Appendix A: Mimas

With a radius of only 198 km, making it 20% smaller than Enceladus, Mimas is ridiculously tiny compared to most ocean world candidates. In fact, it is the smallest known object in our Solar System that is rounded in shape due to its own gravitation. Objects with smaller dimensions start to have potato shapes such as Hyperion (135-km radius) or are half-finished spheres such as Phoebe (106-km radius), both moons of Saturn as well. Mimas is mostly composed of water-ice and has a small rocky core, making it barely massive enough to have an entirely rounded shape, as Saturn's gravity stretches the tiny moon into a slightly egg-shaped ovoid. The diameter facing the planet is longer by 9% than the diameter perpendicular to its orbit (209 × 196 × 191 km).

Mimas is also a densely cratered moon with one side entirely disfigured by a giant impact crater named Herschel after the moon's discoverer. At 139 km across and 5 to 7 km deep, the crater walls rise a further 5 km high, it is one of the biggest craters relative to its parent body in the entire Solar System.

Before the Space Age, Mimas was just a speck of light. This all changed when *Pioneer 11* whizzed past the moon on July 31, 1979, at a distance of 104,263 km, and took an image as it was transiting in front of Saturn. Alas, the image was of poor quality, and planetary scientists had to wait a year later for *Voyager 1's* more capable imaging system to reveal Mimas as we know it now.

Furthermore, *Voyager 1* allowed scientists to accurately calculate Mimas' density at 1.15 g/cm^3, close to that of water, implying that the moon was mainly composed of water-ice contrary to other icy moons of Saturn, which also had a significant rocky core

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like Enceladus, Tethys, Rhea, Dione, and Iapetus. Mimas was a very different type of moon altogether. Some refer to it as a giant snowball.

Nevertheless, scientists felt compelled to compare Mimas with Enceladus, given their relatively similar sizes and location. In addition, both moons are in resonance with another moon – Mimas with nearby Tethys and Enceladus with Dione – and both display eccentricities in their orbits, with Mimas' eccentricity at 0.0196, making it four times bigger than Enceladus' at 0.0047. This was a surprising find. According to a paper published in 1983, given the parameters above, "Mimas should currently be tidally heated at a rate at least twice that of Enceladus if Mimas' rigidity is like that of rock, and as much as 30 times if its rigidity is the same as Enceladus."

Nevertheless, Mimas shows no evidence of recent tectonic activity. Indeed, *Voyager 1* revealed the moon to be solidly frozen at a temperature of 64 K (−209 °C). This became known as the 'Mimas paradox' or 'Mimas test.' As much as Enceladus' surprisingly active geology required explanation, Mimas' inactivity was as compelling. Any theoretical models put forward to account for Enceladus' characteristics also had to do the same for Mimas and vice versa. This paradox proved to be frustratingly tricky for planetary scientists and would only be solved decades later, thanks to new data from the Cassini spacecraft.

Another surprise from the Voyager flyby was, of course, Hershel Crater. It is not unique within the middle-size icy satellites, as Tethys, Dione, Rhea, and Iapetus also host several large impact basins whose diameters are a substantial fraction of the satellite's diameter. (Enceladus is the odd one out here due to its younger surface.) However, Hershel is the most remarkable. At one-third of the moon's diameter, it is the largest in relation to the size of the moon. In some parts, it is 12 km deep and hosts a central peak which rises to 8 km in height. As craters go, this one is extremely deep.

What's more, large troughs similar to shock waves 10 km wide were found across the moon's surface, suggesting global-scale fractures created from the Hershel impact event. If the impactor had been a little bit bigger or come at a faster speed, it might have broken up the moon, which most likely would have ended up as one of Saturn's ring. With such upheaval and no signs of past or present geological activity, how could this small moon have been considered by some to host a subsurface ocean? Images from the Cassini orbiter would prove intriguing.

Observations from the Cassini orbiter during its 13 years within the Saturnian system gave a better picture of Mimas. For a start, Saturn's satellite and ring system were studied in far more detail than had been possible previously, and it was found that due to its position – and despite its low mass – tiny Mimas was responsible for the Cassini division, a 4800-km wide gap between Saturn's A and B rings. Actually, Mimas is locked in resonances with many objects or features within the Saturnian system, such as the Huygens gap, the G-ring, objects lying between the C and B ring, nearby moons Dione and Enceladus as well as with the larger moon Tethys (2:1 resonance) and the tiny moon Pandora located in the outer F Ring (2:3 resonance).

The precise measurements of all these complex interactions allowed scientists to finally resolve the Mimas paradox. Indeed, the moon's resonance with Tethys, which was initially thought to add tidal heating to Mimas (in a similar way Enceladus is in resonance with Dione), is a different type of resonance and isn't responsible for the tiny moon's eccentricity. Instead, the resonance both moons share is related to the inclination in their orbits, as these are tilted with respect to the orbital planes of Saturn's satellite system. As they orbit Saturn – Mimas orbits twice for each orbit of Tethys – they meet up not at the closest point of Mimas' orbit (periapsis) but instead at multiple locations throughout their orbits. As a result, Tethys doesn't pull Mimas into another orbit and is not responsible for the moon's eccentricity. In fact, when we take into account all the interactions Mimas has with the objects orbiting Saturn, we find no source for the moon's eccentricity, suggesting that it is most likely a leftover process, a fossil from earlier times, when the moons were in different orbits. (Saturn's spin would push the moons further away with time thus altering their orbits.) Recent simulations have shown that around 2 billion years ago, Mimas might have gone through a 2:3 resonance with Enceladus, generating much eccentricity that has decayed ever since.

In addition, the high-resolution images from the Cassini orbiter have also revealed that no surface was left intact by the intense bombardment Mimas experienced throughout the ages. With no internal processes to erode or erase them, the frozen surface has preserved the craters for billions of years. However, by carefully studying the surface craters, it was found that the south pole region hosts craters half the average size (ranging from 20 km in diameter or less), hinting at possible resurfacing processes at some point in the moon's life. (Coincidentally, Enceladus' most active region is also located at the south pole.) In support of such interpretation, the depth of the Herschel Crater and soft features observed on its rims indicates that it formed as a flexible, slushy surface, hinting that the moon's surface and interior might have been much warmer in the past, most likely due to greater orbital eccentricity.

As such, an increased eccentricity must have pumped heat into the moon, softening it and giving it its round shape. Some scientists have therefore speculated that it could have potentially been warm enough to allow its small icy interior to melt and form a small subsurface ocean.

Although Mimas' paltry size and lack of meaningful rocky core meant that it probably couldn't retain a subsurface ocean for long periods of time, this idea raised eyebrows among Cassini mission researchers, as a perplexing pattern in the moon's motion was discovered – Mimas was wobbling. Referred to as libration, this perceived oscillation motion might reveal what lies inside the moon. The properties of a raw and a hard-boiled egg are often used to explain this concept. If you place both eggs on the table and spin them, you will notice that the hard-boiled egg spins evenly and at a fast pace, while the raw egg will be slower and spin unevenly as the white and yolk slosh around inside.

By using images returned from Cassini, initial studies published in 2014 found that Mimas wobbles twice as much as predicted if it had a typical solid interior. The study concluded that this could only be explained by two possibilities: either Mimas contains a frozen interior with a non-spherical elongated core in the shape of a rugby ball or an American football, or it hosts a subsurface ocean (like the sloshed liquid inside a raw egg). Both possibilities have problems, though. Hosting a non-spherical core is not what would be expected from a planetary object billions of years old, as central cores relax into a spherical shape with time. On the other hand, the presumed existence of a subsurface ocean was puzzling as well, since the moon hasn't shown any substantial geological activity on its surface for billions of years, and its tiny size should make it impossible to retain heat for a significant period. The study showed that if a subsurface ocean was indeed present, it should lie within 24 to 31 km below the surface and be global. Although most planetary scientists remained skeptical about this study, some were hopeful that Mimas could be an ocean world candidate.

Alas, all this changed when a new paper published in February 2017 put a blow to the subsurface ocean theory. In this new study, it was calculated that the stresses on Mimas' icy crust induced by a subsurface ocean were much too strong and would produce over time large surface fractures within the crust. Since no fractures could be observed on the moon's surface, Mimas never hosted a subsurface ocean. Instead, the moon's libration was best explained by it possessing a small silicate core that initially started as a sphere but was later pushed askew by a strong impact (such as the one creating Herschel Crater), giving the moon such an asymmetric angular moment.

Given this latest research, it seems therefore that despite Mimas experiencing past tidal heating, a subsurface ocean has most likely never been formed. Future missions to Mimas will hopefully provide conclusive evidence that its libration is indeed induced by an ovoid core.

Appendix B: Relic Surface Oceans

Three Waterworlds

Although the main coverage in this book is of the subsurface oceans in our Solar System, there is a sense of perspective to be gained by reviewing planets that had surface oceans in their past.

As explained in Chapter 2, Earth, Mars, and Venus were bombarded by ice-rich bodies after their formation, allowing them to amass a substantial amount of water on their surfaces. Now, imagine these planets – actually no – imagine three waterworlds all bathed in deep blue oceans and ringed by billowing white clouds drifting high up in their atmospheres. On the first of these waterworlds, two continents rise above the water: Ishtar Terra and Aphrodite Terra. Although the latter is the largest, the former hosts the highest peak, towering 11 km above sea level.

On the second of these waterworlds, the northern hemisphere is entirely covered by water, while the southern hemisphere is a giant continent to itself containing a vast inland sea residing inside the most prominent crater on the planet, Hellas Basin.

And finally, the last of these waterworlds holds a vast ocean upon which a supercontinent lies, waiting to be partitioned in a not too distant future. Planetary scientists have proposed that roughly 500 million years after their formation, Venus, Mars, and Earth enjoyed similar if not identical environments for tens of millions of years, including vast oceans, surface temperatures above freezing, and a rich atmosphere.

Interestingly, there are tantalizing clues that life might have already appeared on Earth during this period (see Chapter 3). Could

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life have started on Venus and Mars as well? It is an intriguing thought. Cross-seeding might have occurred between the three planets through the process called panspermia. We might be Martians or Venusians.

But that was then. Nowadays oceans of water are not what one immediately pictures when we think of our neighboring planets. Venus blanketed with a thick atmosphere, suffers average surface temperatures of 735 K (462 °C or 863 F) and atmospheric pressures 92 times that of Earth's. Think of it as a planet-size pressure cooker, making the planet's surface one of the driest places in the Solar System.

Mars, on the other hand, is the opposite. Lacking a dense atmosphere, low pressures inhibit liquid water on the surface, as it will sublime directly into water vapor. Therefore, most of the planet's water is trapped in polar caps or underground ice. Venus' and Mars' primordial oceans changed with time. On Venus, the water moved into the atmosphere, while on Mars it went underground. Luckily for us, Earth had the right conditions to sustain its surface oceans for billions of years. What happened to our neighbors? Why did they lose their surface oceans? Let us review each one in detail.

Blue Mars

Mars is the most well-understood planet in our Solar System after our own. Although this isn't saying much, since there are still large gaps in our knowledge, it does illustrate how the second smallest planet in our Solar System has fascinated us ever since we looked up at the night sky. The figures speak for themselves; at the time of writing Mars had been visited by 55 spacecraft (taking into account all various flybys and gravity assists), making it the most visited object in our Solar System closely followed by Venus with 43 missions. Out of those 55 missions launched since the 1960s, only 25 succeeded in achieving their primary science goal (see Figs. 3.1 and 3.2 in Chapter 3).

The USSR and subsequently Russia holds the unenviable title for the most failed missions, with a total of 20 out of 22. Ironically, the only two Russian spacecraft that did manage to orbit Mars in the early 1970's did so while an unexpected dust storm raged on the entirety of the planet, rendering most images unusable.

Out of the successful missions, though, we've had twelve orbiters, three flybys, two gravity assists, four landers, and four rovers. NASA holds the lion's share by launching nineteen of these missions, ranging from its first flyby that lasted two days (July 14–15, 1965) to its longest-serving planetary robot, Opportunity, now active for more than fourteen years on the surface (as opposed to its original planned mission duration of only three months).

So what have all these robotic emissaries taught us about Mars' past? We now know that it was wet and remained so for a period. In 2015, NASA's Curiosity rover found evidence that Gale Crater had a long-lived lake. The amount of liquid water and the time this water stayed on the surface is still open for debate among planetary scientists, yet a consensus is slowly starting to emerge in the last few years. It now seems that Mars once had an ocean and maybe two. Let's review the evidence.

To start off with, due to the planet's small size, its interior cooled off rather quickly, which brought to a halt tectonic and volcanic activity. As a consequence, the planet's crust solidified early on in its history, contrary to our planet, which regularly resurfaces the crust every few hundred million years. Therefore, original surface features that were erased a long time ago from Earth's surface remain relatively unchanged on Mars, allowing us to travel back in time and analyze rocks and geological formations that are billions of years old, a rarity on Earth. Given this, you would expect that any claim of the existence of ancient oceans on Mars would be backed up by visible evidence of surface features such as shorelines, deltas, and channels feeding into these oceans as well as evidence of inland rivers generated by falling rain (part of the water cycle caused by a nearby ocean).

When the NASA Viking orbiters sent back detailed images of the planet's surface in the 1970's, some researchers thought they had detected ancient shorelines along the boundary between the northern and southern hemispheres. Not everyone was convinced, though, as the evidence was weak at best and subject to interpretation. Images returned from later orbiters weren't conclusive either, despite unprecedented imaging capability. Frustratingly, traces of ancient shorelines and sea cliffs just couldn't be visible despite new lines of evidence uncovered in the last fifteen years in support of the ocean hypothesis.

One such piece of evidence includes numerous regions within the northern hemisphere where scientists found remnants of deep channels carved by rain as well as the existence of lakes that must have lasted millions of years (similar to the one found in Gale Crater). Such features can only be explained if a large body of water was present for a significant amount of time to bring about the conditions required for cloud formation and rainfall. In addition, many ancient deltas were observed at an altitude where the shoreline was thought to be situated by the ocean hypothesis. These deltas, characteristic of a river entering slow-moving or standing water, suggest that this theoretical yet unseen shoreline remained stable for a long period.

In 2012, the European Space Agency published results collected by the Mars Express orbiter revealing a subsurface blanket of low-density material around the northern polar cap. Contrary to the southern hemisphere, which is comprised of hardened volcanic flows, the presence of low-density material in the northern hemisphere, potentially rocky material mixed with ice, suggests sedimentary material, tens of meters thick. This supports the idea that material was deposited on an ocean floor due to standing water.

What's more, in 2015, after six years of atmospheric observations, scientists found a high ratio of deuterium in the planet's atmosphere indicative that ancient Mars contained much higher water levels than it does today. As you might recall from Chapter 2, deuterium is the hydrogen isotope that forms heavy water molecules. In the past, as these molecules of water evaporated from the surface, they encountered lethal solar radiation high up in the atmosphere and got split in the process. The oxygen dissipated into space while the hydrogen isotope accumulated in the atmosphere, acting like a marker. Measuring its concentration in the current atmosphere not only reveals that water molecules were present in the planet's past but also allows us to extrapolate how much quantity there was. Indeed, since water on Earth and Mars started off with the same D/H ratio, we can measure the difference and calculate how much 'light water' was lost. And the figure is telling.

The concentration of deuterium in Mars' atmosphere is about eight times as much as on Earth. This points to a significant loss of water over time, with some models suggesting that Mars had enough water to cover the planet to a depth of 137 m. All this water must have accumulated in an ocean at the lowest point on the planet, the northern hemisphere. The reason for the disappearance of all this water is one of the areas that is still being researched, but it is commonly agreed that Mars' lack of a protective magnetic field prevented its nascent atmosphere from withstanding the continuous blows from the solar wind, stripping it away during millions of years. This, in turn, reduced the atmospheric pressure that led to the slow but inevitable evaporation of the surface water as well as a substantial drop in the temperature, forcing any remaining freezing water to stick to the ground.

Finally, recent discoveries have also shed new light on the paradox of the perplexing lack of clearly defined shorelines. Thanks to the resolution power of NASA's HiRISE; a powerful telescope orbiting the Red Planet, scientists discovered unique surface formations dotted along the boundary between the northern and southern hemispheres. On Earth, these features are mounds of deposited sediments and are called thumbprint terrain. It was previously thought that they were the result of glaciers or mud moving downhill from volcanoes, but it has now been shown to be a leftover feature of one or multiple tsunamis hitting the shorelines. Finding these thumbprint terrains on Mars has led some scientists to suggest that over 3 billion years ago a giant asteroid hit the planet in what was once the northern hemisphere ocean. An asteroid impact could create multiple tsunamis that would have plowed the coastline of the ancient ocean and buried its shorelines with large deposits. In support of such claim, it has been suggested that the impact site for such an event was Lomonosov Crater, a 120-km wide bowl in the northern hemisphere. Such a hypothesis not only provides further evidence for the existence of an ocean, as tsunamis require vast amounts of water to be created, but it would also finally explain why the ancient shorelines haven't been found.

More scientific data will be collected by future Martian missions, allowing scientists to characterize this possible ocean with much greater certainty and detail, as many questions remain to be answered, such as, was it icy cold and slushy or relatively warm? What was its composition? How did it alter through time? How did it interact with the atmosphere?

This very brief outline of the likelihood that an ancient surface ocean was present on the fourth planet from our Sun doesn't do justice to this fascinating subject. Many intriguing points could be explored (such as the possibility of finding, in the northern hemisphere, substantial amounts of water-ice hidden under a thin layer of dust, the leftover of the frozen ocean). On the other hand, some scientists are not convinced of the ocean hypothesis, as current models have a hard time sustaining an atmosphere capable of supporting a surface ocean for an extended period.

Even though our goal in this book is not to cover this topic in great depth, this brief overview showcases how a systematic and comprehensive exploration program of a planetary body can provide multiple lines of evidence that complement each other; it also highlights the vulnerability of surface oceans, which can be disrupted or even lost, if not by catastrophic events, then by the slow disappearance of a protective atmosphere.

In contrast, subsurface oceans can remain stable for billions of years, making them unique environments within our Solar System. Let's now visit the second planet to the sun, Venus, as it also has a story to tell, one that demonstrates the inherent difficulties of space exploration.

Blue Venus

Imagining an ocean of liquid water on Venus' surface seems ludicrous. Extremely high temperatures prevent any liquid water from lingering at its surface today, yet many scientists are now considering the possibility that the planet had a wetter past lasting for hundreds of millions of years, if not billions of years, even though finding the evidence to support such a hypothesis has to face two inescapable realities.

Firstly, due to the harsh conditions present on the surface, no spacecraft, lander, or rover will be capable of investigating the surface of Venus in a similar way that we have methodically explored Mars throughout the last decades. Although the engineering challenge would be welcomed by many, the astronomical cost of building and sending a robot capable of surviving the Venusian surface for extended periods of time would bring sleepless nights to any financial planners. There will never be a 'Venusian Opportunity rover' busy exploring the surface for more than ten years.

Regardless, such a mission is not required, as – and this is the second point – Venus has a very dynamic geology and experiences regular extensive volcanic activity that resurfaces its crust. In complete contradiction with Mars, which has its past out there in the open for anyone curious enough to investigate, Venus has erased all surface evidence of its distant past, leaving little hope for researchers eager to study such features.

So, if we can't see shorelines, deltas, channels, and sedimentary rocks, what makes scientists confident in their assertion that Venus was once a blue planet? The case for past Venusian oceans derives from our understanding of the formation of our Solar System. In effect, the way we appreciate the planet today has benefited from the comprehensive robotic exploration of the Solar System carried out in the last fifty years by the major space agencies. From studying asteroids, comets, and the inner planets, and establishing theories on how these bodies were formed, we have learned to uncover Venus' past.

In Chapter 2, we explored the idea that most inner planets were pounded by water-rich asteroids (and sometimes comets), and both Mars and Earth held vast amounts of water. Venus was no exception. The fact that it resides a bit closer to our Sun than Earth or Mars doesn't change the fact that it was also composed of the same stuff. Therefore, Venus also had deep oceans in the early part of its history. It was a blue planet.

Luckily, in those early years, our Sun was dimmer, according to the standard model, roughly 40% less bright than it is today. Therefore Venus received less heat from solar radiation, and models show that it could have sustained oceans on its surface for a very long time. For how long? We don't know. Maybe for a few hundreds of millions of years to a billion years. Once our star started to increase its energy output, more sunlight hit Venus' thick atmosphere, trapping an increasing amount of heat, warming it up.

This started an evaporation process that sent huge amounts of water vapor into the atmosphere. With no magnetic field present on Venus, ultraviolet radiation from our Sun collided with the water molecules high up in the atmosphere and broke them apart, resulting in the oxygen molecules being leaked out into space. Little by little, Venusian oceans evaporated into the atmosphere, and some parts were blown away into space. Luckily for us, this process has left a trace in Venus' atmosphere, and we have been able to measure the deuterium ratio, as we have done on Mars. Scientists have found a high D/H ratio within Venus' atmosphere today, a clear indicator that the planet had a much wetter past capable of supporting oceans. More robotic exploration is required if we want to unveil Venus' relic ocean.

Once again, the topic of past Venusian oceans is an intriguing one, worth more than the few pages presented here. Although much remains elusive, it does show once again the vulnerability of bodies of water on the surface of a planetary body.

Conversion Tables

Temperature scales

Kelvin (K)	Celsius (°C)	Fahrenheit (°F)
0	−273	−460
173	−100	−148
233	−40	−40
253	−20	−4
255	−18	0
273	0	32
293	20	68
310	37	99
373	100	212
423	150	302
473	200	392
773	500	932
1273	1000	1832
2273	2000	3632

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Distance scales	
Kilometers	**Miles**
1	0.6
50	31.1
100	62.1
150	93.2
200	124.3
250	155.3
300	186.4
350	217.5
400	248.5
450	279.6
500	310.7
650	403.9
700	435.0
750	466.0
800	497.1
850	528.2
900	559.2
950	590.3
1,000	621.4
1,100	683.5
1,200	745.6
1,300	807.8
1,400	869.9
1,500	932.1
2,000	1,242.7
3,000	1,864.1
4,000	2,485.5
5,000	3,106.9
10,000	6,213.7

Astronomical unit

AU	Kilometers
1	15,00,00,000
2	30,00,00,000
3	45,00,00,000
4	60,00,00,000
5	75,00,00,000
10	1,50,00,00,000
15	2,25,00,00,000
20	3,00,00,00,000
30	4,50,00,00,000
40	6,00,00,00,000
50	7,50,00,00,000
100	15,00,00,00,000

Glossary

Albedo (meaning "whiteness") The measure of the solar radiation reflected back from a planetary object.

Archaea One of the three great domains in life (bacteria and eukaryotes are the other two), these simple life-forms lack a nucleus to store their DNA. Archaeans include inhabitants of some of the most extreme environments on the planet and may be the only organisms that can live in extreme habitats such as thermal vents.

Astrobiology The study of the origin, evolution, distribution, and future of life in the universe. It lies at the interface between biological sciences and planetary sciences.

Bacteria One of the three great domains in life (archaea and eukaryotes are the other two), these simple life-forms lack a nucleus to store their DNA.

Biosignature Any phenomenon produced by life.

Core The planetary core consists of the innermost layer(s) of a planetary object and may be composed of solid or liquid matter.

Crust The outermost solid shell of a planetary object. It is usually distinguished from the underlying mantle by its chemical makeup; however, in the case of icy satellites or dwarf planets, it may be recognized based on its phase (solid crust vs. liquid mantle).

Differentiation The transformation of a homogenous body into a heterogeneous body. If a planetary body is large enough it will develop a core, mantle, and crust, each of which may be further subdivided. Each layer of Earth has its own set of subdivisions, for example upper, middle, and lower crust.

Eccentricity The orbital eccentricity of an astronomical object is a parameter that determines the amount by which its orbit around another body deviates from a perfect circle. A value of 0 is a circular orbit, values between 0 and 1 form an elliptical orbit, 1 is a parabolic escape orbit, and greater than 1 is a hyperbola.

Extremophile Any organism (particularly microorganisms) that inhabit extremes of chemical or physical conditions.

Frost line (Snow line or ice line) location in our Solar System where it is cold enough for volatile compounds such as water, ammonia, methane, carbon dioxide, and carbon monoxide to condense into solid ice grains.

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Habitability The potential of a planetary body to have habitable environments hospitable to life, or its ability to generate life endogenously.

HP ice or high-pressure ices: As water-ice (1 h at $P = 1$ atm) is compressed at low temperatures, it undergoes a series of phase transitions between different molecular structures.

Hydrothermal vents Sources of hot, mineral-rich waters located in fractures on deep-ocean submarine ridges. One of the candidates for the emergence of life on Earth.

Late heavy bombardment (LHB) A period from around 4 to 3.8 billion years ago when intense comet and asteroid bombardment occurred.

Mantle The layer between the crust and the outer core. It is often divided into layers of different composition.

Ocean world A planetary object that hosts a subsurface ocean of liquid water (and other non-water components).

Organic chemistry The study of the carbon-based structures, properties, and reactions of matter in its various forms.

Panspermia The theory that life on Earth originated from microorganisms or chemical precursors of life present in outer space and able to initiate life on reaching a suitable environment.

Peroxides Any class of compounds in which two oxygen atoms are linked together by a single covalent bond.

Photochemistry The study of chemical processes that occur because of the absorption of light.

Planetary body A term used to describe planets, satellites, and asteroids.

Planetary protection The prevention of the contamination of other planetary bodies or the contamination of Earth with extraterrestrial organisms.

Serpentinization An exothermic chemical reaction between rocks (rich in magnesium and iron) and water, giving rise to strongly alkaline fluids saturated in hydrogen gas.

Spectra (Pl. of *spectrum*) The full range of all frequencies of electromagnetic radiation.

Subsurface ocean A large body of liquid water lying underneath an icy crust or mantle of a planetary object (mainly in icy satellites or dwarf planets).

Tidal heating Orbital energy dissipated as heat in either a surface ocean or the interior of a planet or satellite.

TNO (Trans-Neptunian Object) Any planetary body in the Solar System that orbits the Sun at a greater average distance (semi-major axis) than Neptune, 30 astronomical units (AU). This includes the Kuiper Belt and the scattered disc.

Tholin Brownish-red substances made of complex organic compounds.

Volatiles Elements or compounds that melt or boil at relatively low temperatures. Examples include hydrogen, helium, methane, and water.

For Further Reading

Books

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