NEW FRONTIERS-CLASS MISSIONS TO THE ICE GIANTS. C. M. Elder[1], A. M. Bramson[2], L. W. Blum[3], H. T. Chilton[4], A. Chopra[5], C. Chu[6], A. Das[7], A. Davis[8], A. Delgado[9], J. Fulton[8], L. Jozwiak[10], A. Khayat[3], M. E. Landis[2], J. L. Molaro[1], M. Slipski[8], S. Valencia[11], J. Watkins[12], C. L. Young[4], C. J. Budney[1], K. L. Mitchell[1], [1]Jet Propulsion Laboratory, California Institute of Technology, [2]University of Arizona, [3]NASA/Goddard Space Flight Center, [4]Georgia Institute of Technology, [5]University of Washington, [6]University of Alaska Fairbanks, [7]Purdue University, [8]University of Colorado at Boulder, [9]University of Texas at El Paso, [10]Johns Hopkins University/Applied Physics Laboratory, [11]Washington University in St. Louis, [12]California Institute of Technology

Introduction: Ice giants are the least understood class of planets in our solar system. The little data available for the ice giants come solely from ground-based observations and the solitary fly-by of the Voyager 2 spacecraft. Unlike gas giants, which are composed primarily of hydrogen and helium, ice giants are thought to be composed primarily of ices and rocks [1]. However, the phase, distribution, and exact composition of these ices and rocks are unknown [1]. The magnetic fields of Uranus and Neptune differ substantially from Jupiter and Saturn with their strong quadrupole moments and significant tilt relative to their spin axes [2]. Furthermore, Uranus and Neptune differ from each other in puzzling ways; for example, Uranus has an extremely high obliquity (98°) [3] and a low heat flux (close to negligible) compared to the similarly sized Neptune [3]. Neptune has just one large satellite, Triton, which is thought to be a geologically active captured Kuiper belt object [4]. Only half of Triton and half of each Uranian satellite were imaged by Voyager 2.

A return to the ice giants is perhaps more important now than ever before. The Kepler mission has found that ice giant sized planets are the most commonly observed type of planet [5]. Observational biases are expected to underreport terrestrial planets; nevertheless, it is striking that ice giants are more common than gas giants in the Kepler data set. Kepler has also discovered many super-Earths which are smaller than ice giants but larger than Earth [5]. Observations show that planets larger than 1.6 $R_\oplus$ are too low density to be comprised of iron and silicates alone [6], so perhaps the ice giants in our solar system are the closest analog for these newly discovered smaller planets.

Both the discovery of over a thousand extrasolar ice giants and the drive to explore our local solar system necessitate another mission to Uranus and/or Neptune in the near future. If Uranus is selected, such a mission should be timed to arrive during a different season than Voyager 2 to maximize science return. Uranus' high obliquity results in extreme seasonal changes which affect several aspects of the Uranus system including: large variations in the intensity of atmospheric dynamics [7]; half of each satellite in shadow during solstices; and changes in the interactions between the magnetosphere and the solar wind as the angle between them changes. Voyager 2 flew past Uranus in 1986, one year after southern solstice. Uranus' next southern solstice will occur in 2070. To study the effect of seasons on the Uranian system, a mission should arrive at Uranus significantly before 2070, preferably close to equinox in 2049. Arriving later than 2049 will mean some portions of the satellites in shadow when Voyager 2 arrived will once again move into shadow until after the next southern solstice in 2070.

OCEANUS: The 2011 decadal survey [8] suggests that the third highest priority Flagship mission in this decade should be a mission to an ice giant. We agree that while a Flagship mission is preferable, a New Frontiers-class mission could supplement such a mission or achieve a subset of the science objectives in the event that a Flagship-class mission is not available. We will discuss the New Frontiers-class mission concept OCEANUS: Origins and Composition of the Exoplanet Analog Uranus System. OCEANUS is the result of the 2016 Planetary Science Summer School (PSSS) hosted by the Jet Propulsion Laboratory (JPL), California Institute of Technology, which aims to offer participants an authentic but primarily educational experience of the mission proposal process [9]. This exercise resulted in a mission concept for a Uranus orbiter with a limited payload that would still be able to achieve several of the highest priority Decadal Survey goals for Uranus.

OCEANUS would be an orbiter, which would enable a detailed study of the structure of the planet's magnetosphere and interior that is not possible with a flyby mission. The instrument suite would include a magnetometer for measurements across the bow shock and magnetopause and of temporal variations in the magnetosphere. Detailed study of the structure of the magnetic field would also constrain models for dynamo generation. OCEANUS would also use the on-board communications antenna for radio science enabling measurements of Uranus' global gravity field to degree and order six, constraining models for the interior structure of Uranus. Our mission concept would also employ an atmospheric probe for in situ measurements of noble gas abundances and isotopic ratios as well as temperature and pressure profiles. This simple instrument suite would enable OCEANUS to achieve four of the decadal survey's science objectives for Uranus (including one of the two highest priority objectives).

The parameters for the 2016 PSSS Uranus orbiter mission included the option to include a "donated" probe. We decided to include this probe despite the additional mass and risk, because it would enable the determination of noble gas abundances and isotopic ratios. These were deemed sufficiently important, because they could reveal where in the solar system Uranus formed and constrain solar system formation models, which have not reached a consensus on how far planets migrated since their formation [10].

Future New Frontiers-Class Missions to Ice Giants: In one week at JPL, the graduate students and postdocs of the 2016 PSSS were unable to develop a mission concept for a Uranus orbiter within the cost constraints of a New Frontiers-class mission as suggested by the decadal survey; this was due to the high cost of reaching Uranus within the next few decades and powering the spacecraft while in orbit. With more time and resources, it is possible that one could develop a viable mission concept to Uranus or Neptune within a New Frontiers budget, but to achieve a competitive pool of multiple New Frontiers proposals for ice giant missions, change is necessary. OCEANUS identified three key areas where advancement could lead to improved mission concepts: power systems, propulsion capabilities, and cost-sharing collaborations.

Solar power is now sufficiently efficient to power some missions to distances as far as the Saturnian system [e.g. 11], depending on their operational needs, but missions to the far-outer solar system continue to face power and cost challenges more significant than missions to the inner and near-outer solar system. For example, OCEANUS would spend over 20% of its budget on Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs). These challenges could be ameliorated by increased investment by NASA in heat source plutonium production by the Department of Energy, and efforts to lower the cost and/or increase the efficiency of MMRTGs, such as the potential enhanced MMRTGs. These developments would also aid larger mission concepts for the inner and near-outer solar system, which may need more power than solar power options can provide.

The current orbital configuration and extreme distance between the ice giants and Earth present additional major hurdles to New Frontiers-class missions to Uranus or Neptune. In particular, opportunities for a Jupiter gravity assist to Uranus or Neptune are rare in the next two decades. OCEANUS overcame this challenge through two Venus gravity assists and an Earth gravity assist along with the use of Solar-Electric Propulsion (SEP) within 1.5 AU. However, the SEP stage would be more than 10% of the total mission cost. Efforts to continue development of SEP technology, potentially lowering the cost, could enable missions to the far-outer solar system without requiring a Jupiter gravity assist. Alternatively, more powerful launch vehicles could also facilitate travel to the outer solar system, but a shorter cruise time would result in a faster approach velocity making orbit insertion more challenging. Continued ground-based observations to characterize the atmospheres of Uranus and Neptune could help to lower the risk of orbit insertions utilizing aerobraking.

Finally, the notable absence of a dedicated mission to an ice giant is felt not just by NASA, but also by ESA [e.g. 12]. The high cost of a mission to the far outer solar system could be shared between NASA and ESA even on a New Frontiers budget. For example, our OCEANUS concept included a donated probe from an unspecified partner for the purposes of the educational exercise, but a mission with a small payload and donated probe could in fact be a model for a collaboration between NASA and ESA, or another space agency.

Conclusion: Missions to Uranus or Neptune are still very difficult to achieve on a New Frontiers budget, although OCEANUS showed that, with a highly-focused mission, current technologies can come close. Continued efforts to develop technologies enabling travel to the outer solar system with the goal of lowering cost could enable robust New Frontiers-class missions to Uranus and Neptune before 2050. Although an exploration-based Flagship-class mission analogous to Galileo or Cassini should be a priority, a more focused New Frontiers-class mission could achieve a significant fraction of the science objectives highlighted by the decadal survey, or could supplement a Flagship mission through a yet-to-be-determined creative approach galvanized by the competitive nature of the New Frontiers program.

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