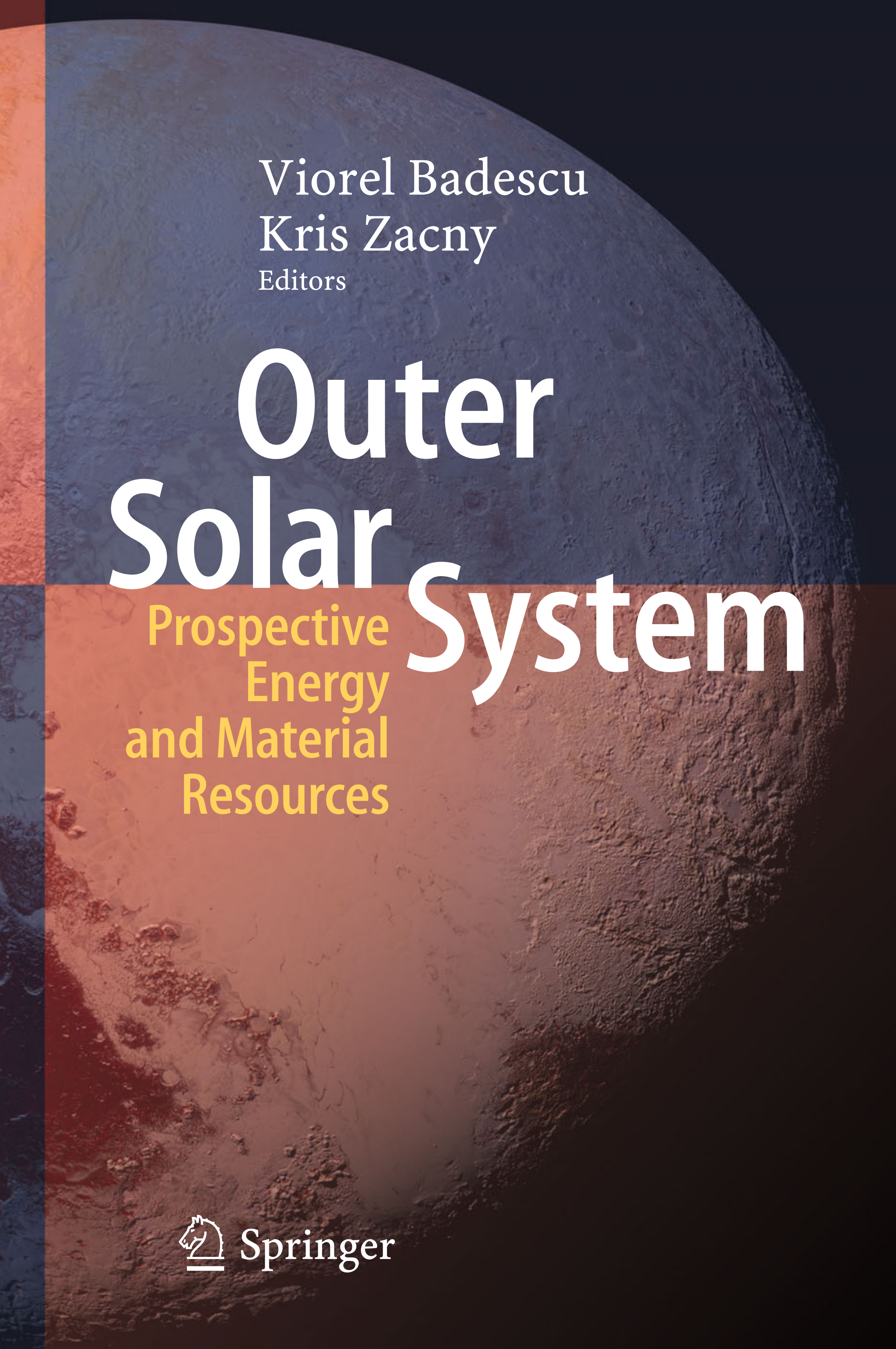

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Kris Zacny
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# Outer Solar System

## Prospective Energy and Material Resources

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*Editors*
Viorel Badescu
Candida Oancea Institute
Polytechnic University of Bucharest
Bucharest
Romania

Kris Zacny
Honeybee Robotics Spacecraft
Mechanisms Corporation
Pasadena, CA
USA

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*The high minded man must care more*
*for the truth than for what people think.*
Aristotle (384–322 BCE)

# Foreword

The frontier is hard and unknown, dangerous, and full of risk. The frontier is not a trail blazed with signposts that guide us to the summit; it is a horizon beyond which we cannot see. The discoveries that beckon beyond the frontier compel us to explore but exploration is never easy. These statements are as true today as they have been throughout the history of human civilization. And throughout history, technological innovations have propelled us forward, making exploration possible. From stone tools and fire, which enabled a migratory hominid population in Africa, to Fridtjof Nansen's rugged and reinforced hull on the Fram, our human capability to make new discoveries has always been tethered to our ability to innovate for new environments. Today, some of the greatest discoveries yet to be made may lie in the outer reaches of our solar system, a frontier filled with challenges that must be overcome.

The discovery that motivates my interest, and the interest of many of my colleagues, is the question of whether or not life exists beyond Earth. Has a second origin of life occurred in our solar system? Does biology work beyond Earth? The answer to these questions could lie beneath the icy shells of moons of the outer solar system—ocean worlds that harbor vast quantities of liquid water and in which life could exist today. These ocean worlds, distant from the warmth of the sun, maintain their liquid water oceans largely through the tidal energy dissipation that occurs as they orbit their massive parent planets (e.g., Jupiter or Saturn).

Europa and Enceladus stand out as premier targets in this search, as their liquid water oceans may be in contact with rocky seafloors that could help build and power life. Titan too is a compelling target, both for its liquid water ocean and for the prospect of "weird life" within the hydrocarbon lakes and seas that populate its icy surface. Along with these three moons, worlds like Pluto, Ganymede, Callisto, and Triton all provide intriguing clues to subsurface liquid environments—perhaps water mixed with ammonia, salts, and other antifreeze components. As further enticement for exploration of the outer solar system, the ice giant Uranus presents numerous puzzles for planet formation and hosts several moons for which we only have a few tantalizing images. Might these moons also harbor oceans? We just do not know…yet.

All of these worlds present severe challenges for spacecraft, robotics systems, and instrumentation. In some cases, the type of exploration—e.g., melting through the ice shells of ocean worlds—is something completely new in the realm of solar system exploration. When it comes to planetary exploration, our mantra has long been “flyby, orbit, land”. In the decades to come, these distant oceans will push us to add “melt and swim” to this list. These are new frontiers and they will push us to advance exploration on Earth as we build the bridge to exploring worlds in the outer solar system.

Technological innovation, such as that presented throughout the chapters in this collected volume, pulls science forward and makes the great discoveries possible. The outer solar system requires us to think in new ways about spacecraft power and propulsion, as the missions must operate for long periods of time at far distances from the sun. The surface properties of many of the moons we will explore are largely unknown, requiring creative and robust solutions that are adaptable to a wide variety of possible terrains. And the exploration of oceans deep within these moons will require autonomy embedded within every aspect of the robotic system, as no engineer is going to be able to “joy stick” an underwater vehicle to safety from a billion kilometers away. Coupled with these challenges is the opportunity to let Mother Nature help us where she can—winds on Titan and within the atmospheres of ice giant planets could serve to power robotic vehicles; cracks in the ice shells of ocean worlds could serve as conduits to the oceans within; and magnetic fields and radiation belts could help drive power systems that help sustain spacecraft. The innovation and creativity need to push this grand frontier in our solar system is well-captured by the many ideas and concepts presented here. It is my hope—or rather prediction—that with the advances that have been made to date, and with many of the advances described in this book, humanity could, within the next 20 years, discover whether or not life exists beyond Earth.

Pasadena, CA, USA
October 2017

Dr. Kevin Peter Hand
NASA Jet Propulsion Laboratory
California Institute of Technology

# Preface

This is the fifth volume of a Springer book series making an inventory of the material and energy resources of our solar system. The first four books, referring to resources existent on Mars, Moon, asteroids, and inner solar system, were published in 2009, 2012, 2013, and 2015, respectively.

This book presents a present-day perspective on the energy and material resources in the outer solar system for prospective human use. One investigates the advantages and limitations of various systems thought-out for future mankind utilization. The book collects together recent proposals and innovative options and solutions.

The book is structured along logical lines of progressive thought and may be conceptually divided into five parts.

The first part deals with *properties of planetary regolith* and contains two chapters. After the introductory Chap. 1, showing what we presently know about the surface composition of Pluto, Chap. 2 refers to the physical properties of icy materials.

The second part of the book deals with *resource, mining, and subsurface access* and contains five chapters. Chapter 3 enters the details of atmospheric mining in the outer solar system; Chap. 4 describes laser-powered cryobots and other methods for penetrating deep ice on ocean worlds under the framework of project Valkyrie. Chapter 5 describes the Europa Drum Sampler, Chap. 6 presents drilling mechanisms using piezoelectric actuators developed at Jet Propulsion Laboratories, while Chap. 7 focuses on ultrasonically assisted penetration of granular and cemented materials.

The third part of the book, dealing with the *missions and mission concepts,* consists of eight chapters. Chapter 8 deals with the flight in the outer solar system and interstellar travel, Chap. 9 describes the Triton Hopper, and Chap. 10 treats sub-ice autonomous underwater vehicle architectures for ocean world exploration and life search. The Titan submarine is presented in Chap. 11, while Chaps. 12 and 13 deal with two novel concepts: the WindBots and Enceladus Vent Explorer, respectively. Chapter 14 focuses on the exploration and exploitation of Kuiper Belt Object resources in the future, and Chap. 15 describes a sample return mission by an Unmanned Interplanetary Spaceship UNIS.

The fourth part of the book, referring to *enabling technologies,* consists of four chapters. Chapter 16 describes spacecraft power systems for the far reaches of the solar system, while Chap. 17 presents hybrid nuclear spacecraft for the outer planets. Chapter 18 refers to the exploration of the outer solar system, reviewing missions and their power systems, and Chap. 19 deals with multi-rendezvous solar electric propulsion mission opportunities to Jupiter Trojans.

The fifth part of the book, dealing with *business cases for resource utilization,* consists of two chapters. Chapter 20 deals with business in the outer solar system, while Chap. 21 focuses on several sources of energy.

Most of the chapters are interdisciplinary by nature, and some of them might be equally well included into more than one part. More details about the 21 chapters of the book are given below.

Chapter 1, by Cathy Olkin and Will Grundy, states that during the summer of 2015, the New Horizons spacecraft flew past Pluto at a distance of $\sim$12,500 km after a journey of more than 3 billion miles. This encounter transformed our understanding of Pluto's geology, surface composition, and atmosphere. Near-infrared spectroscopic imaging allows us to identify compositional units across Pluto's surface. There is a latitudinal pattern across Pluto with dark red complex organic macromolecules dominating the equatorial terrain and methane ice at Pluto's North Pole. The prominent bright area that is the western lobe of Pluto's "heart" is a basin of ices of nitrogen, methane, and carbon monoxide. These ices can coexist in both gas and solid forms at Pluto temperatures ($\sim$40 K). Water ice was also detected on Pluto's mountains and cliff faces. With the high-resolution infrared spectroscopic observations (better than 5 km in some locations), we can see the diversity of compositional units across Pluto.

Chapter 2, by Craig Pitcher and Yang Gao, shows that there is evidence that water ice exists on a number of bodies in the solar system. As ice deposits may contain biomarkers that indicate the presence of life, or can be used as a consumable resource for future missions, confirming these observations with in situ measurements is of great interest. Missions aiming to do this must consider how the presence of water ice in regolith affects both the regolith's properties and the performance of the instruments that interact with it. The properties of icy lunar and Martian regolith simulants in preparation for currently planned missions are examined in this chapter. These results can be used in future instrumentation testing and missions designed to explore other icy bodies in the solar system. The testing of icy lunar regolith simulants is summarized, before focusing on experiments demonstrating the change in properties of frozen NU-LHT-2M, a simulant of the highlands regolith found at the lunar poles, as water is added. Further tests showed a critical point of 5 ± 1% water mass content where the penetration resistance significantly increases. The addition of water to Martian regolith simulants was also examined, with the presence of salts resulting in the formation of cemented crusts under simulated Martian conditions. Additional tests with the ExoMars PSDDS demonstrated how increased internal cohesion caused by the water resulted in the failure of the instrument.

Chapter 3, by Bryan Palaszewski, states that atmospheric mining in the outer solar system has been investigated as a means of fuel production for high energy propulsion and power. Fusion fuels such as helium 3 (3He) and hydrogen can be wrested from the atmospheres of Uranus and Neptune and either returned to Earth or used in situ for energy production. Helium 3 and hydrogen (deuterium, etc.) were the primary gases of interest with hydrogen being the primary propellant for nuclear thermal solid core and gas core rocket-based atmospheric flight. A series of analyses were undertaken to investigate resource capturing aspects of atmospheric mining in the outer solar system. This included the gas capturing rate for hydrogen helium 4 and helium 3, storage options, and different methods of direct use of the captured gases. Additional supporting analyses were conducted to illuminate vehicle sizing and orbital transportation issues.

Chapter 4, by William Stone, Bart Hogan, Vickie Siegel, John Harman, Chris Flesher, Evan Clark, Scott Lelievre, Josh Moor, Bryce Rothhammer, Keith Huffstutler, Omkar Pradhan, Albin Gasiewski, Steve Howe, and Troy Howe, states that ocean worlds (Europa, Enceladus, Titan, and elsewhere) hold the greatest potential in humanity's search for extant life as well as a second, independent origin of life in the solar system beyond Earth. The most likely location for possible life is beneath the surface of these worlds—through ice caps kilometers in thickness—and into full-planet oceans warmed by gravitational tidal heating. Accessing these places and autonomously discovering life, there is one of the greatest engineering and robotics challenges of our age. This chapter discusses several novel options for penetrating kilometers of ice with a starting condition of vacuum and 100K temperature. Such devices will be the essential enablers for the delivery of behavior-based autonomous underwater vehicles capable of full subsurface ocean exploration and life search, which is the subject of Chap. 10. In this chapter, the authors briefly review work to date in the area of ice penetrators. The authors present designs for several types of cryobot vehicles and specifically focus on novel power source options both for analog testing of fully integrated systems here on Earth as well as a range of possible nuclear options for actual flight missions to ocean worlds. The authors describe the four primary impediments to a successful cryobot mission (including the "starting problem" of inserting the cryobot into an ice cap at 100 K temperatures and hard vacuum; the "cruise phase problem" of transferring heat to the vehicle sidewalls to prevent refreeze entrapment; the "debris problem"—that of penetrating impact debris fragments and brine layers embedded within an ice cap; and the "breakthrough problem" where a cryobot first enters a subterranean ocean) and offer possible solutions to these highly unusual problems.

Chapter 5, by Kris Zacny, shows that recently NASA approved the Flagship-class Clipper mission to explore Jupiter's Moon Europa. Europa is the most likely planetary body that could harbor life. The mission will also be augmented with a $\sim$350 kg lander to ground-truth orbital measurements and enhance concentration and detection limits. The lander will be launched as a standalone spacecraft rather than add on to the Clipper flyby. The lander requires a sampling system to capture surface and subsurface material for analysis by onboard instruments. The threshold mission includes chemical analyses of three samples from 10 cm depth or deeper.

Europa's surface topography is unknown on the scale of a lander and even less on the scale of the sampling system itself. This requires the sampling system to be compliant with variable surface features. The Europa surface could be composed of cryogenic water ice of different densities, salt, or frozen sulfuric acid. As such, the sampling system needs to be able to work with any of these materials. The strength of cryogenic water ice is equivalent to the strength of basalt. As such, sampling time, forces, and life of the sampling system could prove to be challenging. Presence of sulfuric acid limits the use of traditional aerospace materials. Since local gravity is 1.3 m/s$^2$, the practical limit of downforce available for the sampling system is in the 10s of Newtons range. This chapter presents a sampling system based on a continuous miner/roadheader design. The cutter drum of the Europa Drum Sampler (EDuS) is compliant with highly variable surface roughness. It is also extremely robust and has been shown to cut through weak and hard rocks. The system is currently being developed.

Chapter 6, by Yoseph Bar-Cohen, Stewart Sherrit, Mircea Badescu, Hyeong Jae Lee, Xiaoqi Bao, and Zensheu Chang, shows that drilling mechanisms are widely used as means of penetrating objects and formations in such fields as domestic, medical, industrial, military, geology, and extraterrestrial applications. Many types of drills have been developed over the years with the majority based on mechanical motion (rotary and/or percussive) of a cutting tool. Mechanical drills use a bit having a tip that interacts with the drilled material and applies forces over a small area to cause large shear and/or impact stresses for cutting or breaking the material. There is a wide variety of bit types that have been developed commercially, which can be readily purchased at local hardware stores. Increasingly, developers of drills for in situ exploration missions are seeking capabilities that address the complex challenges involved with extreme environments found at the planetary bodies where subsurface penetration is needed. The use of piezoelectric actuators offers effective drilling capabilities, particularly in extreme environments. In the last two decades, significant developments have been made in using piezoelectric actuation to perform percussive drilling. In these designs, the cutting surface is fractured by high- and low-frequency impacts that enhance the penetration. The performance is again significantly increased by rotating the bit to introduce shearing and a mechanism to allow the cuttings to be removed from the created borehole. This chapter is focused on the drilling mechanisms that are driven by piezoelectric actuators, which were developed by the authors at the Jet Propulsion Lab (JPL), Pasadena, CA.

Chapter 7, by David Firstbrook, Patrick Harkness, Xuan Li, Ryan Timoney, and Kevin Worrall, states that ultrasonic vibration can be applied to a number of penetration and drilling scenarios, either directly through a penetrator or ultrasonically assisted tool or through the ultrasonic–percussive technique and a physically decoupled drill bit. Considering these different approaches, this chapter describes experiments which indicate that, in granular materials, the addition of ultrasonics can sometimes reduce both the force and power required to reach a given depth. Ultrasonically assisted drills are shown to proceed more quickly than their unassisted counterparts, and ultrasonic–percussive systems are shown to extract samples of permafrost simulant and even Antarctic snowpack in a still-frozen state. In the latter case, the ultrasonic–percussive drill has been combined with a control system and sample-caching architecture to create a workable sample acquisition concept for cold space environments.

In Chap. 8, Alexander Bolonkin states that it is extremely difficult with current and near-future technology to achieve interstellar flight, even in our nearest star system, Alpha Centauri. Such an exploration and launch would require enormous energy, expensive equipment, and long travel time. Current conventional nuclear and thermonuclear onboard reactors cannot solve these problems. The author discusses and estimates the parameters needed to achieve such flight via a mini, automatic probe. Three new possible perspective propulsion systems are proposed: multi-reflex light system using new sell-multi-reflex mirrors and lasers, a cold plasma beam from Earth, and an onboard Micro Black Hole (MBH) nuclear photon rocket. In all approaches, technological innovations to current systems are offered to make it possible to implement within the current technological restraints. The requested launch system (i.e., laser multi-reflect propulsion, cold plasma beam propulsion, or MBH nuclear propulsion), onboard equipment, energy installation (generator and accelerator), environmental constraints, drag allowances, interstellar microparticles, and communication ability with Earth are all described, estimated, and validated. Analysis shows that the most realistic interstellar launch system is a laser beam using the cell reflective mirror or ultra-cold plasma beam.

Chapter 9, by Steven Oleson and Geoffrey Landis, states that Neptune's moon Triton is a fascinating object, a dynamic moon with an atmosphere, and geysers. Triton is unique in the outer solar system in that it is most likely a captured Kuiper belt object (KBO), a leftover building block of the solar system. When Voyager flew by it was the coldest body yet found in our solar system (33 K) and had volcanic activity, geysers, and a thin atmosphere. It is covered in ices made from nitrogen, water, and carbon dioxide, and shows surface deposits of tholins, organic compounds that may be precursor chemicals to the origin of life. Exploring Triton will be a challenge well beyond anything done in previous missions but the unique environment of Triton also allows some new possibilities for mobility. A conceptual design of a Triton Hopping probe was developed that both analyzes the surface and collects it for use to propel its hops. The Hopper would land near the South Pole in 2040 where geysers have been detected. Depending on the details of propulsion chosen, the Hopper should be able to jump over 300 km in 60 hops or less, exploring the surface and thin atmosphere on its way. This craft will autonomously carry out detailed scientific investigations on the surface, below the surface (drilling) and in the upper atmosphere to provide unprecedented knowledge of a KBO turned moon and expanding NASA's existing capabilities in deep space planetary exploration to include Hoppers using different ices for propellant.

Chapter 10 by William Stone, Kristof Richmond, Chris Flesher, Bart Hogan, and Vickie Siegel states that ice-covered oceans are found across the solar system. On Earth, such environments are known to harbor life. On some ocean worlds such as Europa, the unique combination of an actively recycled ice shell and rocky, possibly magmatic interior, may give rise to a geochemical system suitable to life. The entry into sub-ice oceans of ocean worlds enabled by new cryobot technologies calls for the development of autonomous underwater vehicles to explore these water bodies as the next phase of exploration. The most fruitful places to search for life will be at energy sources provided by physical and chemical gradients, which may not necessarily occur at the breakthrough location of a cryobot. This implies exploration using a mobile platform, and this in turn—due to extremely limited bandwidth and hours-long round-trip transmission delay—must be an autonomous platform. To achieve this, an intelligent underwater robotic explorer must be developed that can travel in an ice-covered ocean; identify signs of biological activity; home in on, acquire, and analyze samples; and return to the cryobot to upload data for subsequent transmission to Earth. This chapter investigates technologies required for such an under-ice rover. The authors describe in detail several approaches that have been developed and field-tested at Stone Aerospace during the past 15 years. The authors draw upon and extend technologies that have been developed for oceanography and oil prospecting, then address the unique problems of under-ice exploration where no prior knowledge exists. What is unique about the problems posed by ocean worlds is that it requires a high degree of system robustness, onboard operational and science decision-making, and navigation which has yet to be demonstrated as a complete system in terrestrial oceanographic or even research systems. The goal of a releasing a self-contained system into a completely unknown environment and expecting it to perform sensible exploration is still elusive, but definite progress is being made and the path forward is becoming more clear. The authors describe procedures and algorithms that have been tested in analog environments in Antarctica and elsewhere and suggest where research may be most effectively invested to advance operational capabilities for under-ice autonomous systems.

Chapter 11, by Steven R. Oleson, Jason Hartwig, Jeffrey Woytach, Michael Martini, Anthony Colozza, Robert Jones, Thomas Packard, Paul Schmitz, Amy Stalker, Ralph D. Lorenz, Michael V. Paul, and Justin Walsh, states that the conceptual design of a submarine for Saturn’s moon Titan was a funded NASA’s Innovative Advanced Concepts (NIAC). The effort investigated what science a submarine for Titan’s liquid hydrocarbon ~93 K (180 °C) seas might accomplish and what that submarine might look like. Focusing on a flagship-class science system (~100 kg), it was found that a submersible platform can accomplish extensive and exciting science both above and below the surface of the Kraken Mare. The submerged science includes mapping using side-looking sonar, imaging, and spectroscopy of the sea at all depths, as well as sampling of the sea’s bottom and shallow shoreline. While surfaced, the submarine will not only sense weather conditions (including the interaction between the liquid and atmosphere) but also image the shoreline, as much as 2 km inland. This imaging requirement pushed the landing date to Titan’s next summer period (~2047) to allow for continuous lighted conditions, as well as Direct-to-Earth (DTE) communication, avoiding the need for a separate relay orbiter spacecraft. Submerged and surfaced investigations are key to understanding the hydrological cycle of Titan as well as gather hints to how life may have begun on Earth using liquid/sediment/chemical interactions. An estimated 25 Mb of data per day would be generated by the various science packages. Most of the science packages (electronics at least) can be safely kept inside the submarine pressure vessel and warmed by the isotope power system.

Chapter 12 by Adrian Stoica, Virgil Adumitroaie, Marco Quadrelli, Georgios Matheou, Marcin Witek, Marco Cipolato, Marco Dolci, James Roggeveen, Kyle Petersen, Kristina Andreyeva, Hunter Hall, Benjamin Donitz, and Leon Kim examines the concept of Wind Robots aiming to achieve long-term in situ science exploration of Gas Giants, Jupiter and Saturn. These planets are made almost entirely of hydrogen and helium, and have no hard surface to land on. Their low-temperature atmospheres are characterized by strong winds, at least in the observed upper atmosphere. The atmosphere in the areas of interest has low density, where it is very difficult to stay afloat, especially in conditions of higher gravity than on Earth. Combined with the desire to operate using only locally harvested energy, these aspects make the design of WindBots extremely challenging. As a general mission goal, one aims to operate slightly above and below the clouds region, which is between 0.3 bar and 10 bar on Jupiter, for a year-long-duration mission, in strong (potentially turbulent) winds. For example, WindBots would operate in the eyewall of the Great Red Spot, using the high wind and updrafts of the anticyclone, as well as horizontal gusts. The chapter summarizes the results of a study funded by a Phase I NASA Innovative Advanced Concepts (NIAC). The study looked at both naturally buoyant and winged solutions, as well as hybrids of the two. The chapter examines means of maintaining a long-duration mission and providing controls for the WindBots. It discusses several body configurations and deployment, as well as investigates energy recovery methods using active systems controlling the WindBots and passive systems to harvest naturally occurring wind, pressure, and thermal gradients in the atmosphere. It also reviews autonomy architecture and control schemes to be applied to the autonomous WindBots.

Chapter 13, by Masahiro Ono, Karl Mitchel, Aaron Parness, Kalind Carpenter, Saverio Iacoponi, Ellie Simonson, Aaron Curtis, Mitch Ingham, Charles Budney, Tara Estlin, Carolyn Parcheta, Renaud Detry, Jeremy Nash, Jean-Pierre de la Croix, Jessie Kawata, and Kevin Hand, explores a concept of sending small robots into the erupting vents on Enceladus. Descending into the vent is of great scientific interest not just because it could be a low-energy pathway to the subsurface ocean that may harbor life but also because the vent itself could be habitable. The two greatest challenges for the feasibility of the concept are the dynamic pressure due to the upward flow and the size of vent. The preliminary characterization of Enceladus vent suggests that these two parameters largely depend on the unknown eruption mechanism. With relatively calm “boiling” hypotheses, the dynamic pressure is up to $\sim 10^4$ Pa and the vent width could be in the order of 1 m, while more dynamic “cryovolcanic” hypotheses result in $10^3$–$10^7$ Pa dynamic pressure and 1–30 cm vent width. Meanwhile, the system trade study concluded that the most robust design would be a highly automated limbed robot with ice screw end effector, powered by a separate surface module through a tether. The authors developed a prototype design of the robot, which is $\sim 5 \times 10 \times 30$ cm in size, 3 kg in mass, and can move against $\sim 10^5$ Pa of dynamic pressure at a speed of $\sim 5.5$ m/hr. Therefore, the concept is likely feasible assuming the “boiling” models while the feasibility is undetermined with the current best knowledge under the “cryovolcanic” models.

Chapter 14, by Volker Maiwald, states that the Kuiper Belt is a distant region of our solar system and by now, the discovery of several small worlds, like Pluto, Makemake, or Haumea, have shown that the trans-Neptunian region of the solar system is indeed more inhabited than first meets the eye. The large distance to the Sun makes investigating these worlds challenging but it is known that the Kuiper Belt contains methane, nitrogen, ethane, even water, and other volatiles in some quantity. While the Kuiper Belt is far away and a continuous presence there beyond our current technological capabilities, it is also clear that this large region of the solar system contains a number of useful resources. These could be of use in future endeavors of humankind, establishing a more extended presence (robotic and human) in the solar system. This chapter explains a scenario how the Kuiper Belt can be opened up for humanity and become a ground for exploration and resource exploitation in the future. The chapter discusses an approach involving self-replication of autonomous probes capable to explore Kuiper Belt Objects and harvest their resources, i.e., to replicate and also to transfer resources to other parts of the solar system. It elaborates on the relevant topics like power generation and trajectories and at the same time points out technological open issues that need to be closed for such a scenario to work.

Chapter 15, by Werner Grandl, Ákos Bazsó, and Andreas F. Felsenstein, states that the Outer Solar System (OSS) contains a large number of different objects, e.g., gas giant planets like Jupiter and Saturn, dwarf planets like Pluto, and countless comets and asteroids. In the past, space missions, like Pioneer, Voyager, and more recently New Horizons, have visited and explored some of these remote objects. Although the OSS hosts some of the currently most interesting potential mission targets—among them Trojan asteroids and small Kuiper belt objects—yet there is a lack of ambitious plans for a sample return mission to objects in the OSS. On Earth, we only have access to a very limited sample of rocks from extraterrestrial objects, mostly in the form of lunar rocks collected by the Apollo missions, or meteorites from the Moon or Mars. Meteorites also delivered material from the inner and middle parts of the asteroid belt but the OSS is very sparsely sampled (if at all). For a more complete picture of the formation and early evolution of the solar system, we would also need samples from the OSS including remote objects definitively originating from the Kuiper belt. If we want to utilize the natural resources of the OSS, we should bring back soil and rock samples of celestial bodies in the OSS for chemical analysis to estimate the resources of metals, water, and other useful materials out there. The authors have designed a preliminary concept for a sample return mission to two minor bodies in the OSS, the Jupiter Trojan asteroid (624) Hektor and the Centaur group asteroid (2060) Chiron. The spacecraft UNIS (Unmanned Interplanetary Spaceship) for this long-duration mission (probably lasting some decades) would be assembled in Low Earth Orbit. To reach the targets, it would need to perform several gravity assist maneuvers via planetary encounters in the Inner solar system. After arriving at the targets, a robotic lander (SPIDER) would be activated to descend to and sample the surface. With its six legs, the

SPIDER can walk across the asteroid's surface in any direction. Finally, the stored samples will be returned to Earth to analyze them in laboratories.

Chapter 16, by Robert Cataldo, states that missions to the outer planets present a unique challenge to power systems. Long trip times and the duration of science investigations place a lifetime demand on systems. In addition, extreme low temperatures can require excess power demands on spacecraft thermal management systems for maintaining proper temperatures for avionics and liquid propellants. Historically, missions beyond Mars have utilized nuclear power in the form of Radioisotope Thermoelectric Generators (RTG) to provide sufficient power in the cold and dark regions of space. From the 1970s with Pioneer and Voyager to 2006 on Pluto New Horizons, RTGs have provided both electric power and heat to a host of very successful missions. RTGs carry its own energy source, namely plutonium 238, that provides the heat source for ultimate conversion into electricity. Thus, the power available is independent of the sun. Over the past decade, however, solar cell technologies have made great strides in efficiency from under 20% to over 30% allowing missions like Juno, for use in Jupiter polar orbit. However, the Sun's light intensity at Jupiter is only $\sim 5\%$ than it is at Earth and $\sim 0.1\%$ at Pluto's orbit. The physical size of solar panels becomes very large and difficult to accommodate the further away from the Sun. Every mission is unique in spacecraft design, trip times, mission duration, science instrument requirements, etc. Therefore, the power system of choice is really the result of possible trades with other subsystem's requirements for mass, volume, and area. General guidelines for power system selection are discussed to provide insight into various technology considerations that should be evaluated in performing power system trade studies for the unique conditions of outer planet missions.

Chapter 17, by Mark A. Stull and Ricky Tang, states that chemical rockets are never going to allow us to exploit outer solar system resources, that is going to require massive spacecraft capable of transporting heavy loads of cargo. It is also going to require reducing trip durations to economically viable times, and this must be done at a cost sufficiently low that resources from beyond the asteroid belt can compete with those obtainable within it. Chemical fuels simply cannot produce the power density and specific impulse needed to meet these requirements. Nuclear fuels can provide orders of magnitude greater power density but conventional nuclear thermal propulsion still limits specific impulse to insufficient values. However, a hybrid nuclear reactor can employ a fusion reaction at less than 5% of breakeven in a gas dynamic mirror thruster to generate a flux of neutrons that can drive a subcritical fission reaction in a fissile fuel, or via the thorium cycle, in which fissile $U_{233}$ is bred. The combined fusion and fission reactions can, in theory, generate specific impulse as high as several hundred thousand seconds, with continuous power levels in excess of 100 terawatts. If achievable in practice, this would enable a ship with economically viable cargo capacity to travel under continuous acceleration to all outer solar system bodies, including distant Eris, in economically acceptable times—days or weeks—without requiring prohibitively high amounts of propellant. But the bulk of the power would come from the fission reaction, and converting all or most of the potential fission energy to thrust presents a daunting challenge that present and foreseeable future technology may not be fully able to meet. Nevertheless, a more modest capability appears possible and could still enable high-capacity cargo ships to reach Jupiter and possibly Saturn in commercially viable times.

Chapter 18, by Simon Fraser, summarizes more than 45 years of outer solar system exploration to Saturn, Jupiter, Uranus, Neptune, Pluto, to their moons, and beyond. All past and present exploration missions to the outer solar system are briefly presented and discussed with respect to spacecraft, payload, and scientific objectives. In this, a special emphasis is put on describing the power systems applied with the different mission elements. Radioisotope Thermoelectric Generators (RTGs) are the power sources of choice with all but one mission launched to the outer solar system. RTGs are robust, do not have any rotating or moving parts, a long life, and predictable output power levels. This makes them particularly attractive for multiyear missions into regions of the solar system where solar insolation is very low. The first exception in this preference of RTGs is the most recent mission, where electrical energy was provided by large solar panels instead of a radioisotope-fuelled power source. The second exception consisted of two probes, which were piggybacked to their destination, and only had to be self-sufficient for a very limited period of time; batteries were chosen with both of these probes.

Chapter 19, by Volker Maiwald, states that Jupiter Trojans are a group of small bodies accumulated at the stable $L_4$ and $L_5$ libration points of the Jupiter–Sun system. They are numerous and are scientifically interesting regarding the formation and evolution of the solar system as a whole. Located at stable positions in Jupiter's solar distance, they are currently theorized to be dormant comets, containing volatiles, including water. A dedicated mission to this population of small bodies could verify hypotheses about their origin, thus shed light on the solar system history all-together and at the same time reveal details about their composition. This chapter details how such a mission could be accomplished, including a medium-sized spacecraft (launch mass $< 1600$ kg) and transfer trajectories, allowing a multi-rendezvous mission within a time frame of about 15 years. The spacecraft design, based on solar electric propulsion, contains details about the probe's subsystems and scientific payload, its mass and power budget, and also its configuration. The latter is dominated by the large deployable solar arrays, required to provide several kilowatts of power for the electrical thrusters. The spacecraft is able to reach three to four Trojans altogether, allowing a diverse review of Trojan properties and in general the gathering of a large amount of scientific data—directly facilitating any resource harvesting missions in future years.

Chapter 20, by Mike H. Ryan and Ida Kutschera, shows that the possibilities of future business opportunities that might exist within the outer solar system are explored. Fictional accounts of development within space are used to provide context between imagined paths of exploration and what is more likely within the foreseeable future. Additional observations as to the nature and extent of how business might develop are discussed. Although business creation within the realm of the outer solar system is likely to remain a distant possibility, it is not without terrestrial precedents. It is also probable that business opportunities would occur at a pace faster than expected if either the resources discovered among the planets and moons proved to be of greater value than anticipated or if technology made exploitation less difficult and more cost-effective. It is not if but when and how the resources of the outer solar system will be utilized in the future. In the near-term, business among the outer solar system will continue to be implausible until both opportunity and technology change significantly and catch up with the intriguing vision set forth by science fiction and business visionaries.

In Chap. 21, Alexander Bolonkin details two new mini thermonuclear reactors (cumulative and impulse) and a novel ultra-cold method of getting nuclear energy by cold thermonuclear synthesis. The new reactors are smaller and cheaper than the current and known future reactors by several orders of magnitude. They may be R&D in 2–3 years, may be used for transport vehicles (ships, trains, aircrafts, rockets, cars, and electric stations), and use cheap nuclear fuel.

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The book allows the reader to acquire a clear understanding of the scientific fundamentals behind specific technologies to be used in the outer solar system region in the future. The principal audience consists of researchers (engineers and physicists) involved or interested in space exploration in general and outer solar system exploration in particular. Also, the book may be useful for industry developers interested in joining national or international space programs. Finally, it may be used for undergraduate, postgraduate, and doctoral teaching in faculties of engineering and natural sciences.

Bucharest, Romania — Viorel Badescu
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Viorel Badescu
Kris Zacny

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# Contributors

**Virgil Adumitroaie** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Kristina Andreyeva** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Mircea Badescu** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Xiaoqi Bao** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Yoseph Bar-Cohen** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Ákos Bazsó** University of Vienna, Vienna, Austria

**Alexander Bolonkin** C&R, Brooklyn, NY, USA

**Charles Budney** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Kalind Carpenter** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Robert Cataldo** NASA Glenn Research Center, Cleveland, OH, USA

**Zensheu Chang** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Marco Cipolato** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Evan Clark** Stone Aerospace, Del Valle, TX, USA

**Anthony Colozza** NASA Glenn Research Center, Cleveland, OH, USA

**Aaron Curtis** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Jean-Pierre de la Croix** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Renaud Detry** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Marco Dolci** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Benjamin Donitz** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Tara Estlin** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Andreas F. Felsenstein** University of Vienna, Vienna, Austria

**David Firstbrook** School of Engineering, University of Glasgow, Glasgow, UK

**Chris Flesher** Stone Aerospace, Del Valle, TX, USA

**Simon D. Fraser** Energy Systems Engineering, Graz, Austria

**Yang Gao** Surrey Space Centre, University of Surrey, Guildford, UK

**Albin Gasiewski** University of Colorado Boulder, Boulder, CO, USA

**Werner Grandl** Consulting Architect, Tulln, Austria

**Will Grundy** Lowell Observatory, Flagstaff, USA

**Hunter Hall** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Kevin Hand** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Patrick Harkness** School of Engineering, University of Glasgow, Glasgow, UK

**John Harman** Stone Aerospace, Del Valle, TX, USA

**Jason Hartwig** NASA Glenn Research Center, Cleveland, OH, USA

**Bart Hogan** Stone Aerospace, Del Valle, TX, USA

**Steve Howe** Howe Industries, Tempe, AZ, USA

**Troy Howe** Howe Industries, Tempe, AZ, USA

**Saverio Iacoponi** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Mitch Ingham** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Robert Jones** NASA Glenn Research Center, Cleveland, OH, USA

**Jessie Kawata** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Leon Kim** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Ida Kutschera** Rubel School of Business, Bellarmine University, Louisville, KY, USA

**Geoffrey Landis** NASA Glenn Research Center, Cleveland, OH, USA

**Hyeong Jae Lee** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Xuan Li** School of Engineering, University of Glasgow, Glasgow, UK

**Ralph D. Lorenz** Applied Physics Laboratory, Johns Hopkins University, Laurel, MA, USA

**Volker Maiwald** German Aerospace Center (DLR), Institute of Space Systems, Bremen, Germany

**Michael Martini** NASA Glenn Research Center, Cleveland, OH, USA

**Georgios Matheou** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Karl Mitchel** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Jeremy Nash** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Steven R. Oleson** NASA Glenn Research Center, Cleveland, OH, USA

**Catherine Olkin** Southwest Research Institute, Boulder, USA

**Masahiro Ono** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Thomas Packard** NASA Glenn Research Center, Cleveland, OH, USA

**Bryan Palaszewski** NASA John H. Glenn Research Center, Lewis Field, Cleveland, OH, USA

**Carolyn Parcheta** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Aaron Parness** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Michael V. Paul** Applied Physics Laboratory, Johns Hopkins University, Laurel, MA, USA

**Kyle Petersen** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Craig Pitcher** Surrey Space Centre, University of Surrey, Guildford, UK

**Omkar Pradhan** University of Colorado Boulder, Boulder, CO, USA

**Marco Quadrelli** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Kristof Richmond** Stone Aerospace, Del Valle, TX, USA

**James Roggeveen** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Mike H. Ryan** Rubel School of Business, Bellarmine University, Louisville, KY, USA

**Paul Schmitz** NASA Glenn Research Center, Cleveland, OH, USA

**Stewart Sherrit** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Vickie Siegel** Stone Aerospace, Del Valle, TX, USA

**Ellie Simonson** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Amy Stalker** NASA Glenn Research Center, Cleveland, OH, USA

**Adrian Stoica** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**William Stone** Stone Aerospace, Del Valle, TX, USA

**Mark A. Stull** The Law Office of Mark A. Stull, Manchester, NH, USA

**Ricky Tang** Sandia National Laboratories, Albuquerque, NM, USA

**Ryan Timoney** School of Engineering, University of Glasgow, Glasgow, UK

**Justin Walsh** The Pennsylvania State University, State College, USA

**Marcin Witek** Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Kevin Worrall** School of Engineering, University of Glasgow, Glasgow, UK

**Jeffrey Woytach** NASA Glenn Research Center, Cleveland, OH, USA

**Kris Zacny** Honeybee Robotics Spacecraft Mechanisms Corporation, Pasadena, CA, USA

# Part I
# Properties of Planetary Regolith

# Chapter 1
# A Survey of Pluto's Surface Composition

**Catherine Olkin and Will Grundy**

Pluto was discovered less than 100 years ago (in 1930) by Clyde Tombaugh at Lowell Observatory in Flagstaff, AZ. The founder of the observatory, Percival Lowell, had initiated a systematic search of the sky to find the putative Planet X in 1905 (Tombaugh 1960). The existence of Planet X was predicted because of deviations of the motions of Neptune and Uranus from expected values. Other teams were also searching for Planet X including a team lead by William H. Pickering of Harvard Observatory. Lowell observatory continued the search after the founder's death in 1916, commissioning a new search telescope in 1927 that would allow astronomers to search a larger area of sky (12° × 15° using 14 × 17-in glass plates, Giclas 1980) to a fainter magnitude (16–17th magnitude)—the 13-inch astrograph. Each clear night near new moon, Clyde Tombaugh used the new telescope to image the sky near opposition. Observing the sky near opposition was essential because he was searching for Planet X by looking for its motion against the fixed stars and the motion is a maximum at opposition. An object out beyond Neptune would have a motion in the plane of the sky of $\sim 1$ arcmin/day as compared to asteroids which would move at $\sim 15$ arcmin/day. Clyde uses a machine, called a Zeiss blink comparator, to inspect the plates for moving objects by comparing plates taken a few nights apart. On the afternoon of February 18, 1930, he was comparing images of the sky near Delta Geminorium when he discovered Pluto—a 15th magnitude object that had moved 3.5 mm (about 8.5 arcmin) on two plates taken 6 days apart (Tombaugh 1960). He continued for 14 more years searching the sky for other objects in our solar system. While he

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C. Olkin (✉)
Southwest Research Institute, Boulder, USA
e-mail: catherine.olkin@swri.org

W. Grundy
Lowell Observatory, Flagstaff, USA
e-mail: grundy@lowell.edu

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discovered many asteroids, a comet and six galactic star clusters, he did not discover any more objects out beyond the orbit of Neptune.

Work by Kenneth E. Edgeworth published in the 1940s and by Gerard P. Kuiper in the 1950s on the origin of the solar system indicated that there might be a large number of objects beyond the orbit of Neptune in what is now called the Kuiper Belt (Davies et al. 2008). As technology improved, more distant small bodies were discovered. In 1977, Charles Kowal discovered Chiron (Kowal 1989), a minor planet whose orbit crosses the orbits of Saturn and Uranus. This object was another harbinger of the presence of the Kuiper Belt, as its orbit is unstable and it likely migrated to its current orbit from further out in the solar system.

It wasn't until 1992 when the next Kuiper Belt Object (KBO), after Pluto, was discovered (Jewitt and Luu 1993). In the 1990's, technology advanced to allow discovery of many more distant objects in the solar system. We had larger aperture telescopes, wide-field CCD cameras, and computer algorithms to search the digital images for moving objects. Dedicated searches for KBOs were undertaken, such as the Deep Ecliptic Survey from 1998 to 2003, which searched 550 $\mathrm{deg}^2$ and discovered more than 300 KBOs (Elliot et al. 2005), the Canada–France Ecliptic Plane Survey (CFEPS) from 2003 to 2007, which searched 321 $\mathrm{deg}^2$ and discovered 169 KBOs (Petit et al. 2011) and the on-going Outer Solar System Origins Survey (OSSOS) which reports initial results from the first 42 $\mathrm{deg}^2$ of 85 KBOs (Bannister et al. 2016).

We now know that Pluto is one of more than 2500 known KBOs and it is the largest known object of this population with a radius of 1188.3 km (Nimmo et al. 2017). Pluto was one of the best-studied KBOs, even before the flyby of the New Horizons spacecraft. From color light curves and mutual occultations and eclipses of Pluto and its large moon Charon, it was known that Pluto had large albedo and color variegation. In 1976, using filter photometry in the 1–2 um band, Cruikshank et al. (1976) showed there was methane ice on Pluto's surface. In 1993, Owen et al. used near infrared spectroscopy to identify the signature of $N_2$ ice and CO ice on Pluto. Using Pluto's 6.4-day rotation period, Grundy et al. (2013) investigated longitudinal variations of Pluto's surfaces ices and found that CO ice on Pluto's surface was preferentially located on Pluto's anti-Charon hemisphere, but our knowledge of the distribution of volatiles (molecules on the surface that have an appreciable vapor pressure) on its surface was limited. Cruikshank et al. (2015) presents a review of the state of knowledge about Pluto's surface composition prior to the New Horizons encounter.

Even using the best telescopes available, Earth-based observations provide at most a few resolution elements across Pluto's disk. To significantly advance our understanding of Pluto, a spacecraft was needed. There were a number of Pluto mission studies initiated in the 1990's and NASA released an Announcement of Opportunity for a mission to Pluto and the Kuiper Belt in January 2001. By November 2001, the New Horizons mission was selected by NASA to explore Pluto and its large moon Charon.

The mission's three main objectives were to characterize the geology of Pluto and Charon, to map the surface composition of Pluto and Charon and to characterize the neutral atmosphere of Pluto and its escape rate. These and additional secondary and tertiary science objectives (see Young et al. 2008; Weaver et al. 2008) drove the