Astronomers' Universe

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Exploring the Ocean Worlds of Our Solar System

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To my father

Preface

About 1.2 billion km away from our blue planet, frozen droplets of water orbit Saturn in unison with its majestic rings. These droplets are so abundant that they form a large ring around the planet. Hundreds of thousands of km wide and 2,000 km deep, this ring contains so many frozen water particles that Tethys and Dione, two small moons that happen to lie within the ring, have both developed a blue tint.

By analyzing this ring, the E ring, one of eleven other rings of Saturn (see Chapter 8), we have discovered that the droplets contain traces of sodium chloride (salt) and silicon dioxide (silica), indicating that the body of water from which they originate must be warm, salty, and in direct contact with rocks – very much like our seawater here on Earth. Science tells us that these conditions are favorable for life to develop and flourish, so it doesn't require a big stretch of the imagination to believe that, trapped inside these tiny seawater droplets, we might find microorganisms in the deep freeze – extraterrestrial life.

Scientists recently found the ocean from which these frozen water particles originate, but this ocean is different from the ones we see here on Earth. It is a subsurface ocean that lies many kilometers beneath the surface of one of Saturn's tiny moons, Enceladus. Mighty geysers, powered by the little moon's heating, regularly spout large jets of ocean water into space, where they join the E ring.

We now know that many worlds within our Solar System contain vast subsurface oceans. We call them "ocean worlds," and they are one of the most exciting discoveries in the history of space exploration.

It is remarkable that we live in an age where data collected by robotic space probes allows us to have educated conversations about the possibility of extraterrestrial life. In this book, we'll travel back in time, tracking the discovery of the ocean worlds. Then we'll move through space as we visit each of these worlds, investigating the latest scientific evidence as we contemplate the tricky yet thrilling concept of planetary habitability, the potential to have environments hospitable for life.

The idea of this book germinated more than a year ago during a public outreach event at the Sherwood Observatory in the United Kingdom. It had been a busy yet satisfying event for all of us involved, and as the evening drew to a close, a visitor approached me, as he was eager to share a news article about the newly discovered ocean of liquid water under the surface of Pluto and the possibilities that life might be discovered there by future NASA missions. When he asked for my opinion on this news item, I didn't have good news for him. The existence of a subsurface sea underneath Pluto was, and is still, only suggested by theoretical models, not confirmed by solid evidence as seemed to transpire from the article. In addition, there are much better places for NASA to search for life in our Solar System than Pluto, a far off distant world where, if liquid water existed, it would most likely be rich in ammonia – a powerful antimicrobial agent.

Subsequently, as I gave further public talks at the observatory and interacted with the people attending, I understood that the public was sometimes misled by the press overhyping or grossly distorting the science facts behind the ocean worlds' concept. This was no real surprise here, as anyone taking part in activities aimed at communicating scientific ideas to the public quickly becomes aware how easy it is for the public to misinterpret modern scientific concepts and the intricacies that come with them.

It is in response to these inaccurate interpretations that the book you hold in your hands was conceived, easily accessible by any layperson wanting to know more on subsurface oceans. It aims to guide the reader through the concept of the ocean worlds and provide insights into the latest scientific discoveries, with all the nuances that come along.

In a way, the field of planetary science has always been ripe for misleading interpretations as it involves, more often than not, cutting-edge science where technologies are pushed to their limits, and theoretical models are continuously refined. Add to this mix our never-ending obsession with alien life, and we have a perfect click bait. In this context, it can be difficult for non-experts to separate the wheat from the chaff, and this is where this guide can help.

The book is divided into four parts, each focusing on a specific aspect of the ocean worlds' topic. Part I, consisting of three chapters, aims to cover some basic concepts in planetary science and astrobiology to establish a good foundation upon which we can explore the ocean worlds. Chapter 1 will reveal how the idea of ocean worlds was first introduced through the remarkable journeys taken by NASA's Voyager spacecraft as they visited the outer planets' satellite systems in the last decades of the twentieth century, revolutionizing planetary science in the process. Chapter 2 will cover the origins of water in the universe as well as the processes behind its distribution throughout our Solar System. The possibility of life arising within subsurface oceans and the current approach that is taken in finding it will be described in Chapter 3. In so doing, we will make a slight detour to the planet Mars, where the first ever interplanetary mission to detect alien life was undertaken in the 1970s.

With the essentials covered, our journey to the ocean worlds will start as we move into the second part of the book. There, we will explore in detail the five confirmed ocean worlds of our Solar System, which are in fact moons of Saturn or Jupiter: Ganymede, Callisto, Europa, Titan, and Enceladus. Each one will be covered in a chapter to allow us to explore their history fully, their physical and geochemical properties, and ponder on the prospects of life within their subsurface oceans.

Part III will take us to two moons and two dwarf planets where tantalizing clues suggest that a subsurface ocean or smaller bodies of liquid water could lie under the icy crust but for which we still haven't found definitive proof. Within this part, Ceres and Dione will be covered in Chapter 9, while Triton and Pluto will be explored in Chapter 10. In the following chapter, we will explore numerous planetary objects that could theoretically have hosted a subsurface ocean in the past or might still do so in the present, but for which the limited observational data makes such cases debatable. This category includes, among others, icy moons such as Rhea, Ariel, Titania, and Oberon as well as trans-Neptunian objects (objects lying further than the orbit of Neptune) such as Makemake, Eris, Sedna, and 2007 OR10.

Finally, the last part will review the space missions planned to visit the ocean worlds in the coming decades. In Chapter 12, we will examine the confirmed missions such as ESA's JUICE and NASA's Europa Clipper as well as the proposed ones waiting to be approved, such as the Europa Lander. Given the life-detecting capabilities of these future missions, we will end the chapter, and the book, speculating on the scientific and societal impact if we find evidence of alien life within a subsurface ocean. Ultimately, looking for life forms in these remote and strange habitats is part of a bigger quest, the one for our cosmic origins.

In the appendix section, we will cover Mimas, a small moon of Saturn, which had been previously put forward by some scientists as an ocean world candidate, only to be disproven recently. As such, this moon provides a cautionary tale on the drawbacks in interpreting from a limited set of data. In addition to Mimas, a brief overview of the relic surface oceans of Mars and Venus will complete our investigation of past and present liquid water environments in our Solar System.

What's more, our journey will take us across the entire Solar System to meet numerous objects. From the now-famous Comet 67P/Churyumov-Gerasimenko to the icy surface of Pluto's moon Charon; from Io, the most geologically active object in our Solar System, to some of the remotest objects known, we will venture far and wide, meeting in the process the robotic explorers that unveiled these worlds to us – the spacecraft *Pioneer* 10 and 11, *Voyager* 1 and 2, *Galileo, Rosetta* and *Philae, Dawn, New Horizons*, and *Cassini-Huygens* – and the people that made all this possible. We will also cover the geological and geochemical processes involved in the alteration of planetary bodies such as how water behaves in extreme conditions in Chapter 4 and the external factors that alter a planetary surface exposed to space in Chapter 5. Further processes and concepts will be distilled here and there throughout the chapters.

Key to the approach taken by this book is the fact that planetary science is a comparative science, where we gain much from comparing planetary objects with each other. As such, although it might be tempting to skip chapters and quickly jump to specific parts of the book (e.g., Europa), it is recommended to read in the order the chapters appear, as knowledge on the ocean worlds and the technology used to investigate them builds up progressively. Of course, in the case chapters are read individually, there will be pointers as to where a specific concept or technology has been covered elsewhere in the book.

In keeping with the comparative theme, every ocean world candidate mentioned in this book is presented in an overarching table, located after this preface, where comparisons on fundamental physical properties (such as ratio or mass) and the known characteristics of the subsurface oceans can be made between each candidate. This table should become handy when one wants to quickly check the properties of these objects against what they have read or heard. Furthermore, a schematic diagram establishes where each ocean world candidate is located within the context of the planets and structures of our Solar System, making it easier to locate a given object.

One of the most satisfying aspects of life is sharing with others what you are most passionate about. I genuinely hope you enjoy reading what follows as much as I relished researching and writing it. If anything written herein inspires you to learn more about space or science in general, then I've succeeded in my effort.

Nottingham, UK
April 2018

Bernard Henin

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As can be expected with a project of such scope and depth, the insights and support of numerous people from around the world have proved indispensable.

To start off with, I would like to thank my publisher, Springer, for giving me this unique opportunity to share my passion for this fascinating topic and to inspire future generations of astronomers, space enthusiasts, and scientists. John Watson, working for Springer in the United Kingdom, proved instrumental in getting this project started and was a guiding hand throughout the course of the book proposal stage. I am incredibly grateful to my editor in New York, Maury Solomon, who was the first, with John, to believe in this project from the outset and entrusted me with its writing. Despite her busy schedule, she always made herself available whenever I required support during the 12 months needed to write this book. Her assistant, Elizabet Cabrera, proved helpful as well.

In addition to my publisher, many people were involved in the making of this book. Taryn from Cape Town was responsible for sharpening my writing skills as well as a contributing factor in getting my book proposal accepted, while Karen from London provided insight into the writing process. Their early encouragements and enthusiasm made it all possible.

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Contents

About the Author

Bernard Henin fell in love with planetary science when, as a teenager reading *National Geographic,* he came across images of Neptune taken from NASA's spacecraft *Voyager* 2. He was mesmerized by the giant blue planet and found it both exhilarating and liberating to think that entire new worlds could be explored during his lifetime. Since then, he has closely followed humanity's continued exploration of our Solar System.

Henin is a member of the Sherwood Observatory in the United Kingdom (home to the second largest telescope in the country that is freely accessible for public viewing), where he performs regular talks aimed at the members of the Astronomical Society and the public at large. Writing a book on astronomy was the next obvious step in raising awareness of the fascinating Solar System we inhabit.

Originally from Belgium, Henin has lived in the United States, the United Kingdom, and Hong Kong. His previous work has been published in international magazines.

Contributors

I would like to express my most profound gratitude to the scientists listed below who kindly found the time to talk to me and send me material. Without their contributions, making this book would not have been possible. In alphabetical order, they are:

Dr. Penelope Boston, director of NASA's Astrobiology Institute, Mountain View, California.

Dr. Charles Cockell, director of the UK Centre for Astrobiology and professor of astrobiology in the School of Physics and Astronomy at the University of Edinburgh.

Dr. Amanda Hendrix, senior planetary scientist at the Planetary Science Institute, Tucson, Arizona.

Dr. Luciano Iess, professor of aerospace engineering at the Sapienza University of Rome.

Dr. Jonathan Lunine, the David C. Duncan professor in the physical sciences and director of the Center for Radiophysics and Space Research at the Cornell University, Ithaca, New York.

Dr. Chris McKay, planetary scientist at NASA's Ames Research Center, Mountain View, California.

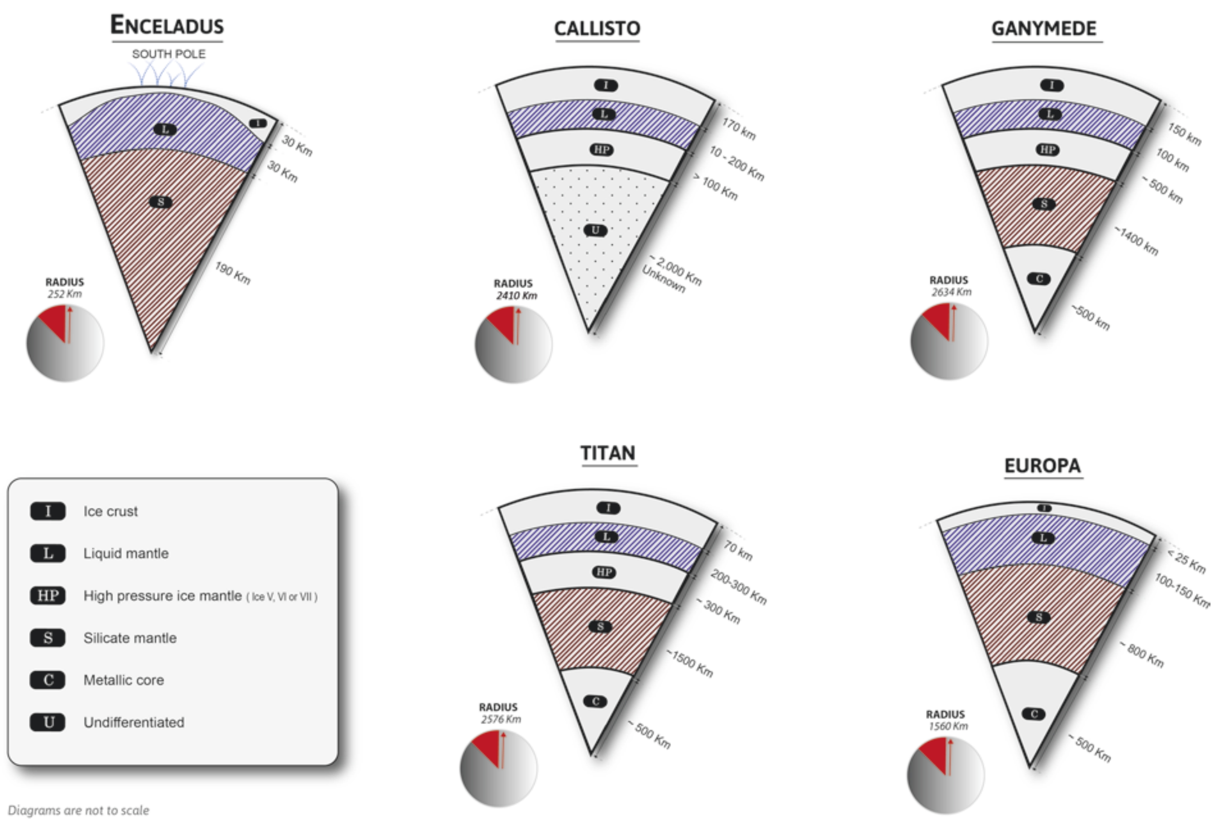
Dr. William B. McKinnon, professor at the Department of Earth and Planetary Sciences, Washington University, St. Louis, Missouri.

Dr. Marc Neveu, astrobiology science assistant at the NASA Headquarters, Washington.

Dr. Olivier Witasse, JUICE project scientist at the European Space Research and Technology Centre, ESA, Noordwijk.

Dr. Steve Vance, lead for the Habitability team of JPL's Icy Worlds Astrobiology group, JPL, Pasadena, California.

Cross section of the five confirmed ocean worlds in our Solar System



Diagrams are not to scale

Confirmed and potential ocean worlds in our Solar System

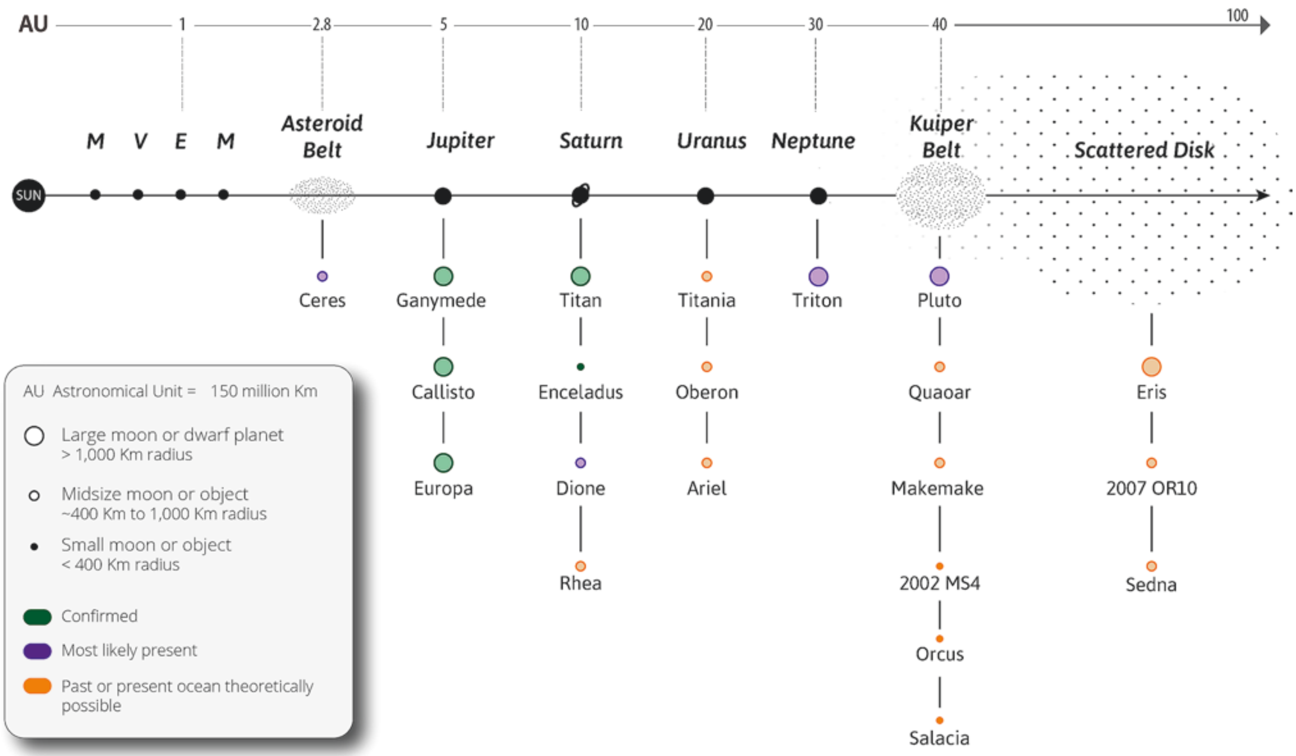


Diagram not to scale

Confirmed or Possible ocean worlds in our Solar System

Name of planetary object	Type of planetary object	Parent planet or Location	Distance from Sun (AU)	Mean Radius (km)	Mass (10^{20} kg)	Mean density (g/cm^3) Water = 1	Subsurface ocean status (past or present)	Lines of evidence of a subsurface ocean	Liquid water adjacent to rocky material	Future missions approved
Ceres	Asteroid, dwarf planet	Asteroid belt	4	473	9	2.16	Likely but unconfirmed	–	Yes	–
Europa	Satellite	Jupiter	5	1,560	480	3.01	**Confirmed**	2	Yes	JUICE, Europa Clipper
Callisto	Satellite	Jupiter	5	2,410	1,076	1.83	**Confirmed**	1	No	JUICE
Ganymede	Satellite	Jupiter	5	2,634	1,482	1.94	**Confirmed**	1	No	JUICE
Enceladus	Satellite	Saturn	10	252	1	1.61	**Confirmed**	+2	Yes	–
Titan	Satellite	Saturn	10	2,575	1,346	1.88	**Confirmed**	2	No	–
Rhea	Satellite	Saturn	10	764	23	1.23	Theoretically possible	–	–	–
Dione	Satellite	Saturn	10	560	11	1.47	Likely but unconfirmed	–	Yes	–
Ariel	Satellite	Uranus	20	579	14	1.59	Theoretically possible	–	–	–
Titania	Satellite	Uranus	20	788	35	1.71	Theoretically possible	–	–	–
Oberon	Satellite	Uranus	20	761	30	1.63	Theoretically possible	–	–	–

(continued)

Name of planetary object	Type of planetary object	Parent planet or Location	Distance from Sun (AU)	Mean Radius (km)	Mass (10^{20} kg)	Mean density (g/cm^3) Water = 1	Subsurface ocean status (past or present)	Lines of evidence of a subsurface ocean	Liquid water adjacent to rocky material	Future missions approved
Triton	Satellite	Neptune	30	1,353	214	2.06	Likely but unconfirmed	–	Yes	–
Makemake	KBO, dwarf planet	Kuiper Belt	40	~720	44	1.4–3.2	Theoretically possible	–	–	–
2002 MS4	KBO	Kuiper Belt	40	~467	–	–	Theoretically possible	–	–	–
Quaoar	KBO	Kuiper Belt	40	~537	~ 14	~2.2	Theoretically possible	–	–	–
Salacia	KBO	Kuiper Belt	40	~425	~4.4	~1.29	Theoretically possible	–	–	–
Orcus	KBO	Kuiper Belt	40	~460	~6.4	~1.5	Theoretically possible	–	–	–
Pluto	KBO, dwarf planet	Kuiper Belt	40	1,188	130	1.85	Likely but unconfirmed	–	Yes	–
Eris	SDO, dwarf planet	Scattered disk	30–100	1,163	166	2.52	Theoretically possible	–	–	–
Sedna	SDO	Scattered disk	80–950	~498	–	–	Theoretically possible	–	–	–
2007 OR10	SDO	Scattered disk	30–100	~751	–	–	Theoretically possible	–	–	–

AU: Astronomical Unit / KBO: Kuiper Belt Objects / SDO: Scattered Disk Objects