Juno mission at Jupiter also alters our thinking of how to study giant planet  
774 atmospheres. In particular, its microwave sounding instrument demonstrates both the  
775 technique’s ability to study the deep troposphere and how little we understand the  
776 circulation, cloud structure, and composition at depth (Bolton et al. 2017). It is likely that  
777 any future ice giant mission will identify a microwave sounder as a key instrument for  
778 probing the atmosphere.

779

780 Finally, we note that while V&V and the IG Study call for international participation, the  
781 details are left to future programmatic decisions and inter-agency discussions. In late 2018,

782 ESA performed its own study of how it could best contribute to a NASA-led ice giant  
783 mission. That report has recently been made public (available at <http://sci.esa.int/future->  
784 [missions-department/61306-cdf-study-report-ice-giants/](http://sci.esa.int/future-missions-department/61306-cdf-study-report-ice-giants/)). It is therefore timely to  
785 execute a follow-on mission study as called for by both the IG Study and the V&V Mid-Term  
786 Review. Such a study could take advantage of improved knowledge of the resources and  
787 objectives NASA and ESA intend to assign to this mission, and explore in more detail  
788 technologies that, while not needed to enable an ice giant mission, are enhancing of such a  
789 mission. These include advanced radioisotope power systems, deep-space liquid  
790 propulsion, aerocapture, and multi-spacecraft options utilizing the SLS launch vehicle. For  
791 maximum effect, this follow-on study should be completed early enough to serve as  
792 guidance both for the last half of the V&V period, should funds allow NASA's initiation of an  
793 ice giant mission, and as input to the next Planetary Science Decadal Survey, scheduled to  
794 initiate in late 2019.

795

796

## 797 **8.0 Summary and Recommendations**

798 We reaffirm the scientific importance and high priority of implementing an ice giant  
799 mission, as recommended in the *Vision and Voyages* report of NASA's most recent Planetary  
800 Science Decadal Survey (National Research Council 2011). Advances since the completion  
801 of that report have driven a re-prioritization of science objectives, but the need for and  
802 basic architecture of a mission remains unchanged. Launching an ice giant mission near  
803 2030 maximizes the possible payload to Uranus or Neptune by utilizing a Jupiter gravity  
804 assist. Uranus launches prior to 2029 may utilize a Saturn gravity assist should that be

805 deemed programmatically preferable. We note that launches to Uranus after the late-  
806 2030's will not be able to image the never-before seen Northern Hemispheres of the  
807 satellites, due to their being in winter darkness (as was the case during the 1986 Voyager 2  
808 flyby).

809

810 To ensure the most productive mission is flown, we recommend the following:

- 811 • An orbiter with probe be flown to one of the ice giants. Based on its cost-conscious  
812 ground rules, the IG Study specified Uranus as the target. Given that the Uranus and  
813 Neptune Systems are equally valuable as science targets, evolving programmatic  
814 considerations can favor Neptune
- 815 • The orbiter carry a payload of at least 50 kg, with 150 kg being preferred
- 816 • The probe carry, at minimum, a mass spectrometer and atmospheric pressure,  
817 temperature, and density sensors
- 818 • The development of eMMRTGs (an improved radioisotope power source) and  
819 HEEET (thermal protection material for an atmospheric probe) be completed as  
820 planned
- 821 • Two-planet, two-spacecraft mission options be explored further
- 822 • Investment in ground-based research, both theoretical and observational, to better  
823 constrain the ring-crossing hazard and conditions in the upper atmosphere (both of  
824 which are important for optimizing the orbit insertion trajectory)
- 825 • Mature the theory and techniques for studying giant planet oscillations
- 826 • International collaborations be leveraged to maximize the science return while  
827 minimizing the cost to each partner

- 828       • A joint NASA/ESA study be executed that uses refined ground-rules to better match  
829           the programmatic requirements each agency expects for a collaborative mission

830  
831 The IG study validated that NASA could implement a mission to the ice giants for under \$2B  
832 (FY15) that would achieve a worthy set of science objectives. Mission architectures and  
833 payloads exist to achieve all priority science objectives for ~\$2.5B. A partnership with  
834 another space agency has the potential to significantly increase the science return while  
835 limiting the cost to each partner. Given the development time scale of outer solar system  
836 missions, the time of the best launch opportunities, and the desire to arrive at the optimal  
837 season, now is the time to begin formulating the next mission to the ice giants.

838

839

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842

843

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## REFERENCES

- Atreya, S.K., Crida, A., Guillot, T., Lunine, J.I., Madhusudhan, N., Mousis, M.: The Origin and Evolution of Saturn, with Exoplanet Perspective. In Baines, K., Flasar, M., Krupp, N., Stallard, T. (eds.) *Saturn in the 21st Century*. Cambridge University Press. In Press [can be downloaded in the interim from <http://arxiv.org/abs/1606.04510>] (2018)
- Banfield, D., Gierasch, P., Dissly, R.: Planetary descent probes: polarization nephelometer and hydrogen ortho\_para instruments. *Aerospace*, 2005 IEEE Conference, pp. 1–7 (2005)
- Bolton, S.J, and 42 co-authors: Jupiter’s interior and deep atmosphere: The initial pole-to-pole passes with the Juno spacecraft. *Science* **356**, 821-825 (2017).  
<https://doi.org/10.1126/science.aal2108>
- Borucki, W.J. and 66 co-authors: Characteristics of planetary candidates observed by Kepler, II: Analysis of the first four months of data. *Ap. J.* **736**, 19 (2011)
- Coradini, A., Magni, G., Turrini, D.: From Gas to Satellitesimals: Disk Formation and Evolution. *Space Science Reviews* **153**, 411-429 (2010)
- Freikh, R., Murray-Clay, R.A.: The formation of Uranus and Neptune: Fine tuning in core accretion. *Astron. Jour.* **154**, 98-106 (2017). <https://doi.org/10.3847/1538-3881/aa81c7>
- Fuller, J.: Saturn ring seismology: Evidence for stable stratification in the deep interior of Saturn. *Icarus* **242**, 283-296 (2014). <https://doi.org/10.1016/j.icarus.2014.08.006>
- Gaulme, P., Schmider, F.-X., Gay, J., Guillot, T., Jacob, C.: Detection of Jovian seismic waves: a new probe of its interior structure. *A&A* **531**, A104-A110 (2011).  
<https://doi.org/10.1051/0004-6361/201116903>
- Gaulme P., Mosser B., Schmider F.-X., Guillot T.: Seismology of Giant Planets. In Tong, V., Garcia, R. (eds.) *Extraterrestrial Seismology*. Cambridge University Press (2015)
- Green, J.: Planetary Science Division status report. A presentation to the 24 August 2015 OPAG meeting. Available at  
<http://www.lpi.usra.edu/opag/meetings/aug2015/presentations/> (2015)
- Guillot, T.: The interiors of giant planets: models and outstanding questions. *Ann. Rev. Earth Planet. Sci.* **33**, 493–530 (2005)
- Häsinger, G.: Cosmic Vision – Exploration of the Universe. Presentation at the 2018 EGU meeting in Vienna. *Geophysical Research Abstracts* **20**, EGU2018-19864 (2018)
- Hedman, M. M., Nicholson, P.D.: Kronoseismology: Using density waves in Saturn’s C ring to probe the planet’s interior. *Astron. J.* **146**, 12–27 (2013)

- Hedman, M. M., Nicholson, P.D.: More Kronoseismology with Saturn's rings. *MNRAS* **444**, 1369-1388 (2014)
- Hendrix, A.R., and 27 co-authors: The NASA Roadmap to Ocean Worlds. *Astrobiology* **19**, 1-27 (2018). <https://doi.org/10.1089/ast.2018.1955>
- Hofstadter, M.D., Simon, A.A., Reh, K., Elliott, J., and the ice giant study team: *Ice Giants Pre-Decadal Survey Mission Study Report*. JPL Document number 100520. Available at [http://www.jpi.usra.edu/icegiants/mission\\_study/](http://www.jpi.usra.edu/icegiants/mission_study/) (2017)
- Lee, E.J. and Chiang, E.: Breeding super-Earths and birthing super-puffs in transitional disks. *Astrophys. J.* **817**, 90-100 (2016)
- Mankovich, C., Marley, M.S., Fortney, J.J., Movshovitz, N.: Cassini ring seismology as a probe of Saturn's interior I: Rigid rotation. Submitted to *Astrophys. J.* arXiv:1805.10286 (2018)
- Morbidelli, A., Tsiganis, K., Batygin, K., Crida, A., Gomes, R.: Explaining why the uranian satellites have equatorial prograde orbits despite the large planetary obliquity. *Icarus* **219**, 737-740 (2012). <https://doi.org/10.1016/j.icarus.2012.03.025>
- Mosqueira I, Estrada P., Turrini D.: Planetesimals and Satellitesimals: Formation of the Satellite Systems. *Space Science Reviews* **153**, 431-446 (2010)
- Mousis, O., and 55 co-authors: Scientific rationale for Uranus and Neptune in situ explorations. *Plan. Sp. Sci.* **155**, 12-40 (2018). <https://doi.org/10.1016/j.pss.2017.10.005>
- National Academies of Sciences, Engineering, and Medicine: *Visions into Voyages for Planetary Sciences in the Decade 2013-2022: A Midterm Review*. Washington, DC: The National Academies Press (2018). <https://doi.org/10.17226/25186>
- National Research Council: *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, DC: The National Academies Press (2011). <https://doi.org/10.17226/13117>.
- Nettelmann, N., Helled, R., Fortney, J.J., and Redmer, R.: New indication for a dichotomy in the interior structure of Uranus and Neptune from the application of modified shape and rotation data. *Plan. Sp. Sci.* **77**, 143-151 (2013)
- Nettelmann, N., Wang, K., Fortney, J. J., Hamel, S., Yellamilli, S., Bethkenhagen, M., Redmer, R.: Uranus evolution models with simple thermal boundary layers. *Icarus* **275**, 107-116 (2016)
- Rowe, J.F., Gaulme, P., Lissauer, J.J., Marley, M.S., Simon, A.A., Hammel, H.B., Aguirre, V.S., Barclay, T., Benomar, O., Boumier, P., Caldwell, D. A., Casewell, S.L., Chaplin, W.J., Colon, K.D., Corsaro, E., Davies, G.R., Fortney, J.J., Garcia, R.A., Gizis, J.E., Haas, M.R., Mosser, B., Schmider,

F.-X.: Time-series analysis of broadband photometry of Neptune from K2. *Astron. Jour.* **153**, 149-160 (2017)

Schubert, G., Soderlund, K. M.: Planetary magnetic fields: Observations and models. *Phys. Earth Planet. Int.* **187**(3), 92-108 (2011)

Simon, A., Stern, A., Hofstadter, M.: *Outer Solar System Exploration: A Compelling and Unified Dual Mission Decadal Strategy*. White Paper available at <https://arxiv.org/abs/1807.08769> (2018)

Soderblom, L.A., Kieffer, S.W., Becker, T.L., Brown, R.H., Cook, A.F. 2<sup>nd</sup>, Hansen, C.J., Johnson, T.V., Kirk, R.L., Shoemaker, E.M.: Triton's geyser-like plumes: Discovery and basic characterization. *Science* **250**(4979), 410-415.

Turrini, D., Politi, R., Peron, R., Grassi, D., Plainaki, C., Barbieri, M., Lucchesi, D.M., Magni, G., Altieri, F., Cottini, V., Gorius, N., Gaulme, P., Schmider, F.-X., Adriani, A., Piccioni, G.: The comparative exploration of the ice giant planets with twin spacecraft: Unveiling the history of our Solar System. *Planetary and Space Science* **104**, 93-107 (2014)

Turtle, E.P., McEwen, A.S., Collins, G.C., Fletcher, L., Hansen, C.J., Hayes, A.G., Hurford, T.A., Kirk, R.L., Barr Mlinar, A.C., Nimmo, F., Patterson, G.W., Quick, L.C., Soderblom, J.M., Thomas, N., Ernst, C.M.: The Europa Imaging System (EIS). LPSC conference abstract #1626 (2016)

Ye, S., Kurth, W.S., Hospodarsky, G.B., Persoon, A.M., Gurnett, D.A., Morooka, M.W., Wahlund, J.E., Seiss, M., Srama, R.: Dust observation by the radio and plasma wave instrument during Cassini's Grand Finale. AGU Fall Meeting, abstract #P23B-2725 (2017)