Water in Differentiated Planets, the Moon, and Asteroids

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~~ESA's Mars Express image shows~~ Korolev crater, an 82-~~kilometre~~-across feature found in the northern lowlands of Mars. The water ice filling the crater is seasonal.

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The distribution of water in differentiated Solar System bodies depends on many factors including size, distance from the Sun, and how they incorporated water. Most of this water is likely locked as hydrogen in mantle minerals and could amount to several Earth~~'s~~ oceans worth in mass for the largest planets. An essential compound for the development of life, water also has a tremendous influence on planetary evolution and volcanism. Only Earth has an active exchange of water between surface and mantle. Surface water on other differentiated bodies mostly results from degassing by volcanoes whose mantle sources are inherited from magma ocean processes early in their history. Airless bodies also acquire surface water by impacts, spallation, and from the solar wind.

KEYWORDS: water; hydrogen; Mercury; Venus; Earth; lunar; Mars; Vesta

INTRODUCTION

Water is a key ingredient for life~~,~~ but also plays fundamental roles in the evolution of planets and asteroids. Solar System bodies that experienced internal melting, resulting in the formation of crust, mantle, and core, are labeled as "differentiated" or "terrestrial". Water in the interior of terrestrial bodies has a tremendous influence on how they cool and differentiate, how rocks deform, how magmas develop, how volcanoes erupt, and how atmospheres and oceans form. Most water is locked in silicate minerals in the mantles of differentiated bodies as trace element hydrogen (H) bonded to structural oxygen. The term water has been colloquially used to refer to this H and is traditionally reported in µg/g H_2O. In the mantle, which is the largest layer by volume in differentiated bodies, these trace amounts of H locked in minerals (tens to hundreds of µg/g H_2O) sum up to the equivalent of several terrestrial oceans in mass inside Earth and possibly in other planets. When the mantle partially melts, H is preferentially partitioned into the melt and is thus classified as an "incompatible" element. When these melts reach the planetary surface during magma ocean or volcanic events, they degas, releasing H as H_2O, H_2, and other H-bearing molecules depending on how oxidized the system is, along with other highly volatile elements (e.g., carbon, sulfur). This degassing can result in the formation of atmospheres (Earth, Mars, Venus) and liquid and frozen water (Earth and Mars) on the surface of planets of sufficient size to retain these volatiles by gravitational pull. Additional H may be acquired on the surface of airless bodies (e.g., the Moon) via solar wind implantation, cosmic ray spallation, or delivery by impactors. This contribution summarizes our current knowledge on the main reservoirs of water in differentiated planets, the Moon, and asteroids in terms of quantities and isotopic ratios (deuterium/hydrogen (D/H) ratio, expressed here in the δD notation in ‰ relative to a terrestrial sea water standard (called SMOW), i.e., the δD of Earth oceans is ~~at~~ ~0 ‰), and explains the role that water played in their evolution and characteristics.

EARTH'S WATER

The uniqueness of Earth in the Solar System comes from the presence of oceans of water on its surface and the ongoing plate tectonic regime that results in an active exchange of water between the interior and surface (ocean and atmosphere) of the planet. This system is dynamic with constant recycling of water through the Earth, from water input at subduction zones to water output when volcanoes degas at the surface, as well as likely exchange between Earth's deeper layers (FIG. 1).

As a result, water is unevenly distributed in Earth, with most of it—one to seven Earth oceans' ~~mass~~, depending on estimations—stored in the mantle as H in silicates (e.g., Peslier et al. 2017). For the crust and upper mantle, we have direct samples (crustal units, crustal and mantle xenoliths, orogenic massifs, abyssal peridotites) and indirect samples (crystallized partial melts from the mantle such as mid-ocean ridge basalts, MORB, and oceanic island basalts, OIB) in which water contents have been measured, primarily by transmission Fourier transform infrared spectrometry (FTIR) and secondary ion mass spectrometry (SIMS). The MORB source (upper oceanic asthenosphere) contains ~50–230 µg/g H_2O, while the OIB sources, being more diverse in composition and depth, are more water-rich (100–750 µg/g H_2O; FIG. 1). The mantle lithosphere, whether under continental or oceanic crust, also has water contents from 50 to 200 µg/g H_2O. Studies of mantle lithosphere xenoliths show that the variation in water contents is mostly linked to metasomatism, i.e., water-bearing fluids or melts circulating through and reacting with the mantle lithosphere (e.g., Peslier et al. 2017). The δD of the upper mantle is estimated to be approximately −100‰ from the analysis of mantle xenoliths, −60‰ to −90‰ from MORB

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analyses, and values as low as −200‰ have been suggested from data on melt inclusions in primitive basalts (Peslier et al. 2017). The relatively low water content of olivine, the main phase of the mantle lithosphere, plays a role in the rigidity of tectonic plates because the strength of olivine increases with decreasing water content (Karato 2006). The upper mantle likely becomes progressively more water-rich with depth, as water solubility increases with pressure in olivine (Peslier et al. 2017). Consequently, in contrast to the lithosphere, the water in olivine facilitates the convection of the asthenosphere by lowering its viscosity (Karato 2006).

Water contents are less constrained deeper in the Earth (Fig. 1), where indirect estimates are obtained using a combination of experimental petrology, mineral physics, and geophysics (e.g., electrical conductivity and seismic attenuation; Karato 2006; Peslier et al. 2017). An exception is one water-rich ringwoodite inclusion found in a diamond originating from the mantle transition zone. This diamond comes from parts of the mantle transition zone thought to be very water-rich (10,000 µg/g H_2O), likely related to subducting water-rich slabs that sometimes stagnate at these depths, while other parts are relatively dry (<6000 µg/g H_2O; Fig. 1). The water content of the lower mantle is a matter of debate, with contradictory results from experiments on its main phases. However, minor water-rich phases are stable in the lower mantle (e.g., hydrous Mg and Al silicate minerals called phases B, D, H, d, Egg), brought down by subducted slabs that can penetrate all the way to the core–mantle boundary. The H content of the core is unknown, but could constitute an important reservoir of "water" in the Earth because of the high solubility of H in liquid and solid iron.

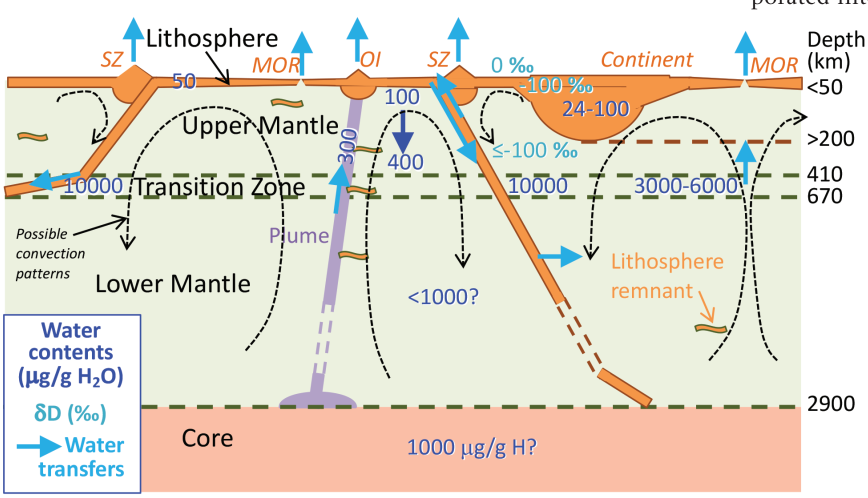

Figure 1 Sketch showing current estimations of water content nd δD distribution in the Earth. Blue arrows shows where the main transfers of water occur between layers. Black dotted arrows indicate asthenospheric mantle convection patterns. SZ = subduction zone; MOR = mid-ocean ridge; OI = oceanic island.

The water content of Earth's interior and surface has evolved through time. Based on the similarity of the δD (≤ −100‰) and other isotopes of the Earth's mantle to the main building blocks of Earth (enstatite chondrites, ~ −100‰ to −150‰; Fig. 2), water in Earth could have been acquired during the planet's accretion from the solar nebula (Peslier et al. 2017; McCubbin and Barnes 2019; Izidoro and Piani 2022 this issue). Others argue that most of Earth's water could have been acquired later, after the planet was already differentiating into core and mantle, and that this water could instead come from carbonaceous chondrite type material (Fig. 2) from the outer Solar System (Peslier et al. 2017; Vacher and Fujiya 2022 this issue). As still growing protoplanets, Earth and other terrestrial bodies are thought to have captured an H_2 atmosphere from the solar nebula, which they likely lost to space in the first billion year (Ga) by being blown off by the extreme UV radiation from a young Sun (Lammer et al. 2018). The next step is the formation of surface magma oceans caused by heat dissipation during a period of giant accretionary impacts, including the one that formed our Moon (Elkins-Tanton 2012). The magma oceans at the surface of Venus, Earth, and Mars degassed and formed a "steam" atmosphere of primarily CO_2 and H_2O (Lammer et al. 2018). The majority of this atmosphere is retained, despite some being ejected during the largest impacts (Elkins-Tanton 2012). After the magma oceans finally solidify, atmosphere cooling over millions of years results in water condensation and liquid water on planetary surfaces. Based on the ages of the oldest banded iron formations that formed from anoxic sedimentary deposition, and of the oldest detrital zircons, it is estimated that oceans were present on Earth as early as 3.8–4.2 Ga ago (e.g., Wilde et al. 2001). The final and still ongoing redistribution of Earth's water is ruled by plate tectonics, which started ~3 Ga (e.g., Debaille et al. 2013). Plate tectonics allows oxidized wet material, such as sediments, serpentinized oceanic crust, and water seeping in fractures at the bending of the plates above mantle wedges, to be subducted into the mantle (Fig. 1). The oxidation process of the mantle is particularly effective after the rise of life-induced oxygen in the atmosphere, 2.2–2.5 Ga (Catling and Zahnle 2020). Melting of this oxidized material has allowed N_2 gas to be released by volcanoes (as opposed to ammonia being incorporated into rocks under reduced conditions), especially at subduction zones (Catling and Zahnle 2020). This resulted in the N_2-dominated composition for the Earth's atmosphere. In addition, CO_2 is captured as carbonates via continental weathering, which is sustained by the continuous presence of liquid water on the planet's surface (Lammer et al. 2018). The temperature variations of the Earth's atmosphere, mainly regulated by the carbon cycle and greenhouse effect (Catling and Zahnle 2020), and resulting global air circulation, generate a low-altitude cold trap. This tropopause layer at 15–18 km makes water condensate and fall back to the surface, instead of being lost to space over time (Wordsworth and Pierrehumbert 2013). Earth's plate tectonics and resulting deep water cycle were therefore essential players that allowed our planet to harbor and sustain life on its surface.

THE MOON'S WATER

The possibility that water is present at the surface of the Moon is crucial for future human exploration. There appears to be water incorporated in lunar regolith (the "soil" derived from the long history of impacts that have pounded the rocks at the surface of our satellite) and ice deposits in the permanently shadowed craters of the poles (Fig. 3C). These sources of water could potentially be harvested for long-term human habitation of the Moon. The evidence for water at the lunar surface is primarily derived from spectroscopic and radar data (McCubbin et al. 2015 and references therein). In particular, Chandrayaan-1's Moon Mineralogy Mapper (M3), NASA's Cassini's VIMS spectrometer, and NASA's Deep Impact/EPOXI probe, have detected a spectral signal at ~3-µm wavelength, consis-

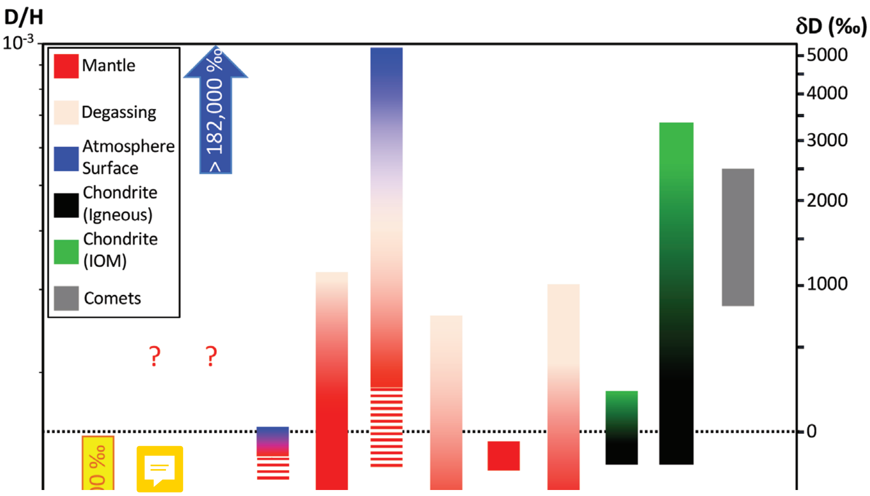

FIGURE 2 Hydrogen isotopic composition (on a log scale of the D/H ratio) of differentiated planetary bodies from their mantle to their surface compared to those of enstatite chondrites (EC), carbonaceous chondrites (CC), and comets (Oort cloud and Jupiter types). IOM = insoluble organic matter. The striped white and red pattern for Earth and Mars shows the extent of lower δD values that have been suggested for the mantle of these planets. The question marks for Mercury and Venus indicate that the δD of their interior is not known.

tent with either water (H_2O) or hydroxyl (OH) on the lunar surface. Recent detection from Earth by the NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA) of a 6-µm emission feature at high lunar latitudes is also likely owing to the presence of molecular water on the lunar surface (Honniball et al. 2021). Moreover, the presence of larger water-ice deposits in the permanently shadowed craters of the poles has been detected by the Lunar Prospector Neutron Spectrometer and confirmed by the neutron detector onboard the Lunar Reconnaissance Orbiter (FIG. 3C) and the Lunar Crater Observation and Sensing Satellite. The near-infrared reflectance spectra provide a global view of water at the lunar surface through the identification of OH or H_2O absorptions in the ~2.6- to 4-µm wavelength region.

Several mechanisms for the origin of water in lunar soil have been proposed (McCubbin et al. 2015; Honniball et al. 2021). One derives from the solar wind, which mainly contains charged protons that interact with airless planetary surfaces. The protons bond to the oxygen atoms of minerals present at the surface and get implanted in the top few microns. This "water" is then mixed in deeper during reworking of the regolith following impacts. Implantation by solar wind is evidenced by the low δD (≤−550‰) measured in lunar soil, which is close to that of the solar wind (−1000‰). Impacts on the lunar surface are also believed to contribute to the polar water-ice deposits. Impacts can release cometary and meteoroidal water into the exosphere and also free solar wind-implanted H. A portion of this water can be retained in impact glasses, and water present in the lunar exosphere can be chemisorbed on grain surfaces. Spallation, the formation of chemical elements via nuclear fission, including hydrogen from the interaction with surface rocks of cosmic rays (highly charged particles from space), can also add water to lunar rocks and regolith, thereby increasing their δD. Finally, some areas of the lunar surface show anomalously high water contents, suggesting that volcanic activity could generate a transient atmosphere at specific locations where water could be trapped.

A temperature dependence has been evidenced for the geographical distribution of surface water, with content increasing toward the poles. A portion of the water released by impacts may migrate to cold traps in permanently shadowed regions where it may remain in the form of ice. Surface water abundance can also vary over a lunar day, suggesting formation and migration of water toward cold traps present at polar regions. This water is likely stored within glasses or in voids between grains sheltered from the harsh lunar environment. However, the weak equatorial 3-µm bands obtained by the Lunar Atmosphere and Dust Environment Explorer (LADEE) are consistent with the uppermost few cm of the regolith being mostly desiccated. The LADEE and M3 data are also consistent with the low water abundances estimated at the equator by SOFIA measurements (Honniball et al. 2021). Conversely, SOFIA data at high latitudes indicate that the regolith is not desiccated, supporting several inferences that show an increase in hydroxyl from the equator to higher latitudes.

An assessment of the water distribution and isotopic characteristics in the Moon's interior is necessary to understand the origin of the Moon's water in the context of planetary formation (addressed in Izidoro and Piani 2022 this issue) and evolution. For this purpose, the various types of lunar rocks brought back by astronauts of the 1969–1973 Apollo missions, by the 2020 Chang'e 5 mission, and found as lunar meteorites, are being systematically analyzed. Trace amounts of water are found in all types of Moon rocks, allowing the role of water during the stages of our satellite's history to be deciphered, in particular during the formation of its crust and later volcanism. The key is to determine how water was distributed in the crust and mantle during these events, and how much was lost by degassing from magmas at the surface of our satellite. Any volatile released during degassing is mostly lost to space because the Moon is too small to retain an atmosphere (Elkins-Tanton 2012; Hauri et al. 2017).

A few µg/g of water have been detected in feldspars from lunar highland rocks (Hui et al. 2017). These represent the oldest Moon rocks, forming 4.3–4.4 Ga by flotation of plagioclase at the top of the crystallizing lunar magma ocean (Elkins-Tanton 2012; Hauri et al. 2017). The resulting crust is dominated by plagioclase and currently covers 83% of the Moon's surface. From these measurements, it has been speculated that the lunar magma ocean contained ~650–2500 µg/g H_2O with a δD of ~300‰ ± 110‰ (Hui et al. 2017; FIG. 2). In contrast, δD values ranging from ~ −750‰ to 800‰ (FIG. 2) are measured in highland apatite, a volatile (H, Cl, F)-rich phosphate that crystallizes late in a magma solidification sequence (Robinson and Taylor 2014; McCubbin et al. 2015; Robinson et al. 2016). The lunar magma ocean could have had pre-degassing δD values as low as those of the low-δD apatites, while the high δD of the plagioclase are thought to result from the preferential loss of H over D during H_2 degassing prior to crust formation (Hui et al. 2017). The remaining 17% of the Moon's surface comprise mare basalts that erupted 3.9–2 Ga, which are crystallized melts sourced in the lunar mantle. The wide δD range of the mare basalt apatites (−280‰ to 1450‰) is interpreted as H isotope fractionation during various degrees of volcanic degassing of melts with δD initially in the lower part of the range, i.e., inherited from their mantle source (Robinson and Taylor 2014; McCubbin et al. 2015; Hauri et al. 2017; Hu et al. 2021). Using melt inclusions in

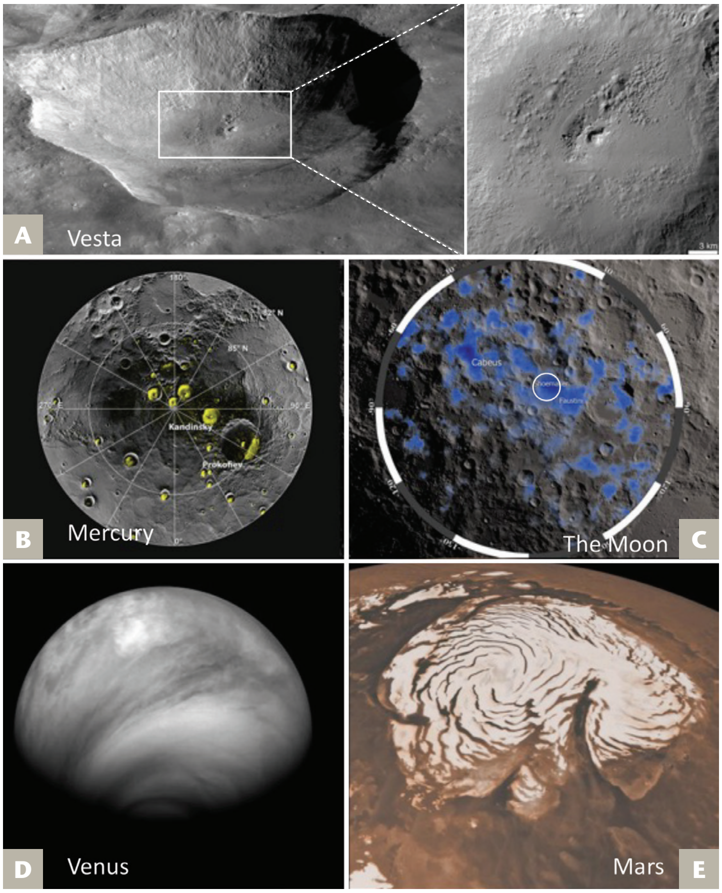

FIGURE 3 Water at the surface of differentiated planetary bodies. (**A**) Marcia crater (68 × 58 km) on Vesta shows an example of "pitted terrain", pothole-like depressions left behind by volatiles degassed from the subsurface. SOURCE: NASA-JPL/CALTECH/UCLA/MPS/DLR/IDA/ JHUAPL. (**B**) Radar image of Mercury's north polar region from the Arecibo Observatory superposed on a mosaic of MESSENGER images of the same area. Yellow areas denote regions of high radar reflectivity, hypothesized to consist of water ice trapped in permanently shadowed areas near Mercury's poles. Kandinsky crater has a diameter of 60 km. SOURCE: NASA/JOHNS HOPKINS U. APL/CIW/NATIONAL ASTRONOMY AND IONOSPHERE CENTER, ARECIBO OBSERVATORY. (**C**) Areas of the Moon's south pole with possible deposits of water ice, shown in blue. The map is based on data taken by NASA's Lunar Reconnaissance Orbiter. Shoemaker crater (dotted white circle) has a size of 50.9 km. SOURCE: NASA. (**D**) Photo of Venus's atmosphere taken by the Venus Monitoring Camera (VMC) on Venus Express. Venus is about the same size as Earth. SOURCE: ESA/MPS/DLR/IDA. (**E**) Orbital view of the north polar region of Mars during summer. The image synthesizes topographic data from Mars orbiter laser altimeter and images from the Mars orbiter camera on NASA's Mars Global Surveyor. The northern polar cap has a diameter of approximately 1000 km during the northern Mars summer. SOURCE: NASA/JPL-CALTECH/MSSS

olivine, the mantle source of primitive lunar basalts was determined to contain as much as or less water than the source of MORB on Earth (80–410 or 10–130 µg/g H_2O depending on the calculation assumptions; Hauri et al. 2017; McCubbin et al. 2015), while analysis of melt inclusions in ilmenite from the youngest Mare basalts suggest that their mantle source is water-poor (1–5 µg/g H_2O; Hu et al. 2021).

All of the rocks mentioned above are from the crust, meaning that any estimate of the water content and δD of the lunar interior must be calculated and has large uncertainties (Robinson and Taylor 2014). Moreover, the overwhelming evidence for degassing processes implies that most analyzed rocks degassed. Consequently, the water contents listed above are likely minimum values and most δD are higher than pre-degassing values. Nevertheless, the presence of trace amounts of water in lunar minerals first implies that the giant collision of a Mars-size object with the proto-Earth, which is thought to have formed our Moon, apparently did not result in total H loss as previously assumed. Water was incorporated at the time of the Moon's accretion and redistributed in its interior during its differentiation. The water and δD of the lunar mantle is likely heterogeneous, with regions having δD (FIG. 2) close to solar nebula values (< −300‰) inherited from the time of the Moon's accretion, and regions with higher δD (~300‰) and lower water contents dating from the time of magma ocean degassing (McCubbin et al. 2015; Hauri et al. 2017; Hu et al. 2021). A more complete understanding of lunar water will be achieved once more primitive samples (i.e., similar to mantle composition) are brought back and analyzed. Mantle samples may have been excavated during large impacts and may be found at the central peaks, peak rings, and regoliths of the largest lunar basins. For this reason and for the potential of ice deposits, the South Pole Aitken region, the largest impact crater on the Moon, is targeted by planned U.S., European/Russian, Japanese, and Chinese missions.

MARS WATER

Water once flowed on Mars, possibly even forming oceans, as evidenced by two main observations (Filiberto and Schwenzer 2018 and references therein). First, geomorphological features evidenced from orbiting spacecrafts are consistent with river channels, canyons, river deltas, and shorelines. Second, chemical analyses performed from space (e.g., by γ-rays, infrared and thermal emission spectrometry on Mars Odyssey, Mars Global Surveyor, Mars Express) and by rovers (e.g., by spectrometry of α-particles, X-rays, gas chromatography, thermal emission, and Mössbauer on NASA Pathfinder, Mars Exploration Rovers Spirit and Opportunity, and Mars Science Laboratory's rover Curiosity). These analyses of the planet's surface show that alteration minerals formed in rivers and lakes. In particular, a shift from phyllosilicates to sulfates indicates that Mars' climate shifted from wet to dry ~3.5 Ga. For about the last 3 Ga, alteration mineralogy has been dominated by anhydrous ferrous oxides—giving Mars its characteristic red color—and wind erosion has ruled. Water on the surface of Mars is presently locked in ice at the polar caps (FIGS. 3E and 4A), but also as underground ice and salty liquid water lakes beneath the polar ice (Filiberto and Schwenzer 2018; Orosei et al. 2018). The drying of the climate has been attributed to atmospheric H loss to space, combined with sequestration in the crust in the form of hydrous alteration minerals. Preferential loss of H relative to D during this H escape process resulted in the particularly high δD of the Martian atmosphere (~5000‰; FIG. 2). Atmospheric H loss is a result of the small size of Mars (a third of Earth's) and consequently low gravity, and of a core dynamo having stopped early in Mars' history, i.e., no magnetic field being generated to shield the planet from solar wind (Lammer et al. 2018).

Estimating how much water the interior of Mars contains and its δD compared to Earth helps us to model planetary formation (Izidoro and Piani 2022 this issue). We are fortunate to have samples from Mars as meteorites, and research is ongoing to analyze water in their various phases, primarily using SIMS. All but one (a crustal breccia) meteorites from Mars are crystallized igneous melts, ranging from cumulate (e.g., nakhlites) to basaltic (shergottites; Udry et al. 2020 and references therein). Shergottites, the most common Martian meteorite type in our collection, have a huge range of radiogenic isotopic compositions, larger than Earth's MORB and OIB combined, with two compositional end-members: "depleted" and "enriched" (Udry et al. 2020). These terms refer not only to radiogenic isotopes, but also to concentrations in incompatible trace elements, such as light rare earths (REE), and redox conditions. The meteorites' compositional differences result from partial melting of compositionally different regions of the Martian mantle (FIG. 4B). After magma ocean degassing and solidification, Mars never had plate tectonics as on Earth, but stayed in a "stagnant-lid" regime, implying little or no mantle convection, and no surface material input into the mantle (Elkins-Tanton 2012). Consequently, the Martian mantle regional compositions, including water content and δD variations, are thought to be inherited from magma ocean crystallization processes (Dudley et al. 2021 and references therein). The lava flows from which shergottites and nakhlites originate erupted <2.4 Ga, which is significantly later than magma ocean processes (Udry et al. 2020).

Calculating the water content of the mantle helps us to constrain the evolution of Mars, from its differentiation to its most recent volcanism, but—given that all Martian meteorites are samples of its crust—some assumptions are required. First crystallized phases (e.g., Mg-rich olivine, pyroxene, and their melt inclusions) are best to estimate the water content of a parent melt, because their water content is less likely to have been affected by crystallization and degassing processes (Dudley et al. 2021 and references therein). The water content of the mantle source of each meteorite can be calculated from that of the parent melt, although large uncertainties are generated through this method. The use of Martian meteorite phases to calculate the water content of the Martian mantle is further hampered by water content and δD being affected by weathering processes on Mars and Earth, and by shock effects when the rock was blasted off from the Martian surface by a meteor impact (Dudley et al. 2021). This is evidenced by the wide range of δD values measured in Martian meteorite phases, which is thought to result from the mixing of two main sources: mantle with low δD (≤300‰–400‰) and surface (up to 5000‰ measured for the Martian atmosphere; Greenwood et al. 2018; FIG. 2). All of these effects imply that the current estimates of water characteristics of the Martian mantle shown in FIGURE 4B are to be taken with a grain of salt. Nevertheless, the water content of the Martian mantle appears to be variable. The water content of shergottite sources is low for the depleted endmember (15–47 µg/g H_2O; Usui et al. 2012) and higher for the enriched endmember (245–900 µg/g H_2O; Dudley et al. 2021). This is consistent with the incompatible behavior of water, where the depleted mantle source underwent a greater extent of incompatible element removal during magma ocean crystallization than the enriched source (FIG. 4B). Nakhlites, pyroxene-rich cumulates, have low to intermediary water contents in their mantle sources, consistent with their relatively depleted isotopic and other trace element characteristics (60–180 µg/g H_2O).

The δD and other isotopes, such as those of N, Cl, and rare gases, are used to understand where Mars water originates (Izidoro and Piani 2022 this issue). Whether the Martian mantle has heterogeneous δD is controversial. Some argue that the high δD (~4000‰) measured in some phases of enriched shergottites is, in fact, a mantle signature and not the result of interaction with surficial Martian material (McCubbin and Barnes 2019), while others posit that enriched shergottites have lower δD (~300‰), as measured in the earliest crystallized phases (Dudley et al. 2021). If the latter interpretation proves correct, then the δD of the mantle sources of all types of Martian igneous meteorites are similar within uncertainties (~300‰–400‰). These values are higher than that of the Earth's upper mantle (~ −100‰); a dichotomy perhaps inherited from the two

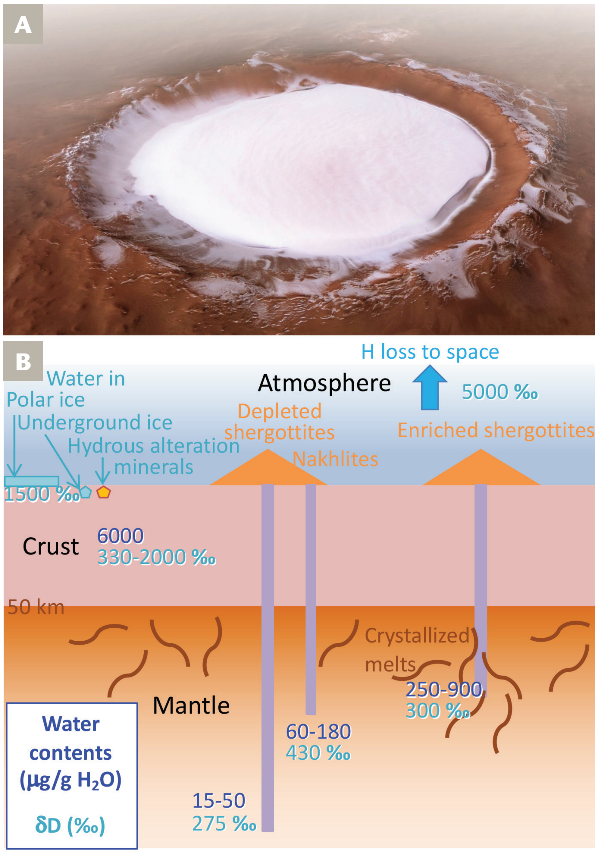

FIGURE 4 (A) The ice-filled Korolev crater near the north pole of Mars. The crater is 81.4 km wide. The photo was taken by the European Space Agency (ESA) Mars Express spacecraft in 2018. SOURCE: ESA/DLR/FU BERLIN. (B) Sketch showing current estimations of water content and δD distribution for Mars since <2.4 Ga. The estimations are for the atmosphere, surficial ice reservoirs, crust, and for the mantle sources of igneous Martian meteorites. Crystallized melts illustrate later stage incompatible-element enriched melts inherited from magma ocean processes. Although the depleted mantle source is shown here as deeper than that of the enriched mantle source, their relative locations, including depths, are not known.

planets having different "feeding zones" during accretion owing to their respective distances from the Sun (Izidoro and Piani 2022 this issue). The crustal breccia meteorite NWA 7034 is water-rich (6000 µg/g H_2O) and records δD (330‰–2000‰) intermediary between those of the Martian mantle and atmosphere (Udry et al. 2020). Although two rovers recently landed on Mars (NASA Mars 2020 Perseverance and China's 2021 Zhurong), the uncertainties on the water characteristics of deep Mars will only be resolved once un-altered igneous rocks are returned from Mars by robotic missions or by astronauts.

VENUS WATER

Venus is considered an "Earth-like" planet because they have a similar size and bulk composition (Greenwood et al. 2018 and references therein). However, the environment is completely different, with surface temperatures of 460 °C, and a dense atmosphere (92 bar) consisting of 96.5% CO_2 and 3.5% N_2 (FIG. 3D). These characteristics are explained by a runaway greenhouse effect having occurred in the past, which led to the complete evaporation of oceans presumed to have been present. However, another scenario is that Venus was always too hot for water to condense into oceans (Greenwood et al. 2018). Hydrogen escape would then have taken place early and rapidly, consequently driving off many other atmospheric constituents. The H escape scenario is confirmed by the high δD (82,000‰–1,600,000‰; FIG. 2) measured in Venus' atmosphere by the Pioneer spacecraft relative to Earth's (~0‰).

Regarding the interior of Venus, atmospheric N and C have been used as proxies to estimate that it contains 10 to 100 times less, or the same amount, of water in its mantle as Earth's (0.12–3000 µg/g H_2O; McCubbin and Barnes 2019). It is likely that Venus accreted with an amount of water similar to that of Earth, because collisional processes by water-bearing planetesimals affected Venus and Earth in a similar way. Although Venus has no plate tectonics, its surface has evidence of resurfacing by recent volcanism, as imaged by the Magellan spacecraft. However, models predict that this volcanic activity, involving mantle downwelling and upwelling and surface degassing, will likely never fully deplete the Venusian mantle of volatiles (Greenwood et al. 2018).

MERCURY'S WATER

Mercury was thought to be depleted in volatile elements largely due to its close vicinity to the Sun. However, the first data from the Mariner 10 mission indicated the presence of H, He, and O in an exosphere, and ground-based observations discovered additional exospheric Na, K, and Ca (Greenwood et al. 2018 and references therein). Moreover, radar data taken from Earth evidenced polar ice deposits, later confirmed by the MESSENGER spacecraft. Neutron data by MESSENGER indicated that Mercury's radar-bright polar deposits contain a H-rich layer below a surficial layer less rich in H (FIG. 3B). Combined radar and neutron data suggest that the H-rich layer consists of nearly pure water ice, derived dominantly from meteoritic and cometary impacts. Other discoveries from MESSENGER indicate that Mercury could contain as much interior water as Mars, having a K/Th ratio most similar to Mars, and a low oxygen fugacity calculated for its silicates (McCubbin and Barnes 2019). Moreover, morphologic features are consistent with explosive volcanism, including pyroclastic deposits and vents. Modeling of the spatial extent of these deposits show that their formation would require a magma with quite high volatile content. Furthermore, it has been estimated that Mercury's explosive volcanism has been occurring over a long period of time (from 3.8 to 1 Ga). Nevertheless, Mercury's volatile inventory, including water, is still an open question.

WATER IN VESTA AND THE HED METEORITES

The differentiated asteroid 4 Vesta is located in the asteroid belt between Mars and Jupiter. It is thought to be the parent body of most of the meteorites belonging to the howardite-eucrite-diogenite (HED) clan. This is based on remote spectral data, especially from the NASA Dawn spacecraft that specifically visited this asteroid in 2011, that match the spectral properties of HEDs obtained in the laboratory (e.g., McSween et al. 2019). Eucrites are basalts and gabbros, diogenites are cumulates of ultramafic compositions, while howardites are a brecciated mix of the two from impacts. As described above for the Moon and Mars, analyzing the water content and δD in these asteroid samples helps refine models of solar nebula accretion and volcanism in extraterrestrial bodies. The mineral apatite in eucrites yields a large δD range, from −500‰ to 700‰ (FIG. 2), interpreted as a δD increase when H was lost during volcanic degassing and thermal metamorphism (Sarafian et al. 2014; Stephant et al. 2021). The pyroxenes, one of the first crystallized phases from the eucrite parent melt, contain low water contents (~ ≤20 µg/g H_2O) compared to terrestrial pyroxenes (typically 100s of µg/g H_2O) and the δD are consistently low at ~ −260‰ ± 70‰ on average (Stephant et al. 2021). All HEDs are crustal lithologies, but from the least thermally metamorphosed eucrite analyzed, the water content of the Vesta mantle (<70 µg/g H_2O) is estimated to be lower than that of the MORB source and its δD is estimated to be ~ −370‰, i.e., lower than that of Earth's upper mantle (~ −100‰; FIG. 2). Vesta is thought to have accreted earlier than Mars, Earth, and even chondrites, from a region of the proto-solar nebula that had a low δD and differed from that where chondrites formed (McCubbin and Barnes 2019; Stephant et al. 2021). Perhaps small bodies like Vesta or the Moon cooled fast enough for their magma oceans to crystallize a conductive lid, blocking most degassing early (Elkins-Tanton 2012). They would then experience less overall degassing than larger planets, thereby preserving a low mantle δD inherited from their accretion material. Alternatively, low-δD areas may exist in the mantles of all differentiated bodies; however, those from large planets like Earth have not been sampled by mantle melts.

On Vesta's surface, Dawn's spectrometers detected the signature of OH in the spectra of the darkest areas of the asteroid's equatorial regions that would indicate a water content as high as 400 µg/g H_2O (De Sanctis et al. 2012). The distribution of the OH signature, shaped as pits and dark patches (FIG. 3A), suggests an exogenic origin, likely delivered by infalling primitive asteroids that are common in the asteroid belt. This material may have been delivered during the early evolution of Vesta (after differentiation and crust formation), either ~10 My after the formation of the first solids or later, during a purported (and controversial) period of late heavy bombardment, when primitive outer Solar System objects were implanted in the outer part of the asteroid belt (De Sanctis et al. 2012).

WATER IN OTHER ACHONDRITE METEORITES

The only other meteorite groups from differentiated parent bodies that have been analyzed for water are angrites and aubrites. Angrites are the oldest basaltic and gabbroic meteorites ever found and are remnants of the first generation of differentiated Solar System bodies. They predate Earth, Mars, and Vesta's accretion, having formed within the first 2 My, and having differentiated within the first 4 My, of the Solar System's history (McCubbin and Barnes 2019). The earliest crystallized phase in angrites, olivine, has < 20 µg/g H_2O, and their first formed melt inclusions contain 600–17,500 µg/g H_2O. From these measurements, it is calculated that 150–2750 µg/g H_2O could be present in the mantle of the angrite parent body (Sarafian et al. 2017; Deligny et al. 2021). Spallation-corrected δD values range from −150‰ to 60‰ in olivine and from −348‰ to −118‰ in their melt inclusions. Phosphates, which formed later in the crystallization sequence, have a wider δD range (−200‰ to 1000‰; FIG. 2) with the higher values having likely resulted from the melt degassing H_2 (Sarafian et al. 2017).

Aubrites accreted from the same solar nebula material as enstatite chondrites. They are typically breccia with mineralogy dominated by pyroxene and very reduced compositions. Aubrites analyzed by bulk-rock gas mass spectrometry record δD of ~ −155‰ to −70‰ (FIG. 2), i.e., similar to that of Earth's upper mantle (Lorenz et al. 2021; Izidoro and Piani 2022 this issue). This is expected because Earth is thought to have formed mainly from enstatite chondrite-like material from which it may have also acquired most of its water (Izidoro and Piani 2022 this issue).

CONCLUSION

The ranges of water contents and δD of the interior and surface of differentiated Solar System bodies are inherited from their long history, starting with initial accretion from the solar nebula, through their impact record, differentiation into crust–mantle–core, volcanism, to their peculiar surface alteration processes. The presence of water at the surface depends on the delicate balance of size, surface temperature, atmosphere composition, if present, and distance from the Sun. Expanding analyses to the whole range of extraterrestrial material available as meteorites, combined with experiments at magma ocean and core–mantle conditions, will ~~in the immediate future~~ improve our understanding of the distribution of water in the Solar System. However, sample return missions will be essential ~~for~~ properly constrain~~ing~~ the role of water in the evolution of each terrestrial planet, moon, and asteroid. Observations of extraterrestrial planetary systems at different stages of evolution will also be crucial to understand how water influences planetary evolution, the creation of habitable zones, and planetary surface conditions favorable to life.

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