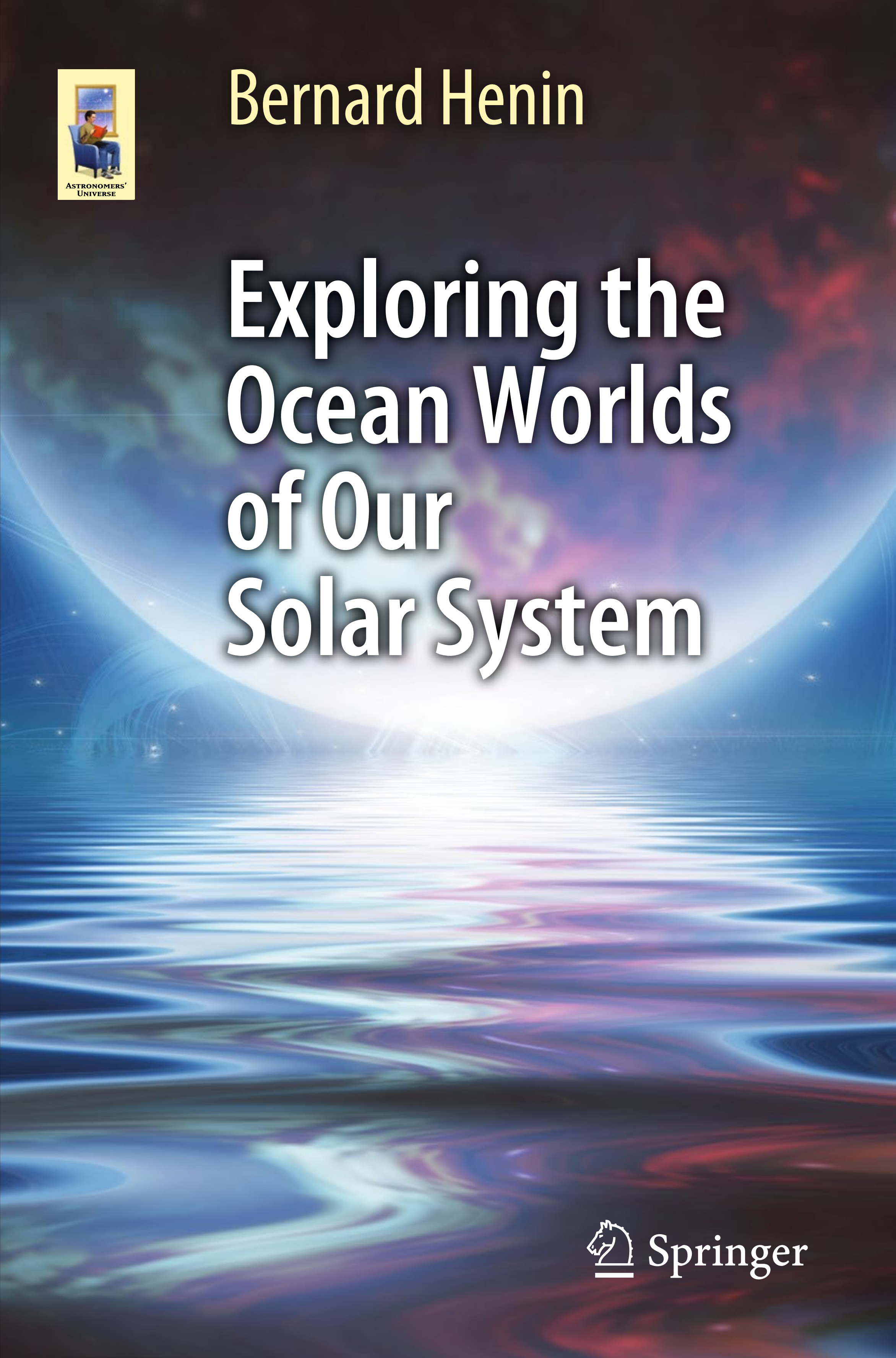

Astronomers' Universe

Bernard Henin

Exploring the Ocean Worlds of Our Solar System

Springer

Astronomers' Universe

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ISSN 1614-659X ISSN 2197-6651 (electronic)
Astronomers' Universe
ISBN 978-3-319-93475-4 ISBN 978-3-319-93476-1 (eBook)
https://doi.org/10.1007/978-3-319-93476-1

Library of Congress Control Number: 2018945895

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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 Bernard Henin
April 2018

Acknowledgments

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.

I would like to thank Piers Bizony, a successful author of space and science-themed books, for his support and counsel as well as the various members of the Sherwood Observatory, United Kingdom, where the idea of the ocean worlds' book germinated. I especially want to single out all the committee members for their warm welcome and continuous support about this project and in particular, Chris D. and Steve W. who took their time to review my first drafts and point out areas that needed clarity.

I need to acknowledge Pierre Beaujean, assistant professor at the University of Namur, Belgium, for reviewing my paragraphs on organic chemistry and Stephen Plasman, my graphic designer in Belgium, for creating most of the schematic representations that are included in this book.

I would have probably gone crazy if it wasn't for Maria Machon, based in Berlin, who assisted me throughout the year with the planning aspect of this project. I doubt I could have succeeded in completing the book on time if it wasn't for her sharp intellect and experience. I will miss our regular meetings related to this project.

In Hong Kong, Thomson and Tiffana pulled out all the stops to find me quiet havens where I could write, while Jessica Faleiro, a writer based in Goa and my trustworthy writing companion, gave me the confidence I needed to carry on this project.

Of course, I can't thank enough the scientists in the United States and Europe that took some of their precious time to contribute to this book via email exchanges, Skype, or phone interviews. The discussions I had with these leading scientists proved to be the highlight of this project. In alphabetical order, they are: Dr. Penelope Boston, Dr. Charles Cockell, Dr. Amanda Hendrix, Dr. Luciano Iess, Dr. Jonathan Lunine, Dr. Chris McKay, Dr. William B. McKinnon, Dr. Marc Neveu, Dr. Olivier Witasse, and Dr. Steve Vance.

No acknowledgments would be complete without thanking my family, close friends, and everyone else who has supported me during the entirety of this project – you know who you are. To my parents who have always supported me throughout my life, my wife who has had to endure endless hours of me rambling on the ocean worlds, and my daughter for bringing me joy every day.

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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.

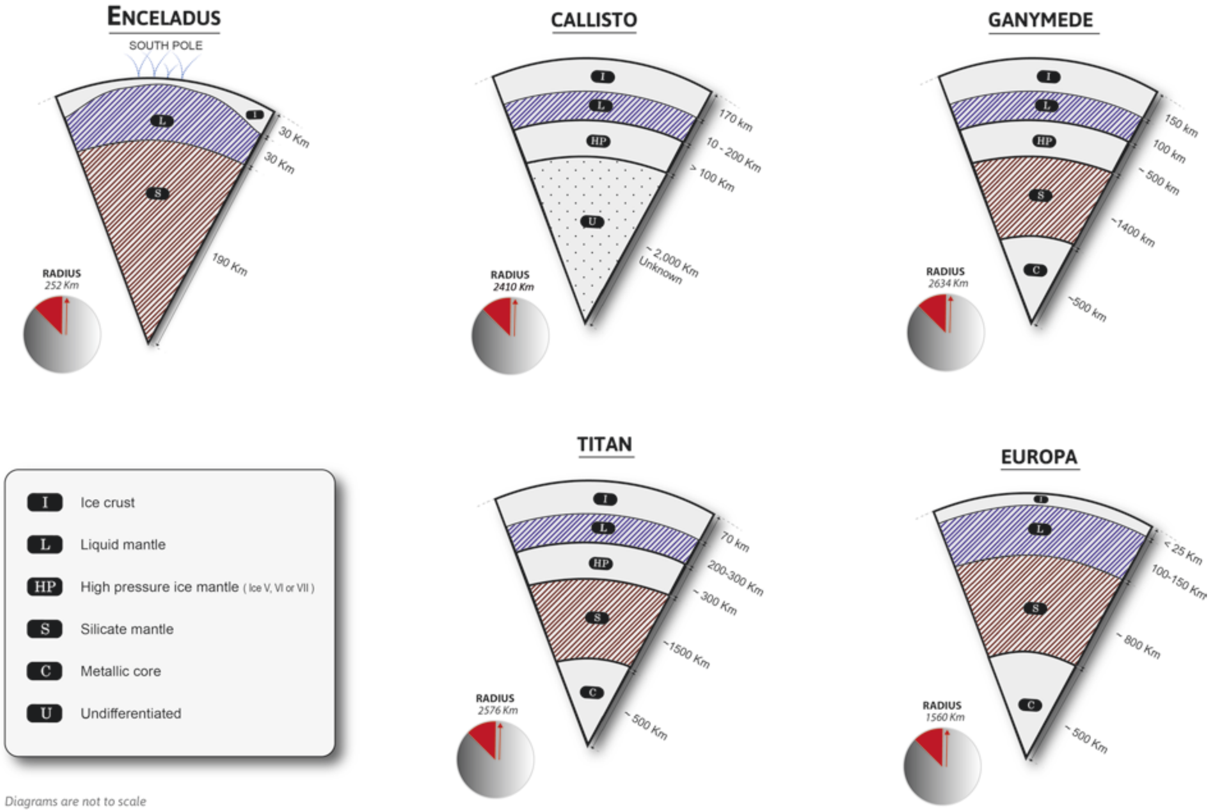
Dr. William B. McKinnon, professor at the Department of Earth and Planetary Sciences, Washington University, St. Louis, Missouri.

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

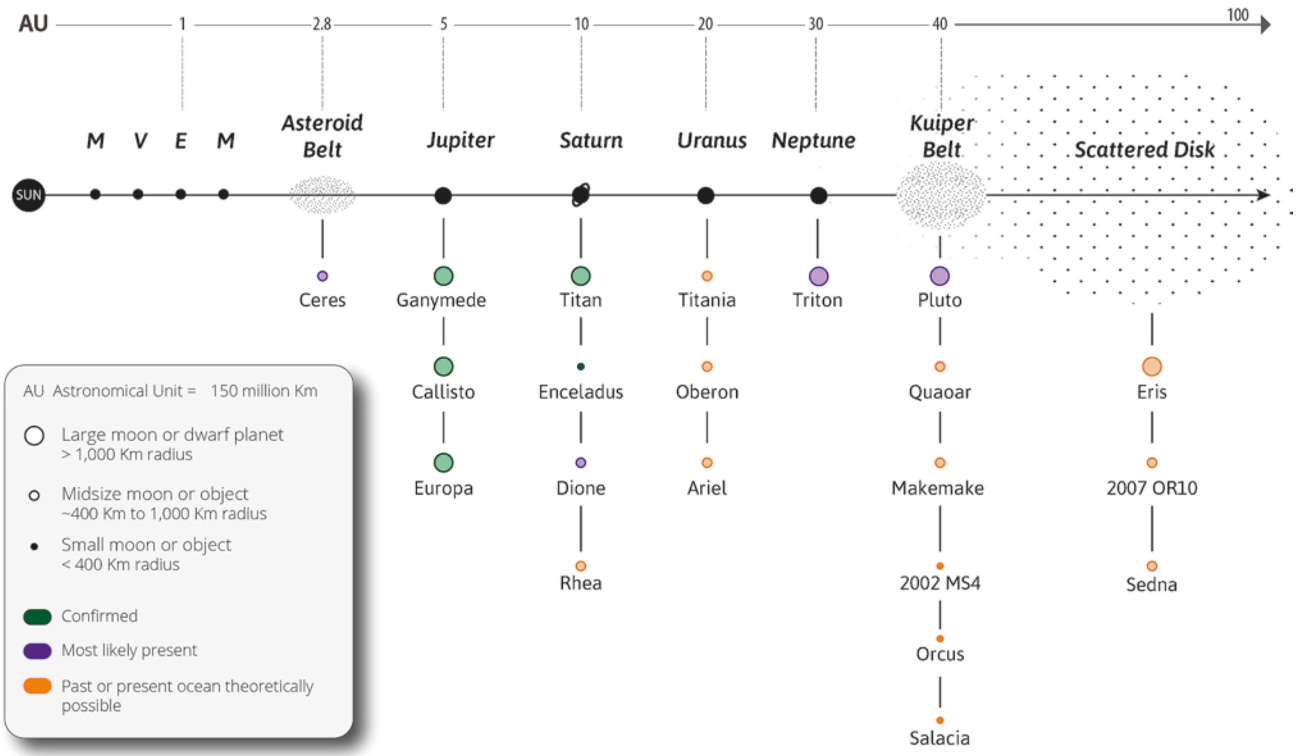


Diagram not to scale

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

Part I
The Origin of Water and Life

> "Equipped with his five senses, man explores the universe around him and calls the adventure Science."
>
> – Edwin Powell Hubble

In Part I, we review the revolution that occurred in planetary science when the *Voyager* space probes visited the outer planets and their satellite systems, bringing back the first hints of ocean worlds in our Solar System. The second chapter deals with the origin of water in space and how it was distributed among the planetary objects orbiting our Sun, while the third chapter deals with the possibility of extraterrestrial life and our attempts to find it.

1. The Voyagers' Tale

Golden Amazons of Venus

The night sky has always been a source of fascination for humankind. Storytellers have turned to it to create fantastic myths and legends for centuries. But it seems that, even within the realms of science fiction, our imaginations are not powerful enough to always uncover truth.

When astronomers first pointed their telescopes at our Moon in the 17th century, they assumed that they were looking at a world awash with liquid water. In fact, our modern lunar maps still feature the watery names Maria (singular mare, Latin for "sea"), Oceanus (singular oceanus, Latin for "ocean"), Lacus (singular lacus, Latin for "lake"), Sinus (singular sinus, Latin for "bay") and Paludes (singular palus, Latin for "marsh"). We now know of course that the Eagle that landed in the 'Sea of Tranquility' 50 years ago landed on struts rather than floats.

Similarly, the discovery of an atmosphere around Venus in 1761 led to speculation that hidden beneath the thick Venusian cloud cover was a lush and humid world. Venus as a 'water world' captured the imaginations of astronomers and science fiction writers alike. A quick browse through some of the science fiction novels written at the time reveals titles such as" Oceans of Venus" by Isaac Asimov, "Swamp Girl of Venus" by H. H. Harmon, and the classic "Golden Amazons of Venus" from J. M. Reynolds. Of course, the last two titles are from the so-called pulp era of science fiction in the 1930s and 40s, when scientific facts were often sidelined by fantastic adventure stories, now referred to as planetary romance.

Alas, the age of Venusian blondes waiting to be rescued by virile Earthlings ended abruptly in 1962 when NASA's *Mariner 2* spacecraft completed the first-ever flyby of the planet (or any planet for that matter). Recording atmospheric temperatures of 500 degrees Celsius (900 degrees Fahrenheit), there was no escaping the fact that the surface of Venus is hot enough to melt lead and that, sadly, there are no seas on Venus of liquid water and no Venusians.

B. Henin, *Exploring the Ocean Worlds of Our Solar System*, Astronomers' Universe, https://doi.org/10.1007/978-3-319-93476-1_1

A similar story followed with Mars, the Red Planet, which has long been a source of intrigue. Mars was first observed through a telescope in 1610 by Galileo Galilei, the father of observational astronomy. Unfortunately, his telescope wasn't powerful enough to reveal the planet's distinct surface features. We had to wait until 1659 when Christian Huygens, a Dutch astronomer, using a telescope he built himself, drew a rudimentary map of Mars, showing darkened surface features.

Convinced that these were signs of vegetation, Huygens published his belief in extraterrestrial life in his influential book *Cosmotheoros.* He was also the first man to see the white south polar cap of the planet, but he didn't recognize it as such. More than a century passed before it was correctly identified as water-ice by Sir William Herschel, a German-born British astronomer who nevertheless postulated that the dark areas on Mars were oceans. Herschel's work on Mars and the realization that the planet showed many similarities to our own gave credibility to the idea that there was liquid water, and therefore life, on the red world. He speculated that Martian inhabitants "probably enjoy a situation similar to our own."

The belief that water was flowing on Mars reached its height in the early 20th century. It was a result of the sloppy translation (Italian to English) of channels that led to the belief that canals built by Martians to irrigate the planet could be seen from Earth. The excitement died down over the course of the century as astronomers gained the ability to see the planet in more detail. The idea was finally laid to rest when the *Mariner 9* spacecraft orbited Mars in 1972 and returned images of a lifeless, utterly dry planet.

Suddenly our Solar System was inhospitable and barren. Gone were the Selenites, Venusians and Martians. Earth, our blue oasis, was the only place that could support life, and science fiction, one of the most imaginative and thought-provoking genres, had reached an impasse. As a result, swashbuckling spacemen moved on to the more promising lands outside of our Solar System with the help of warp engines and other faster-than-light travel methods, while our neighboring planets and moons were shunned.

The Jovian Revolution

As the title of this book gives it away, this would not last. Our understanding of the Solar System changed once again as evidence of liquid water was found in less obvious places – the moons of the outer planets. There, vast oceans of flowing water lie waiting to be explored.

The discovery of these oceans started as the two Voyager spacecraft, ironically conceived in the years when our Solar System was thought to be barren, embarked on long journeys that had, as their first stage, flybys of the Jovian moons. These close encounters would change everything.

In fact, despite their relatively small sizes, the satellites of Jupiter had already been game changers in the past, as they had played a remarkable role in the history of astronomy, science and our understanding of humanity's place within the universe. Described by Galileo Galilei in January 1610 as "three fixed stars, totally invisible by their smallness," they were found to be very close to the giant planet and even moved in a straight line across it. This configuration, and the fact that the 'stars' disappeared behind Jupiter only to reappear once again later, led the Italian astronomer to deduce that these were, in fact, moons. This straightforward yet significant discovery made Galileo the first person to see and understand that objects were orbiting another planet and this led to the unraveling of the Tychonic system (from the ancient Ptolemaic system that Earth was at the center of the universe).

The Italian astronomer, not imprudent, originally named these four moons after his patron, the Medici, and his siblings. Thankfully these names were lost in time, and today, we use the ones chosen by Simon Marius, a German astronomer who named them after Zeus's lovers in Greek mythology: Io, Europa, Ganymede, and Callisto.

Almost 400 years after their discovery, in 1979, Jupiter's moons would once again change our understanding of our Solar System. This time, it wasn't done with the help of Earth-based telescopes similar to Galileo's but with the most advanced technological tools of our modern age. We could now send robotic visitors to the moons.

As such, only twenty years after the Soviets sent the very first artificial object into space, the United States launched not one but two spacecraft: *Voyager 1* and *Voyager 2.* Taking advantage of a favorable alignment of the outer planets of our Solar System (next occurring in the year 2153), these new emissaries embarked on a grand tour, visiting not only Jupiter but Saturn, Uranus, and Neptune, too.

Before the Voyagers' grand tour, the only moon we knew relatively well was our own, whose official name is "Luna." Although magnificent to look at, our Moon is geologically inactive and somewhat dull. This led humankind to make the mistake of assuming that other moons would be like ours – interesting objects to study but much less attractive than a planet. Of course, we had already gathered information about other moons through Earth-based observations, mainly by analyzing their reflected light known as spectra.

These observations revealed not only that specific moons had icy surfaces but that they also displayed albedo and color variations as they rotated (suggesting diverse geological terrains). Because of this, scientists knew that they would encounter different moons. Nevertheless, with only one moon available for close observations – our own – the astronomers' best guesses were just that, guesses.

When the Voyager missions were being conceived, Jupiter's moon Europa (see Chapter 6 for a detailed review of this moon) was thought to be of little importance compared to the other Galilean satellites, as it was the smallest of the four. Io was a far more intriguing subject, with its colorful surface features faintly observed from ground telescopes. Ganymede and Callisto were so big that their size alone was a key attraction. (Let us not forget that Ganymede is bigger than Mercury and almost as big as Mars.) When it came to planning the routes of the Voyagers through the Jovian system, Europa was at the bottom of the list, not warranting a close flyby.

As we now know, scientists were in for a big surprise. When *Voyager 1* first reached the Jovian system in 1979 and flew past Europa, at the intended distance of 2 million km, the low-resolution images returned by the spacecraft were bewildering (Figs. 1.1 and 1.2).

The images returned a bright moon crisscrossed by mysterious intersecting linear features. Furthermore, most scientists expected that small celestial bodies would show a heavily cratered surface (like on our Moon) as they would lack sufficient heat to support active geology that reshapes surfaces and erode or erase craters. Where were the impact craters on Europa? Dark patches could also be seen on the surface, but few scientists had an idea of what these were. Through its density (derived from the mass and volume of the moon) and spectrum, Europa was known to be mainly a rocky moon with a relatively thin layer of water-ice. At first, this led scientists to believe that the lines observed on the surface were deep cracks within the ice crust, caused by unknown tectonic processes. Could it be that Europa was geologically active now?

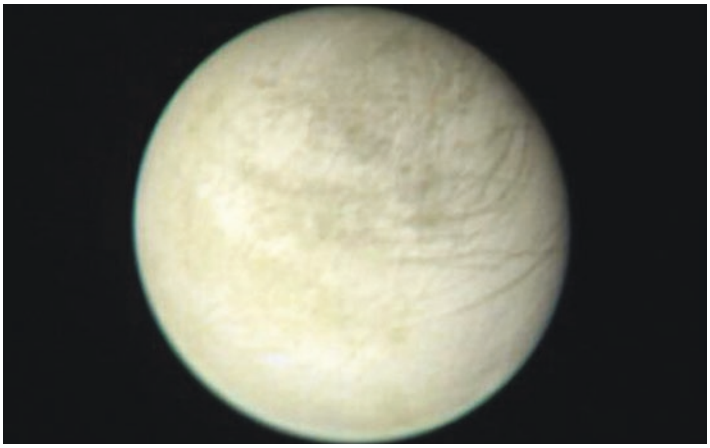


Fig. 1.1. Europa, the icy moon of Saturn, viewed by *Voyager 1* on March 4, 1979. This shot was the best resolution obtained by the spacecraft. We can see bright areas contrasting with dark patches, crisscrossed by long linear structures. (Image courtesy of NASA/JPL.)

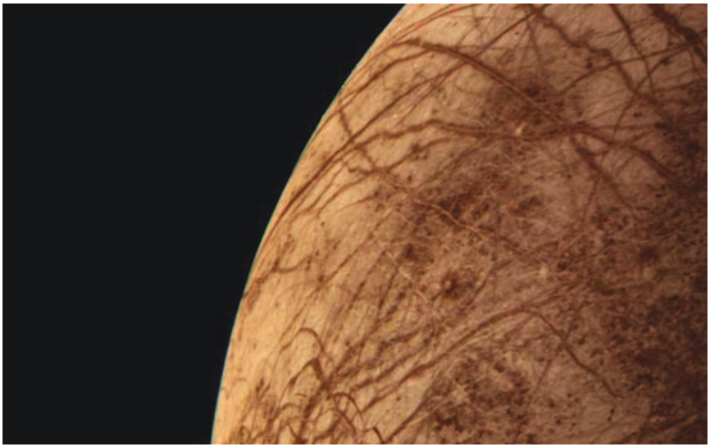


Fig. 1.2. Taken by *Voyager 2* on July 9, 1979. A closer look at Europa revealed few impact craters and a complicated, fractured crust. The lack of any mountains or craters is consistent with a thick ice crust. (Image courtesy of NASA/JPL.)

Fortunately, *Voyager 2* made a closer flyby four months later and returned high-resolution images from the surface.

These images allowed scientists to count the impact craters more precisely and revealed that Europa had very few of them compared to our Moon or the other Jovian icy moons, Callisto and Ganymede. Contrary to most expectations, Europa's icy crust was young – very young – maybe less than 100 million years old, which is a blink of an eye in planetary science. Also, the surface was very smooth, displaying little height variation that can only be explained if a surface is too elastic to keep tall features such as crater rims or cryovolcanoes. Somehow the icy crust wasn't as frozen solid as would be expected from an object lying so far away from the warmth of our Sun. The images returned by *Voyager 2* were unambiguous. Europa was an active moon capable of resurfacing itself.

That Europa, a small icy moon, could retain enough heat to stay active puzzled many scientists, and one hypothesis, tidal heating, proposed a few months before the Voyagers' flybys, soon gained the attention of the scientific community. This process had the potential to melt ices inside a moon, creating vast amounts of liquid water upon which a thick icy crust would rest – in other words, it would form a subsurface ocean. Ultimately heat exchanges between the subsurface ocean and the icy crust could deform and stress the ices, thus creating cracks within the surface. Could this new theory be the cause of the moon's unusual surface features? The scientific community was abuzz.

A New Form of Energy

To understand tidal heating, we must go back to when the Voyagers made close flybys of the moon Io, one of Europa's neighbors, and Jupiter's closest moon. Io had been a priority for the Voyagers, as a visit made five years earlier by another American spacecraft, *Pioneer 11*, hinted at a brightly colored yet undetermined surface. Astronomers were intrigued, and the Voyagers' trajectories were conceived in such a way that close flybys of Io could be performed.

When the high-resolution images from the Voyagers came back (see Fig. 1.3), they also revealed an active world, but this time not of ice but fire. Io was a dream world for volcanologists. The moon was peppered with volcanic calderas and tall mountains, upon which eruption plumes and lava flows, stained yellow and red by oxides of sulfur, would emerge. Remarkably, the surface seemed not to have a single impact crater, suggesting that the moon's surface was continually being renewed by volcanic activity. Io had a lot of energy.

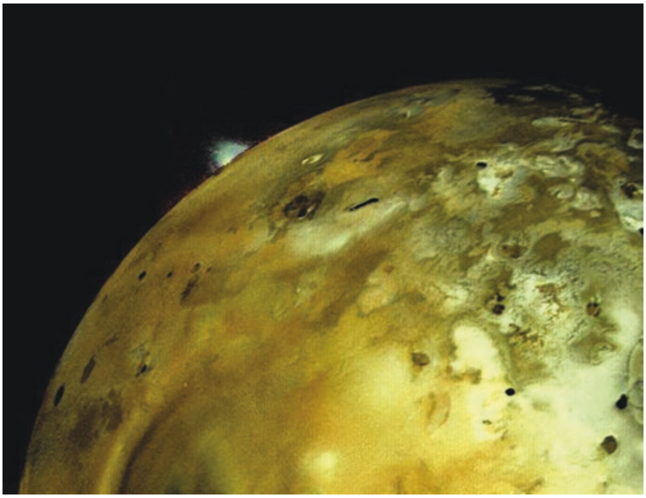


Fig. 1.3. A fiery Io captured by *Voyager 1* on March 4, 1979, the same day that the spacecraft took its best resolution image of Europa. The distance to Io is about 490,000 km (304,000 m). A volcanic explosion can be seen in the upper left ejecting solid material to an altitude of 160 km. (Image courtesy of NASA/JPL.)

Finding such an active world lying far away from the Sun was astonishing and led to a hunt for the source of Io's energy. The explanation came from a paper by Stanton Peale and his colleagues published in the prestigious journal *Science* just a few days before *Voyager 1*'s arrival in the Jovian system. The paper proposed that Io could be experiencing warming as it orbits Jupiter in a non-circular orbit (elliptical orbit), which produces variations in the gravity pull from the giant planet. This process was named tidal heating, and it didn't take long for this new theory to be accepted by the scientific community as the primary heat source driving Io's fiery temper.

What goes on inside Io can be easily demonstrated by using a simple metal wire. If you happen to have one to hand, flex one part of the wire backward and forwards. It doesn't take long for heat to be felt in the bendy part. The explanation is simple. Some of the kinetic energy was transformed into heat through internal friction. A similar process also makes squash balls warm after a match.

The reason behind Io's energy output is its elliptic orbit resulting from a phenomenon known as orbital resonance, which locks each Galilean moon into a specific orbital ratio around

Jupiter. For every two orbits that Io takes around the planet, Europa takes precisely one orbit. Due to orbital mechanics, both moons always come closest to each other at the same location within their orbits, pulling Io closer to Europa, thus making it elliptical instead of circular. (Similarly, for every two orbits that Europa takes, Ganymede makes precisely one orbit. This 4-2-1 sequence dictates the orbital eccentricity of these three Jovian moons, as we shall see in subsequent chapters.) Elliptical orbits are measured by their eccentricity. The greater the eccentricity, the more elliptical the orbit will be and vice versa.

Since Io's orbit around its giant parent planet is not a circular one but an elliptical one, the moon will feel Jupiter's gravitational pull differently along its orbit. This is referred to as tidal forces and is similar to the gravitational effect our Moon has on the seas and oceans of Earth. On Io, the tidal forces will be most influential during the moon's closest approach in orbit (periapsis) than during its furthest point (apoapsis). As it moves from periapsis to apoapsis and back, the tidal forces pull Io at varying intensities, thus creating friction and generating heat as the moon's interior repeatedly distorts and buckles.

Of course, many factors determine how much impact tidal forces can have on an object. The size of the moon in relation to its parent planet as well as the distance of the moon's orbit will be determining factors. As importantly, the composition of the moon itself will dictate how strongly it responds to these distortions. If the object is rocky, like our Moon, it will distort far less than if it is made entirely of ice. The measurement of the rigidity of a planetary body, and the ability of its shape to change in response to a tidal potential, is called the Love number (introduced in the early 20th century by the famous British mathematician Augustus Edward Hough Love).

By analyzing its orbit around Jupiter, astronomers deduced that Io has roughly the same density as silicate rock, which means that the inside of the moon must consist mainly of rocky material. This material is flexible enough to feel the effects of Jupiter's strong gravitational pull, but not so fragile as to be pulled apart by it. Therefore, the rocky core and mantle get stretched and squashed at every orbit, producing vast amounts of heat through friction, which in turn fuels the volcanism observed on the surface.

With Io's power source now well understood, Europa's mysterious heat source was a mystery no more. Due to its resonance with Ganymede and Io, it was also being pulled apart by tidal forces, although not as intensely as Io. Could the heat generated by the tidal forces be capable of melting parts of Europa's thin icy crust and – gasp – create a subsurface ocean? No one could tell for sure, but this was undoubtedly the central thesis proposed to explain the moon's deformed surface. Future investigations would be required to test this idea.

After Io and Europa, scientists turned their attention to Ganymede and Callisto. Ganymede's surface didn't have Europa's pizzazz, but it did show two distinct terrains: one dark and cratered (and therefore old), and the other grooved, with fewer craters (implying recent geological or tectonic activity). Was this a result of tidal heating? Was the moon still generating heat, like Io and Europa were? If so, was this activity sufficient to create and maintain a subsurface body of water? Unfortunately, none of these questions could be answered confidently with the images returned by the Voyagers' flybys. We would have to wait for future missions to start providing some answers. (Chapter 4 reviews Ganymede in more detail) (Figs. 1.4 and 1.5).

Fig. 1.4. This picture of Ganymede was taken on March 5, 1979, by *Voyager 1* at a distance of 272,000 km. The bright areas contain grooves and ridges indicating geological activity, while many older impact craters have been eroded over time. (Image courtesy of NASA/JPL.)