The when and where of water in the history of the universe

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Abstract

It is undeniable that life as we know it depends on liquid water. It is difficult to imagine any biochemical machinery that does not require water. On Earth, life adapts to the most diverse environments and, once established, it is very resilient. Considering that water is a common compound in the Universe, it seems possible (maybe even likely) that one day we will find life elsewhere in the universe. In this study, we review the main aspects of water as an essential compound for life: when it appeared since the Big Bang, and where it spread throughout the diverse cosmic sites. Then, we describe the strong relation between water and life, as we know it.

Keywords

water; life; universe; H₂O; astrobiology

1. Introduction. Why water is essential for life?

It is well known that liquid water has played the essential and undeniable role in the emergence, development, and maintenance of life on Earth. Two thirds of the Earth’s surface is covered by water, however fresh water is most valuable as a resource for animals and plants. Thus, sustainability of our planet’s fresh water reserves is an important issue as population numbers increase. Water accounts for 75% of human body mass and is the major constituent of organism fluids. All these facts indicate that water is one of the most important elements for life on Earth. Thus, “follow the water” has become a mantra of the science of astrobiology (Irion 2002).

Water is present on the surface of our planet at ambient temperatures and pressures in three different states: liquid, vapor and solid. Water is also found everywhere in the universe: in the most distant galaxies, among the stars, on the Sun, on planets and their satellites and ring systems, in asteroids, and in comets. Water exhibits unique properties that make it extremely important for life as known on Earth. First, it is the only substance on Earth that is abundant in liquid form at temperatures commonly found on the planet’s surface. Second, it is a superb solvent, implying that other substances can easily dissolve in it. Thus, water carries nutrients to cells and is used to wash away the waste (Lynden-Bell et al. 2010).

Water is formed from two very abundant elements in the universe: hydrogen, the most abundant element, and oxygen, the third (Helium is second) most abundant element in the universe.
In this chapter we discuss when did water appear after the Big Bang, where did it spread in the universe, what potential roles did it play in the emergence of life? First we discuss the physical and chemical characteristics, and then, turn to the history of water in the universe, its cosmic formation, and abundance. Next, we individually discuss the diverse cosmic sites, from distant galaxies to nearer stars and planets, where water has been discovered. Finally, we describe the strong relation between water and life, as we know it, and formulate conclusions about the great endeavor of determining the when and where of water in the universe’s history.

2. What is water?

2.1. Chemical properties of water

Water molecule includes two hydrogen atoms and one oxygen atom, connected with a strong polar covalent bond. Water molecule are stable and can last for millions and even billions of years. Water forms in a chemical reaction of two molecules of hydrogen (H\textsubscript{2}) with one molecule of oxygen (O\textsubscript{2}), as shown in Eq. .1:

\[ H_2 + H_2 + O_2 = H_2O + H_2O \] (1)

This process is one of the most exothermic among known chemical reactions, with released energy of 572 kJ/mol (Hanslmeier 2010).

The water molecule is not linear but has a shape of a triangle (Fig.1). At the apex is the oxygen atom, with two hydrogen atoms forming an angle of 104.5°. With six valence electrons, oxygen needs eight to fill its valence shell. Thus, it shares two electrons from the two hydrogen atoms, which become positively charged. Since the small hydrogen atoms have weaker affinity for electrons than the large oxygen atom, the molecule is bent, and the two hydrogen atoms appear on the same side. Water is thus classified as a polar molecule because of its polar covalent bonds and its bent shape (Encrenaz 2007).

The polarity of water explains why it is an excellent solvent. Water can induce temporary dipoles in even non-polar molecules, and interact differently with charged and polar substances. The polar molecules interact with the partially positive and negative ends of the water molecule, which results in the formation of a three-dimensional sphere of water molecules surrounding the solute. Water can thus solve and accumulate a variety of substances that are important for life. If the bonds were linear, then water would not be a strong solvent, which could affect the origin of life on Earth.

2.2. Physical properties

On Earth, water is the only substance that exists naturally in all three phases: gas, liquid, and solid. Its unique properties have allowed life to be possible on Earth. Hanslmeier (Hanslmeier 2010) wrote:

- Liquid water is more dense than water ice. This is essential for life because ice always forms at the surface, protecting life bellow it from freezing:
The pH of pure water is neutral, value of 7, which is neither acidic nor basic;

Water boils at 100°C and freezes at 0°C under normal pressure conditions.

Liquid water boils at a temperature at which vapor pressure reaches the environmental pressure around the liquid. The higher is the environmental pressure, the higher is the temperature at which the liquid will boil. This temperature is known as the boiling point. At standard pressure\(^1\), water boils at 100°C. The pressure on the top of Mount Everest is 260 Pa, where the boiling point of water is 69°C.

The curves on the phase diagram shown in Fig. 2 correspond to the boundaries between the different phases of water, according to the temperature and pressure. The triple point, at the intersection of the three curves, indicates the pressure and temperature where water can coexist in all three phases. It is at a temperature of 0.01 °C (273.16K) and a pressure of 611.657 Pa. At a low pressure of just 7,000 Pa, water boils at 38.5°C. This is about one order of magnitude higher than the atmospheric pressure on Mars. Therefore, liquid water cannot exist on the Martian surface at present. Despite that, salty liquid water seems to flow from some steep, relatively warm slopes on the surface of Mars (Gough et al. 2016). This is addressed in the Section 4.5.3.

\(^1\) The standard pressure is the pressure at 1 bar (100 kPa, the current IUPAC - International Union of Pure and Applied Chemistry - definition). The standard reference conditions are: temperature 0°C, pressure 100 kPa. The standard atmosphere (symbol: atm) is a unit of pressure defined as 101,325 Pa (1.01325 bar)
Figure 2: Log-lin pressure-temperature phase diagram of water. The Roman numerals indicate various ice phases. Credit: By Cmglee (original work), via Wikimedia Commons
3. When did water appear?

The raw materials for producing water molecules are hydrogen and oxygen atoms. Here we discuss where these elements come from, and how they were formed.

Spectroscopic analysis of sunlight indicates that the Sun’s photosphere is composed of hydrogen (74.9%), helium (23.8%), and other heavier elements (Lodders 2003b,a). Among the heavier elements, the most abundant is oxygen (around 1% of the solar mass) (Hansen et al. 2004). The abundance of the metals is usually estimated considering not just the spectroscopy of the Sun’s photosphere but also the measures from meteorites that are believed to contain the original Solar composition (Piersanti et al. 2007).

However, our Sun was not created in the first generation of stars in the universe. It is only approximately 4.6 billion years old, while the universe is known to be approximately 13.7 billion years old. In fact, the chemical composition of our Sun was inherited from the interstellar medium, which was produced from previous generations of stars. Moreover the ingredients of the first stars were generated in the Big Bang nucleosynthesis.

The simplest chemical element in nature is hydrogen. Through stellar evolutions and nuclear fusion hydrogen leads to other elements, including oxygen. In the current section, we present how, when, and where these elements were and are being created in the universe.

3.1. Primordial nucleosynthesis

After the Big Bang, the early universe was initially very dense and hot. It cooled down as it expanded, and the quark-gluon plasma gave origin to neutrons and protons (and other hadrons, but in very small quantities). The universe continued to cool, and quickly (after 15 to 30 minutes) the nucleosynthesis ceased because it became too cold (Rauscher and Patkós 2011). The decay time of a free neutron is approximately 10 min. However, before their decay, neutrons interact with protons forming deuterium nuclei. The deuterium obtains another neutron and form tritium, which in turn absorbs a proton to form a $^4\text{He}$ helium. There is no stable element of mass 5 or 8. Therefore, it is generally not possible to have additional nucleosynthesis via $\text{H} + ^4\text{He} = ^5\text{Li}$ or $^4\text{He} + ^4\text{He} = ^8\text{Be}$; nevertheless, traces of one or two heavier elements, most notably $^7\text{Li}$ lithium, do form. Most of the matter was then hydrogen and $^4\text{He}$ helium, with a small amount of deuterium, and just traces of $^3\text{He}$ helium and $^7\text{Li}$ lithium. Neutrons and protons started to form only after the first 1/1000th of a second from the Big Bang, when the temperatures dropped low enough. From the first 1/100th of a second up to 3 or 4 min after the Big Bang, the abundances of the first very light atomic nuclei were defined. The ratio of cosmic abundance today, expressed in terms of mass, is approximately 71% of hydrogen, 28% of helium, and 1% for all the remaining elements. However, at most 4% of this helium could be the result of burning hydrogen inside of stars since the beginning of the universe. Then, the initial ratio must have been approximately 24% of helium and 76% of hydrogen (Rauscher and Patkós 2011).

Therefore, the primordial stars in the universe formed from a gaseous mixture of hydrogen and helium, as well as a very few traces of some rare light elements, such as $^7\text{Li}$ lithium, or isotopes such as deuterium or $^3\text{He}$ helium (Karlsson et al. 2013). They did not have any oxygen.
3.2. Energy production in stars

One of the most intense research areas in the early 20th century was the source of stellar energy. A seminal paper on the subject was written by Hans Bethe in 1939, entitled “Energy Production in Stars”, in which he presented two processes as being the main sources of stars’ energy (Bethe 1939). In 1967, Bethe received the Nobel Prize in Physics for his discovery. The first process is the proton-proton chain reaction (see fact box 1), which is the main source of energy for stars with the same or smaller mass than that of the Sun. However, the carbon-nitrogen-oxygen cycle (CNO; see fact box 2), which was also considered by von Weizsacker (1938), is the one that dominates in more massive stars.

It is interesting to note that the initial goal was to explain the source of energy of the stars, but these studies also showed how some light chemical elements could have been generated. The studies of Bethe did not address the creation of heavy nuclei. This was studied later by Fred Hoyle (Hoyle 1946, 1954). He showed that stars with advanced fusion stages were able to synthesize elements in the mass range from carbon and iron. The works of Hoyle are considered fundamental for the field of stellar nucleosynthesis (Clayton 1968, 2008).

**BOX 1: PROTON-PROTON CHAIN**

The fusion of hydrogen occurs primarily following a chain of reactions called proton-proton chain (Wallerstein et al. 1997):

\[
\begin{align*}
4^1H &\rightarrow 2^2H + 2e^+ + 2\nu_e \\
2^1H + 2^2H &\rightarrow 2^3He + 2\gamma \\
2^3He &\rightarrow 4He + 2^1H
\end{align*}
\]

(.2)

The overall reaction corresponds to the following equation:

\[
4^1H \rightarrow 4He + 2e^+ + 2\nu_e + 2\gamma
\]

(.3)

As illustrated in Figure 3, four nuclei of hydrogen (i.e., protons) collide in pairs of two. Each collision results in a nucleus of deuterium, positron, and neutrino. The positrons collide with electrons and become annihilated, emitting gamma rays, whereas each nucleus of deuterium collides with a nucleus of hydrogen (proton) generating a nucleus of \(^3\)He and emitting energy. In the last stage of the cycle, the two nuclei of \(^3\)He are fused forming a nucleus of helium (\(^4\)He) and two nuclei of hydrogen. In stars of the mass our Sun or smaller, the proton-proton chain is the dominating reaction. In the core of the Sun, the proton-proton chain occurs approximately \(9.2 \times 10^{37}\) times per second, converting \(3.7 \times 10^{38}\) protons into helium nuclei (Phillips 1995).
Figure 3: The proton-proton chain reaction. CREDIT: Wikipedia
**Figure 4:** The CNO cycle reaction. CREDIT: Wikipedia

**BOX 2: CNO CYCLE**

The Carbon-Nitrogen-Oxygen (CNO) cycle is the other set of fusion reactions that convert hydrogen into helium in the stars. Unlike the proton-proton chain reaction, CNO is a catalytic cycle. In stars with mass larger than 1.3 solar masses, the CNO cycle is the main source of energy according to theoretical models (Salaris and Cassisi 2005). As illustrated in Figure 4, four protons fuse, using isotopes of carbon, nitrogen and oxygen as catalysts, producing one alpha particle, two electron neutrinos and two positrons. The same result is obtained in the CNO cycles, despite the different paths and catalysts involved.

3.3. Stellar nucleosynthesis

In his Nobel Prize Lecture, Hans Bethe said “Stars have a life cycle much like animals. They are born, they grow, they go through a definite internal development, and finally die, to give back the material of which they are made so that new stars may live” (Bethe 1968). Stars exist in the balance between two forces. On one hand, the star’s gravity attempts to compress the stellar material into the smallest possible sphere, and on the other hand, enormous pressure and heat are produced by nuclear reactions at the center of the star pushing all the material outward. The outcome of this balance depends largely on the star’s total mass. The stars are traditionally divided into three categories (Rauscher and Patkós 2011):

1. stars less massive than the Sun;
2. stars with mass larger than the Sun and smaller than approximately eight solar masses; and

3. stars more massive than eight solar masses.

The dominant reaction within small stars (in the first category) is the conversion of hydrogen into helium, whereas stars in the second mass category have further reactions that convert helium to carbon and oxygen (see fact box 3). Only very massive stars in the third category support chain reactions that produce heavy elements up to the mass of iron.

**BOX 3: NUCLEOSYNTHESIS OF CARBON AND OXYGEN**

When the fusion of protons into helium continues until the star has exhausted its hydrogen, the temperature in its core rises to about a few times $10^8$ K, allowing the fusion of helium into heavier nuclei. In the first reaction two nuclei of helium, $^4\text{He}$, fuse with each other, creating the nucleus of beryllium, $^8\text{Be}$. However, the $^8\text{Be}$ nucleus has an extremely short mean life of just $10^{16}$ s, before it decays back again to two $^4\text{He}$ nuclei. The rate of production equals the rate of destruction of $^8\text{Be}$ nucleus:

$$^4\text{He} + ^4\text{He} \leftrightarrow ^8\text{Be} \quad (4)$$

Nevertheless, the $^8\text{Be}$ can capture another $^4\text{He}$ nucleus producing the $^{12}\text{C}$ nucleus by the reaction:

$$^8\text{Be} + ^4\text{He} \rightarrow ^{12}\text{C} + \gamma \quad (5)$$

The reactions in Equations 4 and 5 are called the triple-alpha reaction, because three $^4\text{He}$ nuclei or alpha particles are necessary for the creation of $^{12}\text{C}$. This reaction can only create carbon in appreciable amounts because of the existence of a resonance in $^{12}\text{C}$ at the relevant energy for helium burning. Through this resonance the reaction in Equation 5 is enhanced by many orders of magnitude.

The production of oxygen nuclei $^{16}\text{O}$ is the result of a capture of another $^4\text{He}$ nucleus by the carbon nuclei created in helium burning:

$$^{12}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O} + \gamma \quad (6)$$

About half of the carbon nuclei produced are converted into oxygen.

It is interesting to note that the elements $^8\text{C}$ and $^{16}\text{C}$ are extremely fine-tuned with respect to the nuclear force. In the case of the strength of this force were just 0.5% different from their current values, the average abundance of carbon or oxygen in the universe would be more than two orders of magnitude smaller. That would make life based on carbon much more difficult to occur (Oberhummer et al. 2000; Schlattl et al. 2004).

### 3.4. Water molecule

Once a star like the Sun has exhausted its nuclear fuel, its core collapses and the outer layers are expelled as a planetary nebula, while the massive stars (more than eight solar masses) can explode
in a supernova as their inert iron cores collapse. At these stages huge quantities of new nuclei are rapidly synthesized in the nuclear reactions triggered by the flood of neutrons. Most of the elements heavier than the iron group are generated either by nucleosynthesis, or by radioactive decay of unstable isotopes that were produced. This material ejected at the end of life of such stars resulted in huge interstellar clouds of gas and dust. In general, the gas is made of about 90% hydrogen, 9% helium, and 1% heavier atoms, while the dust is composed of silicates, carbon, iron, water ice, ne-thane, ammonia, and some organic molecules (Dalgarno 2006).

Therefore, the first water molecules of the universe might have been emerged in interstellar clouds produced at the end of life of the first generation of massive stars. Interstellar clouds are abundant in our galaxy, and it is generally considered that all stars and planets have been formed from them.

4. Distribution of water in the universe

4.1. Water in galaxies

Water vapour in galaxies is best detected by observing maser emissions. Masers (Microwave Amplification by Stimulated Emission of Radiation) are similar to lasers, only emitting microwave radiation instead of visible light. Water molecules can absorb energy available around them in High Mass Star-forming Regions (HMSR) or near dying stars, and re-emit it as microwave radiation. Several water masers were found in our Milky Way galaxy (Walsh et al. 2008). Mochizuki et al. (2009) studied water masers from young stellar objects (YSOs) in the outer regions of the galaxy.

Water masers were also found in nearby galaxies (Darling et al. 2008, 2016). Braatz and Gugliucci (2008) reported eight new sources of water maser emission in surveys conducted in nuclei of a hundred of galaxies. van der Tak (2015) reviewed the presence of water in nearby galactic nuclei and galactic interstellar clouds and concluded that the emission of radiation is necessary to detect water in those sites.

4.2. Water in stars and interstellar space

The space between stars, the interstellar medium (ISM), is permeated with dust, gas in atomic, molecular and ionic forms, and cosmic rays. Stars are born out of dense regions within molecular clouds in the interstellar space and, when they die, the interstellar medium is enriched with elements heavier than helium (see Section 3) (Hanslmeier 2010). The Orion nebula is an example of star-forming regions (Fig. 5).

Water ice is abundant in the interior of molecular clouds (Allamandola and Sandford 1988). Cheung et al. (1969) were the first to detect of water molecules in the interstellar medium. Elitzur et al. (1989) proposed a comprehensive model of water masers in star-forming regions. Felli et al. (2007) monitored a sample of 43 masers within star-forming regions for 20 years and created a database of their variability. More than 1010 galactic water maser sources have been listed in the Arcetri catalogue (Brand et al. 1994; Valdettaro et al. 2001) and there is a distinction between water masers associated with star forming regions and late-type stars. Furuya et al. (2003) investigated water masers in low-mass young stellar objects.

Mira was the first star, where water was detected in its spectrum, in 1963 (Kuiper 1963).
Figure .5: Water signatures in M42, the Orion nebula. Mosaic picture made from more than 40 individual Hubble Space Telescope (HST) images. Credit: ESA/NASA
Russell (1934) had already predicted the presence of water in the atmosphere of late type stars\(^2\). He showed theoretically that water should be the most abundant molecule beside atomic or molecular hydrogen in stars of approximately 2800K.

Late type stars generally show strong mass loss and in many cases they form a circumstellar shell. Maercker et al. (2008) reported high water abundance in the circumstellar envelope of the star W Hya (an M-dwarf) and investigated water in the envelopes of six other M-type stars. They concluded that high amounts of water found in the majority of these sources may be explained by some kind of internal chemical processes. Updates on their research were reviewed by Maercker et al. (2009, 2016)

Jones et al. (2002) analysed the spectra of a range of M stars and concluded that their observations match well with previous ground-based observations.

Tsuji (2000) reported the presence of water in the spectrum of the M2 supergiant star \(\mu\) Cephei. Winnberg et al. (2008) investigated the variability of water masers in circumstellar shells of late-type stars, using RX Bootis and SV Pegasi as representatives of semiregular variable stars (SRVs).

### 4.3. Water in planetary disks

Most emerging stars (protostars) have a protoplanetary disk that forms from a molecular cloud. Water was present in the molecular cloud that gave birth to our solar system. The presence of water played an important role as the cloud settled to form the protoplanetary disk from which the planets were formed (Mottl et al. 2007).

T Tauri are young stars that are often immersed in large molecular clouds and have accretion disks around them. Shibahara et al. (1993) conducted a survey of 52 T Tauri stars and found water vapor in the disk of 17 of them. They measured the temperature of the water vapor, which appeared to be 2000 K. It is expected that the temperatures vary throughout the disk: water is likely solid in the outer regions of the disk and in gas phase in the inner regions where the temperature is higher than the evaporation point (\(\sim 150\) K).

The habitable zone can be predicted as the distance range from the central star, where water can be found in liquid phase on a planet surface. In the solar system, it has been calculated by Kasting et al. (1993) to be from 0.95 to 1.15 AU. Other estimates were reported by Rasool and de Bergh (1970); Hart (1979); Fogg (1992); Spiegel et al. (2010); Abe et al. (2011); Kopparapu et al. (2013) and Way et al. (2014).

The snowline is the distance from the protostar where water (and other volatiles) condensates into ice. The amount of water on the surface of terrestrial planets in the habitable zone depends on the snowline location, which is determined by the temperature profile of the disk, properties of the star, mass accretion rate, and size distribution of dust grains (Mulders et al. 2015). Mulders et al. calculated the snowline location in disks around different stars using estimates of mass accretion rates as a function of stellar mass. They used N-body simulations to predict the amount of water on the surface of terrestrial planets within the habitable zone. In addition, they determined that the variation of the snowline locations strongly affects the range of the water availability on terrestrial planets. They showed that a significant fraction of terrestrial planets in the habitable zone around Sun-like stars remained dry (assuming ISM-like dust sizes) and no water was predicted on planets.

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\(^2\)Stars cooler than the Sun (less than 5200 K), with a yellow-orange-red color variation
within the habitable zones of low-mass M stars ($< 0.5 \text{ M}_\odot$). When considering larger grains of
dust, the snowline got closer to the star and that enabled water to be delivered to the habitable
zone of a significant fraction of M stars and all FGK stars.

A protoplanetary disk has its temperature and density profiles defined by the mass fraction
of micrometre-sized dust grains and on their chemical composition (Bitsch and Johansen 2016).
The larger is the abundance of micrometre-sized grains, the higher is the overall temperature of
the disk, and the further away from the star is the snowline. If the dust abundance is kept the
same, an increase in the water fraction inside the disk may lower the temperature in the inner
regions and increases the temperature in the outer regions of the disk. Disks with a smaller water
fraction have the opposite effect. Bitsch and Johansen (2016) studied the formation and migration
of planets exploring the dust composition and its abundance in the disk. Their results imply that
hot and warm super-Earths may contain a significant fraction of water, if they have formed beyond
the snowline and migrated inwards.

Water vapor was found in the circumstellar disks such as AA Tauri (Hanslmeier 2010), TW
Hydrae (Salinas et al. 2016), and APM 08279+5255 (Lis et al. 2011). Eisner (2007) reported water
within 1 AU of the young star MWC 480, which is believed to have resulted from the sublimation
of inwards migrating icy bodies, that provided water for potential terrestrial planets. Salyk et al.
(2015) reported the presence of water vapor in the protoplanetary disk around DoAr 44.

4.4. Water in extrasolar planets

By 2016, more than 3,300 extrasolar planets have been confirmed, with more than 570 multi-planet
systems were reported (NASA 2015). Detecting atmospheres on extrasolar planets is a challenging
task.

The planet HD209458b was detected in 1999 and was the first extrasolar planet confirmed by
the transit method. It is a giant planet with mass of approximately 63% the mass of Jupiter. It
is 100 times closer to the central star than Jupiter. With this proximity to the star, it is assumed
that the planet continuously loose volatiles, and the outflow is estimated to be $10^4$ tons/s. Water
is among these volatiles as revealed by the data from Hubble Space telescope (Rauer et al. 2004).

Planets with masses between 1 and 10 of Earth masses are known as super-Earths. The
habitability of super-Earth planets was discussed, for example, by Kaltenegger and Kasting (2008).
It is likely that super-Earths have a wide range of atmospheres types. Miller-Ricci et al. (2009)
argued that some of them may have hydrogen-rich atmospheres.

Dominguez (2016) analysed the abundance of water and its dependency on stellar metallicity
in extrasolar planetary systems. They found that the ratio of $\text{H}_2\text{O}/\text{SiO}_2$ produced in a molecular
cloud of solar metallicity can account for the ratio of these compounds on Earth today, supporting
the “wet” hypothesis that implies that Earth could have obtained enough water locally during
its formation (Stimpfl et al. 2004). Bialy et al. (2015) studied the first step of $\text{H}_2\text{O}$ formation in
molecular clouds with extremely low metallicity, and showed that these clouds could have high
abundances of water vapor. Some of this water may have contributed to forming planets if the
cloud collapses into a protoplanetary disk.

Ehrenreich et al. (2007) searched for water in the transit exoplanet HD189733b by using the
Spitzer telescope and showed that the observational capabilities in that moment were insufficient
for detecting water vapor. Water vapor was confirmed in the atmospheres of extrasolar planets HD
189733 b (Barman 2008; McCullough et al. 2014), HD 209458 b (Beaulieu et al. 2010), Tau Botis b (Lockwood et al. 2014), HAT-P-11b (Fraine et al. 2014; Hanslmeier 2010), XO-1b, WASP-12b, WASP-17b, and WASP-19b (Mandell et al. 2013).

4.5. Water in the solar system

Water is very abundant in the solar system. It is present even in the Sun, as confirmed for example by Wallace et al. (1995).

The solar system can be divided in two distinct group of planets by their position relative to the snowline: in the inner solar system, the volatiles are in a gaseous form and planets are relatively dry, small and rocky - the terrestrial planets, whereas in the outer solar system, the volatiles are in a solid form and planets are big, gaseous with a solid rocky-ice inner core - the giant planets.

4.5.1. Water in the outer solar system

Water is an important constituent of the four giant planets - Jupiter, Saturn, Uranus, and Neptune (Stevenson and Fishbein 1981). All these planets have similar structure, with a rocky-ice core and a huge gaseous layer consisting mainly of hydrogen and helium.

The abundance of water in Jupiter’s atmosphere was studied by Roos-Serote et al. (2004). They found that the O/H ratio in the atmosphere of Jupiter was comparable with the one in the sun. Water in Jupiter was also reported by Bjoraker et al. (1986). (Hueso and Sánchez-Lavega 2004) studied water storms in the atmosphere of Jupiter and concluded that they may develop velocities of up to 150 m/s.

Jupiter has four large satellites, known as the Galilean satellites: Io, Europa, Ganymede, and Callisto. Water keeps flowing away from Io (Pilcher 1979), which may be explained by the thermal escape. Kumar and Hunten (1982) investigated the atmospheres of Io and other Jupiter satellites and found that Europa, Ganymede, and Callisto may have oxygen atmospheres resulting from photolysis of water vapor. Moreover, these three satellites may have internal oceans more than a hundred kilometers thick (Spohn and Schubert 2003). Leitner et al. (2014) developed a model for the analysis of oceans on Europa and Ganymede, and compared the results with the measured composition of brines on the surface of Europa. Vance et al. (2014) analysed the influence of salinity on the internal structure of Ganymede and predicted that water ice may be present in the aqueous magnesium sulfate. They concluded that the stability of ice under high-pressure implies water-rock contact.

Water in the deep atmosphere of Saturn was studied by Visscher and Fegley (2005), who discussed chemical constraints for the abundance of water in the planet. Saturn has 60 confirmed moons. In 1997, water was detected in the atmosphere of Titan, the largest satellite of Saturn. The observed water abundance appeared to be four times lower than that in comets, suggesting that Titan’s atmosphere was formed by outgassing from the interior rather than having a cometary origin (Coustenis et al. 1998). More recent data are in good agreement with these findings (Nixon et al. 2006; Bjoraker et al. 2008). Raulin (2008) describes Titan as “another world, with an active prebiotic-like chemistry, but in the absence of permanent liquid water on the surface: a natural laboratory for prebiotic-like chemistry”. Dunaeva et al. (2013) built models of Titan’s possible internal structure and predicted that Titan consists of the rock-iron core, rock-ice mantle and
outer water-ice shell.

There is a water influx from the Saturnian rings that is caused by its satellite Enceladus (Mueller-Wodarg et al. 2006); this has been discussed earlier by Connerney and Waite (1984). This sixth largest moon of Saturn is mostly covered by clean fresh ice, being one of the most reflective bodies of the solar system. In 2004, Cassini detected water vapor and complex hydrocarbons emerging from the geologically active south-polar region of Enceladus (Spencer et al. 2006). Tobie et al. (2008) showed that its particular location at the south pole and the magnitude of dissipation rate can only be explained by the models that assume a liquid water layer at a certain depth. Ingersoll and Pankine (2010) affirmed that the existence of liquid water on Enceladus depends on the efficiency of subsurface heat transfer. Iess et al. (2014) studied the interior structure of Enceladus and its gravity field; their results suggest that the body deviates mildly from the hydrostatic equilibrium.

Atreya et al. (2006) assessed the existence of an ocean of water-ammonia on Neptune and Uranus. They argued that the tropospheric cloud structure and the existence of a magnetic field must be maintained by a water-ammonia ionic ocean creating a dynamo action.

The five main satellites of Uranus, Miranda, Ariel, Umbriel, Titania and Oberon, have weaker bands of water ice in their infrared spectra than those in the spectra of Saturn’s icy moons and Galilean satellites. The difference may be explained by the presence of other ices (e.g., NH$_3$ and CH$_4$) besides water on their surfaces (Encrenaz 2007).

So far, water has evaded detection on the dwarf planet Pluto based on Earth-bound observatories. Cook et al. (2015) analysed all data on Pluto from the Linear Etalon Imaging Spectral Array (LESIA: a component of the New Horizons spacecraft) searching for the presence of water. Brown and Calvin (2000) presented evidences of water ice on Charon, Pluto’s Satellite.

4.5.2. Water in small bodies

In 2006, the International Astronomical Union defined the term ‘Small Solar System Body’ (SSSB) as an object in the solar system that is not sufficiently massive to be a planet or a dwarf planet, and it is not a satellite. SSSBs are generally located in the main asteroid belt between Mars and Jupiter, in the Kuiper belt outside the orbit of Neptune, and in the Oort cloud extended as far as 50,000 AU from the Sun. Comets and asteroids consist mainly of pristine material and are remnants from the formation of the solar system about 4.6 billion years ago.

**Comets**

Comets are icy SSSBs that start a process of outgassing when approach the inner solar system. Comets expel vaporized volatile materials, carrying dust away with them. They may have been an important source of water on Earth and other terrestrial planets, as well as on satellites. Water is the main component of interstellar and cometary ices (Allamandola and Sandford 1988).

Water in comets was first detected in 1970 from H and OH observations in comet Halley (Mumma et al. 1986; Combes et al. 1988). The comet Hale-Bopp (C/1995 O1) had its spectra analysed by Davies et al. (1997), who found that “some of the absorption features can be matched by an intimate mixture of water ice and a low-albedo material such as carbon on the nucleus”. Cosmovici et al. (1998) detected water on comet Hyakutake (C/1996 B2). Bockelée-Morvan et al. (2009) used the Spitzer Space Telescope to detect water on the comets 71P/Clark and C/2004 B1 (Linear). Schulz et al. (2006) detected water ice grains on Comet 9P/Tempel 1 by analysing the
results of the DEEP IMPACT mission. de Bergh (2004) presented general remarks about water ice and organics in the Kuiper belt objects.

Hsieh and Jewitt (2006) discovered comets in the main asteroid belt, a new class of objects in the solar system. The activity of these comets is consistent with dust ejection driven by water-ice sublimation.

**Asteroids** Asteroids and comets were previously thought to be of different origin: it was assumed that asteroids formed inside the orbit of Jupiter and comets originated from the outer solar system. However, the discovery of main-belt comets and recent findings like the returned sample of comet 81P/Wild 2 (Ishii et al. 2008) have blurred the distinction between comets and asteroids.

Every year, thousands of new asteroids are found and several thousands of asteroids have been studied. The first evidence of water in an asteroid was found in Ceres, now classified as a dwarf planet. Lebofsky (1978) estimated that Ceres’s surface may contain 10%–15% water of hydration\(^3\). Küppers et al. (2014) indicated that at least \(10^{26}\) water molecules per second are being evaporated from the dwarf planet, and this phenomenon could be due to “comet-like sublimation or cryo-volcanism, in which volcanoes erupt volatiles instead of molten rocks”.

Fanale and Salvail (1989) analysed the spectral signature of water in asteroids and confirmed that 66% of the C-class asteroids in the investigated sample have hydrated silicate surfaces. Although it was believed that D-type asteroids do not have water (Barucci et al. 1996), Kanno et al. (2003) suggested that these asteroids could contain water ice or hydrated minerals.

Yang and Jewitt (2007) investigated spectral signatures of water ice on Trojan asteroids\(^4\) and their analysis showed no signs of water. Treiman et al. (2004) analysed the meteorite Serra de Mag, an eucrite believed to come from the asteroid 4 Vesta, and inferred that polar ice deposits in Vesta and similar asteroids are possible remainders from comet impacts, similar to water ice deposits on the Moon and Mercury. Campins et al. (2009) used IR observations to confirm water ice on the surface of asteroid 24 Themis.

**Meteorites** A meteoroid is a small rocky or metallic body moving around the Sun or in the outer space. They are significantly smaller than asteroids or comets. Most meteoroids are fragments from asteroids or comets, other originated from debris ejected from impacts on bodies such as Mars or the Moon. A meteoroid that reaches the surface of the Earth without being completely vaporized is called meteorite.

Ashworth and Hutchison (1975) analysed hydrous alteration products of olivine (a magnesium iron silicate) in an ordinary chondrite and an achondrite — two classes of meteorites in which hydrous minerals are rare. Their observations suggest that both meteorites have unusual volatile constituents, and they argue that the Nakhla achondrite contains water of extraterrestrial origin, and this may also be the case for the Weston chondrite.

The Shergotty–Nakhla–Chassigny meteorites, believed to be of martian origin, contain 0.04%–0.4% water by weight. Karlsson et al. (1991) used oxygen isotopic analysis to resolve whether this water was terrestrial or extraterrestrial. The results revealed that some of the water was extraterrestrial.

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\(^3\) Hidration implies that water molecules are components of the crystal structure of a mineral. In this case a new mineral is created, a hydrate.

\(^4\) These asteroids are located near the equilibrium points L4 and L5 in the Sun-Jupiter system.
Carbonaceous chondrites are a class of chondritic meteorites that includes the most primitive known meteorites. They contain high percentages of water (3% to 22%) (Norton 2002) and organic compounds. Water and D/H ratios in the Chainpur (an ordinary chondrite) and Orgueil (a carbonaceous chondrite) meteorites were measured by Robert et al. (1978). Orgueil is one of the most studied meteorites, owing to its unique primitive composition and relatively large mass (Gounelle and Zolensky 2014).

4.5.3. Water on Earth and other terrestrial planets

Mercury, Venus, Earth, Mars and their satellites, have very different histories. Water is present in all these terrestrial planets, but in very distinct patterns: Mercury has ice at the poles; Earth has very abundant water, in lakes, oceans, underneath the surface, and in icy continents; Venus has vapor in the atmosphere; and Mars has ice at the poles, liquid water in salty flows, and vapor in the atmosphere.

**Mercury** Mercury, the smallest and closest planet to the Sun, has temperature of 450°C on the dayside and −180°C on the nightside. This extreme contrast is a consequence of the lack of substantial atmosphere. Butler et al. (2001) used a radar system to analyse Mercury surface and found that water could persist near the poles of Mercury inside of deep craters. Wood et al. (1992) structured a thermal model that predicted the temperatures on the surface of Mercury and argued that, despite the proximity to the sun, temperatures at the poles could be low enough to permit water ice, as long as the albedo was high. Water was confirmed on Mercury by MESSENGER in 2012 (Lawrence et al. 2013).

**Venus** Venus is similar to Earth in its size and has a dry surface hidden by dense clouds. Contrary to Mercury, it has a dense atmosphere mainly consisting of the greenhouse gas CO₂, with a surface pressure of 90 times that of Earth’s. The mean surface temperature is approximately 460°C, and thus finding ice or liquid water near the poles of Venus is unlikely. Water vapor is an important component of the atmosphere and contributes to the global greenhouse effect. Water is mainly found below the cloud base at approximately 47 km above the surface (Hanslmeier 2010). Fedorova et al. (2008) measured vertical distributions and mixing ratios of H₂O and HDO in Venus’ mesosphere. They reported an increase of deuterium closer to the surface indicating a lower escape rate of D atoms comparing to H atoms or (and maybe also) a lower photodissociation of HDO comparing to H₂O. Water loss of Venus was measured by Delva et al. (2009) as 10^{24} molecules per second.

**Earth** Earth is the largest terrestrial planet, and the oceans comprise 2/3 of its surface. Between a very hot and a very cold planet lies the Earth, where the average surface temperature of 288 K and pressure of 1 bar create a favorable environment for life, and where water can be found as vapor, ice, and liquid, simultaneously.

Water is present in large quantities in the Earth’s atmosphere, along with 77% of N₂, 22% of O₂, and 1% of other gases. An estimate of the amount of water inside Earth points to values ranging from 1 O_⊕^{5} to 50 O_⊕, with ~10 O_⊕ being the most likely value (Drake and Campins 2006).

\[5O_⊕ = \text{mass of Earths oceans} = 1.4 \times 10^{24} \text{ g}\]
The origin of water on Earth is one of the most intriguing and debated issues in astronomy. One way to tackle the question is to analyse the proportion between the heavy water (HDO) and the light water (H$_2$O), also known as the D:H ratio, in Earth’s water and in different potential sources. This ratio in the present day Earth mantle and oceans (Standard Mean Ocean Water, SMOW) is about 6 times higher than in the gas of the proto-planetary disk. Other bodies in the solar system present a great variation in their water D/H ratio, as shown in Fig. 6. Although the comparison of this ratio on Earth with those of various meteorite types suggests that the water on Earth was derived mainly from asteroids, the remnants of the protosolar nebula are still present in the Earth mantle, presumably signing the sequestration of nebula gas at an early stage of planetary growth (Marty 2012). Marty has proposed that a small ($\leq$10\%) fraction of the mantle volatiles might have been derived from the protosolar nebula during an early stage of the proto-Earth growth. A small contribution, up to 10\%, may have come from comets (Morbidelli et al. 2000). Izidoro et al. (2013) developed a model that considers all main possible sources of water and uses the D:H ratio to evaluate potential relative contributions from each source.

Regarding our satellite, Sridharan et al. (2010) reported evidences of water ice at high latitudes on the moon surface.

**Figure 6:** The different values of the deuterium-to-hydrogen ratio (D/H ratio) in water, observed in various bodies of the solar system. (Source: ESA (2017))
Mars

Mars, the outmost terrestrial planet, has a mass of 0.1 M⊕ and surface temperatures in the range from −100°C to 0°C. Water ice is present in the two polar caps of the planet: it forms almost the entire north polar cap and the bottom layer of the south polar cap (Bibring et al. 2004; Christensen 2006). Water vapor was detected in the atmosphere of Mars by Owen and Mason (1969), and later quantified using Viking observations (Fedorova et al. 2010) and data from the Curiosity rover Mahaffy et al. (2013).

Masson et al. (2001) presented geomorphologic evidence that the planet underwent hydrologic cycle with liquid water on its surface in the past. Ojha et al. (2015) presented new evidences that salty liquid water flows sporadically on the present-day Mars despite of the low atmospheric pressure (1% of that on Earth) and low temperature. Features known as recurring slope lineae (RSL), first identified in 2011, apparently resulted from the flows of salty liquid water on the surface of Mars. The look as dark streaks (Figure 7) and appear seasonally. The water remains in a liquid phase at low temperatures due to the presence of salt, which also protect the water from boiling off in the thin atmosphere of Mars. Gough et al. (2016) analysed the formation of liquid water via the deliquescence of calcium chloride at low temperatures and concluded that calcium chloride may help to form liquid water that could cause slope streaks on Mars. Pál and Kereszturi (2016) also predicted the appearance of microscopic amount liquid water on the hygroscopic mineral surfaces on Mars.

5. Water and life

It is not easy to define life in the astrobiology context. First there is no consensus on the time and mechanisms of the origin of life. Second, the distinction between living and non-living systems can get vague. Are viruses forms of life? Is there any kind of artificial life?

Despite of this uncertainty, the established features of living organisms include: an organized structure to perform specific functions, including cells as fundamental units of life; performing of anabolic and catabolic reactions to sustain life (metabolism); regulation of internal conditions to keep them stable even in the unstable external environments (homeostasis); reaction to the environment stimuli or changes (response); growth; reproduction; and adaptation of organisms and populations to the environment (evolution) (Koshland 2002).

Other aspects of life like being carbon-based or having its genetical information in the form of DNA, may also be considered. Even then, all these characteristics define a single model of life as we know it. It is an arduous task to envision different forms of life that may exist elsewhere in the universe. That is why, so far, we only seek for established aspects the can provide conditions to support life as we know it.

Water is essential for life as we know it due to its unique properties. Because water can be found in all three phases on Earth, it allows an ample diversity of climates, habitats, and complex synergies between physical and chemical reactions (Schulze-Makuch and Irwin 2004). It is an ideal solvent because of its polarity, and thus it can dissolve many different chemicals essential for
metabolic reactions. Furthermore, the dipole character of water allows for hydrophobic organic molecules (e.g., lipids) to make cellular membranes. Alternate solvents may be possible, but there is a consensus that water is a prerequisite for life (Mottl et al. 2007).

However, the presence of water does not imply life. So far we know very little about the probability of the emergence and evolution of life in a cosmic body that contains water. This uncertainty stems from the fact we still do not know how life began on Earth. Was it brought from outside, or may be Earth formation and evolution somehow made it possible for life to begin here? In this case, are those initial conditions replicable somewhere in the universe? The necessary chemical reactions and environmental conditions that allowed the emergence of life on Earth are still debated (Line 2002; Trevors and Abel 2004; Pascal et al. 2006; Jortner 2006; Benner and Kim 2015). At the present date, it remains impossible to determine precisely all the circumstances that led to the emergence of first living cells on Earth (Pascal et al. 2006).

Nevertheless, one thing is certain: water must be in liquid state for all the living organisms we know. Although water is present everywhere in the universe (see Section 4), liquid water seems to be extraordinarily rare. The water we have found so far on the surface of other cosmic bodies is always in the solid or gaseous states, but not liquid. The only exception we know so far (besides Earth itself) is the potential presence of small amounts of surface water on Mars. Direct measurement of temperature and pressure that could favour liquid water on remote planets and satellites is generally not possible today. Therefore, we are still far from mapping where life could emerge and evolve outside our planet (Encrenaz 2007).

In the last two decades, the astrochemical and astrophysical conditions for the emergence and evolution of life have been intensively debated (e.g., Ehrenfreund et al. (2002) and Chyba and Hand (2005)). Water on Earth, in the solar system and in the interstellar medium, and its strong association with life, has been reviewed by Mottl et al. (2007). Cottin et al. (2015) presented an interdisciplinary review of astrobiology, covering the most recent facts and hypotheses.

Even though we still have no evidence of the extraterrestrial life, the resilience and presence of life in a wide variety of environments on Earth, even in very challenging niches, suggest that life may not be restricted to our planet. Since the discovery of extremophilic microbes (Rothschild and Mancinelli 2001; Rampelotto 2010), there has been less scepticism regarding the possibility of extraterrestrial life (Sagan 1996; Chyba 1997; Montmerle et al. 2006). Essentially, there are no chemical or physical barriers to extremophiles: where there is liquid water, there is life on Earth (Rothschild and Mancinelli 2001). Therefore, all the recent discoveries, including liquid water on Mars (Ojha et al. 2015), the possibility of liquid oceans underneath the surface of Europa and Enceladus (Raulin 2005; Tobie et al. 2008), and also the presence of organic molecules on Titan (Raulin 2008), have fueled astrobiological interest in the solar system and beyond.

Finding extraterrestrial life seems to be only a question of time now. As we have seen in this chapter, water is a key aspect in this search. That is why understanding how water came to be and spread in the universe give us the first steps in this great endeavour of looking for life outside of our planet. Once we succeed, it will certainly expand our knowledge about what is to be a living organism in this vast universe. Once knowing we are not alone, human beings will never look at themselves at the same way again.
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6. Acronyms

HMSR - High Mass Star-forming Regions
HST - Hubble Space Telescope
ISM - Interstellar Medium
LESIA - Linear Etalon Imaging Spectral Array
Masers - Microwave Amplification by Stimulated Emission of Radiation
RSL - Recurring Slope Lineae
SMOW - Standard Mean Ocean Water,
SRVs - Semiregular Variable Stars
SSSB - Small Solar System Body
YSOs - Young Stellar Objects

References

Abe, Y., Abe-Ouchi, A., Sleep, N. H., and Zahnle, K. J. (2011). Habitable Zone Limits for Dry Planets. *Astrobiology*, 11:443–460.

Allamandola, L. J. and Sandford, S. A. (1988). Laboratory simulation of dust spectra. In Bailey, M. E. and Williams, D. A., editors, *Dust in the Universe*, pages 229–263.

Ashworth, J. R. and Hutchison, R. (1975). Water in non-carbonaceous stony meteorites. *Nature*, 256:714.

Atreya, S. K., Baines, K. H., and Egeler, P. A. (2006). An Ocean Of Water-ammonia On Neptune And Uranus: Clues From Tropospheric Cloud Structure. In *AAS/Division for Planetary Sciences Meeting Abstracts #38*, volume 38 of *Bulletin of the American Astronomical Society*, page 489.

Barman, T. S. (2008). On the Presence of Water and Global Circulation in the Transiting Planet HD 189733b. *The Astrophysical Journal Letters*, 676:L61.

Barucci, M. A., Fulchignoni, M., and Lazzarin, M. (1996). Water ice in primitive asteroids? *Planetary and Space Science*, 44:1047–1049.

Beaulieu, J. P., Kipping, D. M., Batista, V., Tinetti, G., Ribas, I., Carey, S., Noriega-Crespo, J. A., Griffith, C. A., Campanella, G., Dong, S., Tennyson, J., Barber, R. J., Deroo, P., Fossey, S. J., Liang, D., Swain, M. R., Yung, Y., and Allard, N. (2010). Water in the atmosphere of HD 209458b from 3.6-8 μm IRAC photometric observations in primary transit. *Monthly Notices of the Royal Astronomical Society*, 409:963–974.

Benner, S. A. and Kim, H.-J. (2015). The case for a Martian origin for Earth life. In *Instruments, Methods, and Missions for Astrobiology XVII*, volume 9606 of *Proceedings of the SPIE*, page 96060C.
Bethe, H. A. (1939). Energy Production in Stars. *Physical Review*, 55:434–456.

Bethe, H. A. (1968). Energy Production in Stars. *Science*, 161:541–547.

Bialy, S., Sternberg, A., and Loeb, A. (2015). Water Formation During the Epoch of First Metal Enrichment. *The Astrophysical Journal Letters*, 804:L29.

Bibring, J.-P., Langevin, Y., Poulet, F., Gendrin, A., Gondet, B., Berthé, M., Soufflot, A., Drossart, P., Combes, M., Bellucci, G., Moroz, V., Mangold, N., Schmitt, B., OMEGA Team, Erard, S., Forni, O., Manaud, N., Poulleau, G., Encrenaz, T., Fouchet, T., Melchiorri, R., Altieri, F., Formisano, V., Bonello, G., Fonti, S., Capaccioni, F., Cerroni, P., Coradini, A., Kottsov, V., Ignatiev, N., Titov, D., Zasova, L., Pinet, P., Sotin, C., Hauber, E., Hoffman, H., Jaumann, R., Keller, U., Arvidson, R., Mustard, J., Duxbury, T., and Forget, F. (2004). Perennial water ice identified in the south polar cap of Mars. *Nature*, 428:627–630.

Bitsch, B. and Johansen, A. (2016). Influence of the water content in protoplanetary discs on planet migration and formation. *Astronomy & Astrophysics*, 590:A101.

Bjoraker, G., Achterberg, R., Anderson, C., Samuelson, R., Carlson, R., and Jennings, D. (2008). Cassini/CIRS Observations of Water Vapor in Titan’s Stratosphere. In *AAS/Division for Planetary Sciences Meeting Abstracts #40*, volume 40 of *Bulletin of the American Astronomical Society*, page 448.

Bjoraker, G. L., Larson, H. P., and Kunde, V. G. (1986). The abundance and distribution of water vapor in Jupiter’s atmosphere. *ApJ*, 311:1058–1072.

Bockelée-Morvan, D., Woodward, C. E., Kelley, M. S., and Wooden, D. H. (2009). Water in Comets 71P/Clark and C/2004 B1 (Linear) with Spitzer. *The Astrophysical Journal*, 696:1075–1083.

Braatz, J. A. and Gugliucci, N. E. (2008). The Discovery of Water Maser Emission from Eight Nearby Galaxies. *The Astrophysical Journal*, 678:96–101.

Brand, J., Cesaroni, R., Caselli, P., Catarzi, M., Codella, C., Comoretto, G., Curioni, G. P., Curioni, P., Di Franco, S., Felli, M., Giovanardi, C., Olmi, L., Palagi, F., Palla, F., Panella, D., Pareschi, G., Rossi, E., Speroni, N., and Tofani, G. (1994). The Arcetri catalogue of H2O maser sources update. *Astronomy & Astrophysics Supplement*, 103.

Brown, M. E. and Calvin, W. M. (2000). Evidence for Crystalline Water and Ammonia Ices on Pluto’s Satellite Charon. *Science*, 287:107–109.

Butler, B. J., Slade, M. A., and Muhleman, D. O. (2001). The Nature of the Mercury Polar Radar Features. In Robinbson, M. and Taylor, G. J., editors, *Workshop on Mercury: Space Environment, Surface, and Interior*, volume 1097, page 9.

Campins, H., Hargrove, K., Howell, E. S., Kelley, M. S., Licandro, J., Mothé-Diniz, T., Ziffer, J., Fernandez, Y., and Pinilla-Alonso, N. (2009). Confirming Water Ice on the Surface of Asteroid 24 Themis. In *AAS/Division for Planetary Sciences Meeting Abstracts #41*, volume 41 of *AAS/Division for Planetary Sciences Meeting Abstracts*, page 32.05.
Cheung, A. C., Rank, D. M., Townes, C. H., Thornton, D. D., and Welch, W. J. (1969). Detection of Water in Interstellar Regions by its Microwave Radiation. *Nature*, 221:626–628.

Christensen, P. (2006). Water at the poles and in permafrost regions of mars. *Elements*, 2(3):151–155.

Chyba, C. F. (1997). Life on other moons. *Nature*, 385:201.

Chyba, C. F. and Hand, K. P. (2005). Astrobiology: The study of the living universe. *Annual Review of Astronomy and Astrophysics*, 43:31–74.

Clayton, D. D. (1968). *Principles of stellar evolution and nucleosynthesis*. McGraw-Hill, New York.

Clayton, D. D. (2008). Fred Hoyle, primary nucleosynthesis and radioactivity. *Nucleic Acids Research*, 52:360–363.

Combes, M., Crovisier, J., Encrenaz, T., Moroz, V. I., and Bibring, J.-P. (1988). The 2.5-12 micron spectrum of Comet Halley from the IKS-VEGA Experiment. *Icarus*, 76:404–436.

Connerney, J. E. P. and Waite, J. H. (1984). New model of Saturn’s ionosphere with an influx of water from the rings. *Nature*, 312:136–138.

Cook, J. C., Cruikshank, D. P., Dalle Ore, C. M., Ennico, K., Grundy, W. M., Olkin, C. B., Protopapa, S., Stern, S. A., Weaver, H. A., and Young, L. A. (2015). The Search for Pluto Water. In *AAS/Division for Planetary Sciences Meeting Abstracts*, volume 47 of *AAS/Division for Planetary Sciences Meeting Abstracts*, page 200.02.

Cosmovici, C. B., Montebuognoli, S., Orfei, A., Pogrebenko, S., and Cortiglioni, S. (1998). The puzzling detection of the 22 GHz water emission line in Comet Hyakutake at perihelion. *Planetary and Space Science*, 46:467–470.

Cottin, H., Kotler, J. M., Bartik, K., Cleaves, H. J., Cockell, C. S., de Vera, J.-P. P., Ehrenfreund, P., Leuko, S., Ten Kate, I. L., Martins, Z., Pascal, R., Quinn, R., Rettberg, P., and Westall, F. (2015). Astrobiology and the Possibility of Life on Earth and Elsewhere. . . . *Space Science Reviews*.

Coustenis, A., Salama, A., Lellouch, E., Encrenaz, T., Bjoraker, G. L., Samuelson, R. E., de Graauw, T., Feuchtgruber, H., and Kessler, M. F. (1998). Evidence for water vapor in Titan’s atmosphere from ISO/SWS data. *Astronomy & Astrophysics*, 336:L85–L89.

Dalgarno, A. (2006). Interstellar Chemistry Special Feature: The galactic cosmic ray ionization rate. *Proceedings of the National Academy of Science*, 103:12269–12273.

Darling, J., Brogan, C., and Johnson, K. (2008). Ubiquitous Water Masers in Nearby Star-Forming Galaxies. *The Astrophysical Journal Letters*, 685:L39.

Darling, J., Gerard, B., Amiri, N., and Lawrence, K. (2016). Water Masers in the Andromeda Galaxy. I. A Survey for Water Masers, Ammonia, and Hydrogen Recombination Lines. *The Astrophysical Journal*, 826:24.
Davies, J. K., Roush, T. L., Cruikshank, D. P., Bartholomew, M. J., Geballe, T. R., Owen, T., and de Bergh, C. (1997). The Detection of Water Ice in Comet Hale-Bopp. *Icarus*, 127:238–245.

de Bergh, C. (2004). Kuiper Belt: Water and Organics. In Ehrenfreund, P., Irvine, W. M., Owen, T., Becker, L., Blank, J., Brucato, J. R., Colangeli, L., Derenne, S., Dutrey, A., Despois, D., Lazcano, A., and Robert, F., editors, *Astrobiology: Future Perspectives*, volume 305 of *Astrophysics and Space Science Library*, page 205.

Delva, M., Volwerk, M., Mazelle, C., Chaufray, J. Y., Bertaux, J. L., Zhang, T. L., and Vörös, Z. (2009). Hydrogen in the extended Venus exosphere. *Geophysical Research Letters*, 36:L01203.

Domínguez, G. (2016). On the Abundance of Water in Extrasolar Planetary Systems as a Function of Stellar Metallicity. In *American Astronomical Society Meeting Abstracts*, volume 228 of *American Astronomical Society Meeting Abstracts*, page 404.02.

Drake, M. J. and Campins, H. (2006). Origin of water on the terrestrial planets. In Daniela, L., Sylvio Ferraz, M., and Angel, F. J., editors, *Asteroids, Comets, Meteors*, volume 229 of *IAU Symposium*, pages 381–394.

Dunaeva, A. N., Kronrod, V. A., and Kuskov, O. L. (2013). Numerical Models of Titan’s Interior with Subsurface Ocean. In *Lunar and Planetary Science Conference*, volume 44 of *Lunar and Planetary Science Conference*, page 2454.

Ehrenfreund, P., Irvine, W., Becker, L., Blank, J., Brucato, J. R., Colangeli, L., Derenne, S., Despois, D., Dutrey, A., Fraaije, H., Lazcano, A., Owen, T., Robert, F., and International Space Science Institute Issi-Team (2002). Astrophysical and astrochemical insights into the origin of life. In Lacoste, H., editor, *Exo-Astrobiology*, volume 518 of *ESA Special Publication*, pages 9–14.

Ehrenreich, D., Hébrard, G., Lecavelier des Etangs, A., Sing, D. K., Désert, J.-M., Bouchy, F., Ferlet, R., and Vidal-Madjar, A. (2007). A Spitzer Search for Water in the Transiting Exoplanet HD 189733b. *The Astrophysical Journal, Letters*, 668:L179–L182.

Eisner, J. A. (2007). Water vapour and hydrogen in the terrestrial-planet-forming region of a protoplanetary disk. *Nature*, 447:562–564.

Elitzur, M., Hollenbach, D. J., and McKee, C. F. (1989). H2O masers in star-forming regions. *The Astrophysical Journal*, 346:983–990.

Encrenaz, T. (2007). *Searching for Water in the Universe*. Springer Praxis Books. Springer.

ESA (2017). ESA’s Rosetta site 2015, Rosetta fuels debate on Origin of Earth’s oceans. [http://www.esa.int/Our_Activities/Space_Science/Rosetta/Rosetta_fuels_debate_on_origin_of_Earth_s_oceans](http://www.esa.int/Our_Activities/Space_Science/Rosetta/Rosetta_fuels_debate_on_origin_of_Earth_s_oceans). [Online; accessed 09-May-2017].

Fanale, F. P. and Salvail, J. R. (1989). The water regime of asteroid (1) Ceres. *Icarus*, 82:97–110.

Fedorova, A., Korablev, O., Vandaeele, A.-C., Bertaux, J.-L., Belyaev, D., Mahieux, A., Neefs, E., Vilquet, W. V., Drummond, R., Montmessin, F., and Villard, E. (2008). HDO and H2O vertical distributions and isotopic ratio in the Venus mesosphere by Solar Occultation at Infrared spectrometer on board Venus Express. *Journal of Geophysical Research (Planets)*, 113:E00B22.
Fedorova, A. A., Trokhimovsky, S., Korablev, O., and Montmessin, F. (2010). Viking observation of water vapor on Mars: Revision from up-to-date spectroscopy and atmospheric models. *Icarus*, 208:156–164.

Felli, M., Brand, J., Cesaroni, R., Codella, C., Comoretto, G., Di Franco, S., Massi, F., Moscadelli, L., Nesti, R., Olmi, L., Palagi, F., Panella, D., and Valdettaro, R. (2007). Water maser variability over 20 years in a large sample of star-forming regions: the complete database. *Astronomy & Astrophysics*, 476:373–664.

Fogg, M. J. (1992). An Estimate of the Prevalence of Biocompatible and Habitable Planets. *Journal of the British Interplanetary Society*, 45:3–12.

Fraine, J., Deming, D., Benneke, B., Knutson, H., Jordán, A., Espinoza, N., Madhusudhan, N., Wilkins, A., and Todorov, K. (2014). Water vapour absorption in the clear atmosphere of a Neptune-sized exoplanet. *Nature*, 513:526–529.

Furuya, R. S., Kitamura, Y., Wootten, A., Claussen, M. J., and Kawabe, R. (2003). Water Maser Survey toward Low-Mass Young Stellar Objects in the Northern Sky with the Nobeyama 45 Meter Telescope and the Very Large Array. *The Astrophysical Journal, Supplement*, 144:71–134.

Gough, R. V., Chevrier, V. F., and Tolbert, M. A. (2016). Formation of liquid water at low temperatures via the deliquescence of calcium chloride: Implications for Antarctica and Mars. *Planetary and Space Science*, 131:79–87.

Gounelle, M. and Zolensky, M. E. (2014). The Orgueil meteorite: 150 years of history. *Meteoritics and Planetary Science*, 49:1769–1794.

Hansen, C. J., Kawaler, S. D., and Trimble, V. (2004). *Stellar interiors: physical principles, structure, and evolution*. Springer New York.

Hanslmeier, A. (2010). *Water in the Universe*. Astrophysics and Space Science Library. Springer Netherlands.

Hart, M. H. (1979). Habitable Zones about Main Sequence Stars. *Icarus*, 37:351–357.

Hoyle, F. (1946). The synthesis of the elements from hydrogen. *Monthly Notices of the Royal Astronomical Society*, 106:343.

Hoyle, F. (1954). On Nuclear Reactions Occuring in Very Hot STARS.I. the Synthesis of Elements from Carbon to Nickel. *The Astrophysical Journal, Supplement*, 1:121.

Hsieh, H. H. and Jewitt, D. (2006). A Population of Comets in the Main Asteroid Belt. *Science*, 312:561–563.

Hueso, R. and Sánchez-Lavega, A. (2004). A three-dimensional model of moist convection for the giant planets II: Saturn’s water and ammonia moist convective storms. *Icarus*, 172:255–271.

Iess, L., Stevenson, D. J., Parisi, M., Hemingway, D., Jacobson, R. A., Lunine, J. I., Nimmo, F., Armstrong, J. W., Asmar, S. W., Ducci, M., and Tortora, P. (2014). The Gravity Field and Interior Structure of Enceladus. *Science*, 344:78–80.
Ingersoll, A. P. and Pankine, A. A. (2010). Subsurface heat transfer on Enceladus: Conditions under which melting occurs. *Icarus*, 206:594–607.

Irion, R. (2002). Astrobiologists try to 'follow the water to life'. *Science*, 296(5568):647–648.

Ishii, H. A., Bradley, J. P., Dai, Z. R., Chi, M., Kearsley, A. T., Burchell, M. J., Browning, N. D., and Molster, F. (2008). Comparison of Comet 81P/Wild 2 Dust with Interplanetary Dust from Comets. *Science*, 319:447.

Izidoro, A., de Souza Torres, K., Winter, O. C., and Haghighipour, N. (2013). A Compound Model for the Origin of Earth's Water. *The Astrophysical Journal*, 767:54.

Jones, H. R. A., Pavlenko, Y., Viti, S., and Tennyson, J. (2002). Spectral analysis of water vapour in cool stars. *Monthly Notices of the Royal Astronomical Society*, 330:675–684.

Jortner, J. (2006). Conditions for the emergence of life on the early Earth: summary and reflections. *Philos. Trans. R. Soc. Lond. B:Biol. Sci.*, 361:1877.

Kaltenegger, L. and Kasting, J. (2008). Session 22. Habitability of Super-Earths. *Astrobiology*, 8:394–396.

Kanno, A., Hiroi, T., Nakamura, R., Abe, M., Ishiguro, M., Hasegawa, S., Miyasaka, S., Sekiguchi, T., Terada, H., and Igarashi, G. (2003). The first detection of water absorption on a D type asteroid. *Geophysical Research Letters*, 30:1909.

Karlsson, H. R., Clayton, R. N., Gibson, E. K., Mayeda, T. K., and Socki, R. A. (1991). Extraterrestrial water of possible Martian origin in SNC meteorites: Constraints from oxygen isotopes. In *54th Annual Meeting of the Meteoritical Society*, volume 766 of *LPI Contributions*.

Karlsson, T., Bromm, V., and Bland-Hawthorn, J. (2013). Pregalactic metal enrichment: The chemical signatures of the first stars. *Reviews of Modern Physics*, 85:809–848.

Kasting, J. F., Whitmire, D. P., and Reynolds, R. T. (1993). Habitable Zones around Main Sequence Stars. *Icarus*, 101:108–128.

Kopparapu, R. K., Ramirez, R., Kasting, J. F., Eymet, V., Robinson, T. D., Mahadevan, S., Terrien, R. C., Domagal-Goldman, S., Meadows, V., and Deshpande, R. (2013). Habitable Zones around Main-sequence Stars: New Estimates. *The Astrophysical Journal*, 765:131.

Koshland, D. E. (2002). The seven pillars of life. *Science*, 295(5563):2215–2216.

Kuiper, G. P. (1963). Infrared spectra of stars and planets. II. Water vapor in Omicron Ceti. *Comm. Lunar Planet. Lab.*, 1:179–188.

Kumar, S. and Hunten, D. M. (1982). The atmospheres of Io and other satellites. In Morrison, D., editor, *Satellites of Jupiter*, pages 782–806.

Küppers, M., O’Rourke, L., Bockelée-Morvan, D., Zakharov, V., Lee, S., von Allmen, P., Carry, B., Teysier, D., Marston, A., Müller, T., Crovisier, J., Barucci, M. A., and Moreno, R. (2014). Localized sources of water vapour on the dwarf planet (1)Ceres. *Nature*, 505:525–527.
Lawrence, D. J., Feldman, W. C., Goldsten, J. O., Maurice, S., Peplowski, P. N., Anderson, B. J., Bazell, D., McNutt, R. L., Nittler, L. R., Prettyman, T. H., Rodgers, D. J., Solomon, S. C., and Weider, S. Z. (2013). Evidence for Water Ice Near Mercury’s North Pole from MESSENGER Neutron Spectrometer Measurements. *Science*, 339:292.

Lebofsky, L. A. (1978). Asteroid 1 Ceres - Evidence for water of hydration. *Monthly Notices of the Royal Astronomical Society*, 182:17P–21P.

Leitner, M. A., Bothamy, N., Choukroun, M., Pappalardo, R. T., and Vance, S. (2014). Ocean Compositions on Europa and Ganymede. *AGU Fall Meeting Abstracts*.

Line, M. A. (2002). The enigma of the origin of life and its timing. *Microbiology*, 148:21–27.

Lis, D. C., Neufeld, D. A., Phillips, T. G., Gerin, M., and Neri, R. (2011). Discovery of Water Vapor in the High-redshift Quasar APM 08279+5255 at z = 3.91. *The Astrophysical Journal Letters*, 738:L6.

Lockwood, A. C., Johnson, J. A., Bender, C. F., Carr, J. S., Barman, T., Richert, A. J. W., and Blake, G. A. (2014). Near-IR Direct Detection of Water Vapor in Tau Boötis b. *The Astrophysical Journal, Letters*, 783:L29.

Lodders, K. (2003a). Abundances and Condensation Temperatures of the Elements. *Meteoritics and Planetary Science Supplement*, 38.

Lodders, K. (2003b). Solar System Abundances and Condensation Temperatures of the Elements. *The Astrophysical Journal*, 591:1220–1247.

Lynden-Bell, R., Morris, S., Barrow, J., Finney, J., and Harper, C. (2010). *Water and Life: The Unique Properties of H2O*. CRC Press, Boca Raton.

Maercker, M., Danilovich, T., Olofsson, H., De Beck, E., Justtanont, K., Lombaert, R., and Royer, P. (2016). A HIFI view on circumstellar H$_2$O in M-type AGB stars: radiative transfer, velocity profiles, and H$_2$O line cooling. *Astronomy & Astrophysics*, 591:A44.

Maercker, M., Schöier, F. L., Olofsson, H., Bergman, P., Frisk, U., Hjalmarson, Å., Justtanont, K., Kwok, S., Larsson, B., Olberg, M., and Sandqvist, A. (2009). Circumstellar water vapour in M-type AGB stars: constraints from H$_2$O(1{10}-1{01}) lines obtained with Odin. *Astronomy & Astrophysics*, 494:243–252.

Maercker, M., Schöier, F. L., Olofsson, H., Bergman, P., and Ramstedt, S. (2008). Circumstellar water vapour in M-type AGB stars: radiative transfer models, abundances, and predictions for HIFI. *Astronomy & Astrophysics*, 479:779–791.

Mahaffy, P. R., Webster, C. R., Atreya, S. K., Franz, H., Wong, M., Conrad, P. G., Harpold, D., Jones, J. J., Leshin, L. A., Manning, H., Owen, T., Pepin, R. O., Squyres, S., Trainer, M., and Team, M. S. (2013). Abundance and Isotopic Composition of Gases in the Martian Atmosphere from the Curiosity Rover. *Science*, 341:263–266.
Mandell, A. M., Haynes, K., Sinukoff, E., Madhusudhan, N., Burrows, A., and Deming, D. (2013). Exoplanet Transit Spectroscopy Using WFC3: WASP-12 b, WASP-17 b, and WASP-19 b. *The Astrophysical Journal*, 779:128.

Marty, B. (2012). The origins and concentrations of water, carbon, nitrogen and noble gases on Earth. *Earth and Planetary Science Letters*, 313:56–66.

Masson, P., Carr, M. H., Costard, F., Greeley, R., Hauber, E., and Jaumann, R. (2001). Geomorphologic Evidence for Liquid Water. *Space Science Reviews*, 96:333–364.

McCullough, P. R., Crouzet, N., Deming, D., and Madhusudhan, N. (2014). Water Vapor in the Spectrum of the Extrasolar Planet HD 189733b. I. The Transit. *The Astrophysical Journal*, 791:55.

Miller-Ricci, E., Seager, S., and Sasselov, D. (2009). The Atmospheric Signatures of Super-Earths: How to Distinguish Between Hydrogen-Rich and Hydrogen-Poor Atmospheres. *The Astrophysical Journal*, 690:1056–1067.

Mochizuki, N., Hachisuka, K., and Umemoto, T. (2009). Survey of Outer Galaxy Molecular Lines Associated with Water Masers. In Hagiwara, Y., Fomalont, E., Tsuboi, M., and Yasuhiro, M., editors, *Approaching Micro-Arcsecond Resolution with VSOP-2: Astrophysics and Technologies*, volume 402 of *Astronomical Society of the Pacific Conference Series*, page 384.

Montmerle, T., Claeyts, P., Gargaud, M., López-García, P., Martin, H., Pascal, R., Reisse, J., and Selsis, F. (2006). From Suns to Life: A Chronological Approach to the History of Life on Earth 9. Life On Earth... And Elsewhere? *Earth Moon and Planets*, 98.

Morbidelli, A., Chambers, J., Lunine, J. I., Petit, J. M., Robert, F., Valsecchi, G. B., and Cyr, K. E. (2000). Source regions and time scales for the delivery of water to Earth. *Meteoritics and Planetary Science*, 35:1309–1320.

Mottl, M., Glazer, B., Kaiser, R., and Meech, K. (2007). Water and astrobiology. *Chemie der Erde / Geochemistry*, 67:253–282.

Mueller-Wodarg, I., Mendillo, M., and Moore, L. (2006). Water on Saturn: Global effects on ionospheric densities. *AGU Fall Meeting Abstracts*.

Mulders, G. D., Ciesla, F. J., Min, M., and Pascucci, I. (2015). The Snow Line in Viscous Disks around Low-mass Stars: Implications for Water Delivery to Terrestrial Planets in the Habitable Zone. *The Astrophysical Journal*, 807:9.

Mumma, M. J., Weaver, H. A., Larson, H. P., Williams, M., and Davis, D. S. (1986). Detection of water vapor in Halley’s comet. *Science*, 232:1523–1528.

NASA (2015). NASA EXOPLANET ARCHIVE. [http://exoplanetarchive.ipac.caltech.edu/]. [Online; accessed 28-September-2016].

Nixon, C. A., Jennings, D. E., de Kok, R., Coustenis, A., and Flasar, F. M. (2006). Water in Titan’s Atmosphere from Cassini CIRS Observations. In *AAS/Division for Planetary Sciences Meeting Abstracts #38*, volume 38 of *Bulletin of the American Astronomical Society*, page 529.
Norton, O. R. (2002). *The Cambridge Encyclopedia of Meteorites*. Cambridge University Press, Cambridge.

Oberhummer, H., Csótó, A., and Schlattl, H. (2000). Stellar Production Rates of Carbon and Its Abundance in the Universe. *Science*, 289:88–90.

Ojha, L., Wilhelm, M. B., Murchie, S. L., McEwen, A. S., Wray, J. J., Hanley, J., Massé, M., and Chojnacki, M. (2015). Spectral Evidence for Hydrated Salts in Seasonal Brine Flows on Mars. *European Planetary Science Congress 2015*, 10:EPSC2015–838.

Owen, T. and Mason, H. P. (1969). Mars: Water Vapor in Its Atmosphere. *Science*, 165:893–895.

Pál, B. and Keresztori, Á. (2016). Possibility of microscopic liquid water formation at landing sites on Mars and their observational potential. *ArXiv e-prints*.

Pascal, R., Boiteau, L., Forterre, P., Gargaud, M., Lazcano, A., Lopez-Garcia, P., Maurel, M.-C., Moreira, D., Pereto, J., Prieur, D., and Reisse, J. (2006). Prebiotic chemistry biochemistry emergence of life (4.42 Ga). *Earth Moon Planets*, 98:153.

Phillips, K. J. H. (1995). *Guide to the Sun*. Cambridge University Press, Cambridge.

Piersanti, L., Straniero, O., and Cristallo, S. (2007). A method to derive the absolute composition of the Sun, the solar system, and the stars. *Astronomy & Astrophysics*, 462:1051–1062.

Pilcher, C. B. (1979). The stability of water on Io. *Icarus*, 37:559–574.

Rampelotto, P. H. (2010). Resistance of Microorganisms to Extreme Environmental Conditions and Its Contribution to Astrobiology. *Sustainability*, 2:1602–1623.

Rasool, S. I. and de Bergh, C. (1970). The Runaway Greenhouse and the Accumulation of CO\textsubscript{2} in the Venus Atmosphere. *Nature*, 226:1037–1039.

Rauer, H., Collier-Cameron, A., Barnes, J., and Harris, A. W. (2004). Search for Signatures of an Atmosphere of HD209458 b. In Penny, A., editor, *Planetary Systems in the Universe*, volume 202 of *IAU Symposium*, page 109.

Raulin, F. (2005). Exo-Astrobiological Aspects of Europa and Titan: From Observations to Speculations. *Space Science Reviews*, 116:471–487.

Raulin, F. (2008). Astrobiology and habitability of Titan. *Space Science Reviews*, 135:37–48.

Rauscher, T. and Patkós, A. (2011). *Origin of the Chemical Elements*. Springer, Netherlands.

Robert, F., Merlivat, L., and Javoy, M. (1978). Water and Deuterium Content in the Chainpur and Orgueil Meteorites. *Meteoritics*, 13:613.

Roos-Serote, M., Atreya, S. K., Wong, M. K., and Drossart, P. (2004). On the water abundance in the atmosphere of Jupiter. *Planetary and Space Science*, 52:397–414.

Rothschild, L. J. and Mancinelli, R. L. (2001). Life in extreme environments. *Nature*, 409:1092–1101.
Russell, H. N. (1934). Molecules in the Sun and Stars. *The Astrophysical Journal, 79*:317.

Sagan, C. (1996). Circumstellar Habitable Zones: An Introduction. In Doyle, L. R., editor, *Circumstellar Habitable Zones*, page 3.

Salaris, M. and Cassisi, S. (2005). *Evolution of Stars and Stellar Populations*. Wiley-VCH, New Jersey.

Salinas, V. N., Hogerheijde, M. R., Bergin, E. A., Cleeves, L. I., Brinch, C., Blake, G. A., Lis, D. C., Melnick, G. J., Panić, O., Pearson, J. C., Kristensen, L., Yıldız, U. A., and van Dishoeck, E. F. (2016). First detection of gas-phase ammonia in a planet-forming disk. NH$_3$, N$_2$H$^+$, and H$_2$O in the disk around TW Hydreae. *Astronomy & Astrophysics, 591*:A122.

Salyk, C., Lacy, J. H., Richter, M. J., Zhang, K., Blake, G. A., and Pontoppidan, K. M. (2015). Detection of Water Vapor in the Terrestrial Planet Forming Region of a Transition Disk. *The Astrophysical Journal Letters, 810*:L24.

Schlattl, H., Heger, A., Oberhummer, H., Rauscher, T., and Csótó, A. (2004). Sensitivity of the C and O production on the 3α rate. *Astrophysics & Space Science, 291*:27–56.

Schulz, R., Owens, A., Rodriguez-Pascual, P. M., Lumb, D., Erd, C., and Stüwe, J. A. (2006). Detection of water ice grains after the DEEP IMPACT onto Comet 9P/Tempel 1. *Astronomy and Astrophysics, 448*:L53–L56.

Schulze-Makuch, D. and Irwin, L. N., editors (2004). *Life in the universe. Expectations and constraints*, volume 3.

Shiba, H., Sato, S., Yamashita, T., Kobayashi, Y., and Takami, H. (1993). Detection of water vapor in T Tauri stars. *The Astrophysical Journal, Supplement, 89*:299–319.

Spencer, J. R., Pearl, J. C., Segura, M., Flasar, F. M., Mamoutkine, A., Romani, P., Buratti, B. J., Hendrix, A. R., Spilker, L. J., and Lopes, R. M. C. (2006). Cassini Encounters Enceladus: Background and the Discovery of a South Polar Hot Spot. *Science, 311*:1401–1405.

Spiegel, D. S., Raymond, S. N., Dressing, C. D., Scharf, C. A., and Mitchell, J. L. (2010). Generalized Milankovitch Cycles and Long-Term Climatic Habitability. *The Astrophysical Journal, 721*:1308–1318.

Spohn, T. and Schubert, G. (2003). Oceans in the icy Galilean satellites of Jupiter? *Icarus, 161*:456–467.

Sridharan, R., Ahmed, S. M., Pratim Das, T., Sreelatha, P., Pradeepkumar, P., Naik, N., and Supriya, G. (2010). 'Direct’ evidence for water (H$_2$O) in the sunlit lunar ambience from CHACE on MIP of Chandrayaan I. *Planetary and Space Science, 58*:947–950.

Stevenson, D. J. and Fishbein, E. (1981). The Behavior of Water in the Giant Planets. In *Lunar and Planetary Science Conference*, volume 12 of *Lunar and Planetary Science Conference*, pages 1040–1042.
Stimpfl, M., Lauretta, D. S., and Drake, M. J. (2004). Adsorption as a Mechanism to Deliver Water to the Earth. *Meteoritics and Planetary Science Supplement*, 39.

Tobie, G., Čadek, O., and Sotin, C. (2008). Solid tidal friction above a liquid water reservoir as the origin of the south pole hotspot on Enceladus. *Icarus*, 196:642–652.

Treiman, A. H., Lanzirotti, A., and Xirouchakis, D. (2004). Ancient water on asteroid 4 Vesta: evidence from a quartz veinlet in the Serra de Magé eucrite meteorite. *Earth and Planetary Science Letters*, 219:189–199.

Trevors, J. T. and Abel, D. L. (2004). Chance and necessity do not explain the origin of life. *Cell Biol Int.*, 28:729–739.

Tsujii, T. (2000). Water in Emission in the Infrared Space Observatory Spectrum of the Early M Supergiant Star μ Cephei. *The Astrophysical Journal, Letters*, 540:L99–L102.

Valdettaro, R., Palla, F., Brand, J., Cesaroni, R., Comoretto, G., Di Franco, S., Felli, M., Natale, E., Palagi, F., Panella, D., and Tofani, G. (2001). The Arcetri Catalog of H_2O maser sources: Update 2000. *Astronomy and Astrophysics*, 368:845–865, https://arxiv.org/pdf/1511.09352.

van der Tak, F. (2015). Water in the interstellar media of galaxies. *ArXiv e-prints* - https://arxiv.org/pdf/1511.09352.

Vance, S., Bouffard, M., Choukroun, M., and Sotin, C. (2014). Ganymede’s internal structure including thermodynamics of magnesium sulfate oceans in contact with ice. *Planetary and Space Science*, 96:62–70.

Visscher, C. and Fegley, Jr., B. (2005). Chemical Constraints on the Water and Total Oxygen Abundances in the Deep Atmosphere of Saturn. *The Astrophysical Journal*, 623:1221–1227.

von Weizsacker, C. F. (1938). Über Elementumwandlungen im Inneren der Sterne II. *Physikalische Zeitschrift*, 39:633–646.

Wallace, L., Bernstein, P., Livingston, W., Hinkle, K., Busler, J., Guo, B., and Zhang, K. (1995). Water on the Sun. *Science*, 268:1155–1158.

Wallstein, G., Iben, I., Parker, P., Boesgaard, A. M., Hale, G. M., Champagne, A. E., Barnes, C. A., Käppeler, F., Smith, V. V., Hoffman, R. D., Timmes, F. X., Sneden, C., Boyd, R. N., Meyer, B. S., and Lambert, D. L. (1997). Synthesis of the elements in stars: forty years of progress. *Rev. Mod. Phys.*, 69:995–1084.

Walsh, A. J., Lo, N., Burton, M. G., White, G. L., Purcell, C. R., Longmore, S. N., Phillips, C. J., and Brooks, K. J. (2008). A Pilot Survey for the H_2O Southern Galactic Plane Survey. *Publications of the Astronomical Society of Australia*, 25:105–113.

Way, M., Del Genio, A. D., Kelley, M., Aleinov, I. D., and Clune, T. (2014). Exploring the Inner Edge of the Habitable Zone in the Early Solar System. *AGU Fall Meeting Abstracts*.

Winnberg, A., Engels, D., Brand, J., Baldacci, L., and Walmsley, C. M. (2008). Water vapour masers in long-period variable stars. I. RX Bootis and SV Pegasi. *Astronomy & Astrophysics*, 482:831–848.
Wood, S. E., Vasavada, A. R., and Paige, D. A. (1992). Temperatures in the Polar Regions of Mercury: Implications for Water Ice. In AAS/Division for Planetary Sciences Meeting Abstracts #24, volume 24 of Bulletin of the American Astronomical Society, page 957.

Yang, B. and Jewitt, D. (2007). Spectroscopic Search for Water Ice on Jovian Trojan Asteroids. The Astronomical Journal, 134:223–228.