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Editorial: Topical Collection on the Delivery of Water to Proto-Planets, Planets and Satellites

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The review papers of this Topical Collection of Space Science Reviews devoted to the delivery of water to proto-planets, planets and satellites provide a coherent and comprehensive portrait of the knowledge in this fascinating field. We provide here a key of lecture of the volume, by summarizing the content of each review and proposing a logical order of reading, then attempting a broad summary of the state of the art as it emerges from the reviews altogether.

The Delivery of Water to Protoplanets, Planets and Satellites
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The review by F. Westall and A. Brack focuses on the importance of water for life. It may be possible to conceive theoretically life based on compound-solvent pairs other than carbon-based molecules and liquid water, but this paper makes clear that organic material and liquid water have physical and chemical properties that make them optimal among all known molecules. This is the reason why water is at the core of exobiology and the focus of considerable research, as described in this Collection. Westall and Brack argue that hydrothermal environments most likely played a key role in the appearance of life, because hot rock-water interfaces can provide the chemical disequilibria to fuel reactions, and rocks and minerals can provide the reactive surfaces needed to help the formation and stability of prebiotic molecules. Moreover, once life emerged, rocks and minerals provided the required nutriments for life to prosper. This intimate relationship between liquid water, organic material and hot rocks for the sustainability of life comes back later in the collection when discussing habitability in the sub-surface oceans of some giant planet's satellites (see the review by Grasset et al.) or water-rich extrasolar planets (see the review by Noak et al.).

Four review papers make the inventory of water throughout the Solar System. The review by Alexander et al. describes the water budgets (and, more generally, volatile budgets) in small bodies. The review by Peslier et al. focusses on the water budget on Earth and its main reservoirs (core, mantle, crust and hydrosphere). The review by Greenwood et al. extends the analysis to the other terrestrial planets and the Moon, while the review by Grasset et al. describes the giant planets, their satellites, trans-Neptunian objects and the dwarf planet Ceres in the asteroid belt. Altogether, these reviews establish a clear distinction between a water-poor inner Solar System and a water rich outer Solar System, with the exception of the asteroid belt, where water-rich and water-poor asteroids co-exist in the same region (but might have been separated at origin). The water budget on Earth is uncertain because water concentrations in the lower mantle and the core are poorly known, but it seems likely that our planet is intermediate in terms of bulk water content between water-poor and water-rich asteroids. Venus and Mars have, or started with, water budgets comparable to the Earth's, whereas this is unknown for Mercury. The Moon, long-thought to be bone-dry, seems now to have a considerable water budget, perhaps 1/10 of that of the Earth. From the isotopic point of view (D/H and $^{14}N/^{15}N$ ratios), the Earth and Mars are very similar to water-rich asteroids, but distinct from comets: they are probably made of a mixture of dryer bodies and about 2% carbonaceous chondrites. A signature of cometary bombardment, however, has been found by comparing the Xenon isotope composition in the escape-corrected terrestrial atmosphere with those in asteroids and comets (see the review by Alexander et al.), concluding that 20% of atmospheric Xenon should be of cometary origin. The corresponding amount of cometary material would provide a negligible contribution to the terrestrial water budget.

Three review papers discuss the formation of planetary systems and the fate of water in the various phases of this process. The review by Hartmann et al. focusses on protoplanetary disks and in particular it discusses the evolution of the so-called snowline that separates the part of the disk where water is in vapor form from that where water ice is stable. If the detection of the water snowline is still beyond observational capabilities (and therefore remains an issue investigated on the basis of theoretical models), interferometric observations are now providing constraints on the positions of CO snow lines, testing disk models at large scales. The review by Paardekooper and Johansen is a very complete compendium of all processes leading to giant planet formation: dust coagulation in the form of pebbles, aerodynamic radial drift of these particles, formation of self-gravitating clumps of pebbles leading to the birth of large planetesimals, the subsequent growth of planetesimals due to mutual collisions and continued pebble accretion until forming protoplanetary cores, gas accretion onto these cores and—last but not least—planet migration in the different planetary mass regimes. The review of O'Brien et al. instead focusses on the terrestrial planets of the Solar System, describing the leading models that attempt to reproduce their orbital and physical properties. As the giant planets formed before the terrestrial planets, the Paardekooper and Johansen review sets the stage for the O'Brien et al. one. A specific emphasis is put on the dispersal of water-rich planetesimals during giant planet growth and migration, eventually "contaminating" the growing terrestrial planets with this molecule so precious for life, as well as other volatiles.

After this description of planet formation at large scale, we suggest reading the 4 reviews devoted to specific processes related to water that affected the geochemical evolution of planets and their precursors, without which the present properties of the planets cannot be understood in details. The review by Ikoma et al. describes the absorption of water in silicate magma. During the magma ocean stage a planet can store a large amount of water, either produced by oxygen-hydrogen reaction between the silicate and a primitive H-rich atmosphere or delivered by water-rich planetesimals. The silicate-metal segregation in the magma ocean, leading to core formation, partitions the water between the mantle and the core, possibly making H one of its major light elements. As the magma ocean cools off, water exolves and eventually it outgasses into the growing atmosphere. The review by Monteux et al. describes the flip side of this process, that is how water influences the differentiation process by increasing the oxygen fugacity of the planet. It is likely that the differentiation observed in/for icy worlds, such as Ganymede, probably occurred in two stages: rock-ice differentiation, then metal silicate differentiation within the rocky core. The review discusses also water losses during radioactive heating in planetesimals. The review by Tian et al. describes atmosphere losses due to stellar irradiation, i.e. the process of hydrodynamic escape (the loss of H-molecules dragging heavier species into space). This process is very important for water. In fact, if water is dissociated, the escape of hydrogen is fatal for the final water budget of the atmosphere. This is most likely what happened on Venus (see the review by Greenwood et al.). But this process could also be important for planets in the so-called habitable zone of M-type star, due to the strong XUV radiation that these stars emit relative to a G-type, Sun-like star. The review by Schlichting and Mukhopadhyay focusses on a different process removing the atmosphere, i.e. the role of impacts. The review describes that giant impacts are much less effective in removing an atmosphere than a large number of impacts from small planetesimals for the same total impacting mass. Using geochemical arguments, it also demonstrates that, for the Earth, atmospheric impact losses have been dominant over hydrodynamic escape; moreover part of the Earth's water survived the Moon-forming giant impact.

Last but not least, the review paper by Noak et al. addresses the habitability of extrasolar planets. It describes the current census of the extrasolar planet population and the present and future techniques for determining the composition of the planets and particularly their water abundance. But it also shows that, contrarily to what could be naively expected, water-rich planets are likely *not* favorable for the development of life. The reason is that a large amount of surface water would inevitably produce a layer of high-pressure ice between the liquid layer and the rocky mantle, preventing the interaction between liquid water, rock and minerals that the review by Westall and Brack argues to be essential for the development and sustainability of life. The same happens on large icy moons of the Solar System, such as Ganymede or Titan (but not on the smaller Europa; see the review by Grasset et al.). If this is true, then the habitability of the Earth is due to our planet acquiring some water but not too much in the chaotic game of planet formation. Understanding the conditions that led to this result is then essential to predict the likelihood that other truly habitable worlds exist around other stars.

From all the review papers presented in this collection it seems that the origin of terrestrial water, for long-time considered to be a major open question, is now almost a closed problem. In fact, geochemical and cosmochemical measurements, astronomical observations and theoretical models converge to a quite coherent common view, although some gray areas still subsist, as described below.

In all evidence, proto-planetary disks are hot in their inner part and cold in their outer part. So, there is no surprise that, at first order, the inner Solar System objects are water-poor, while the outer Solar System bodies are water-rich. The problems start when we compare things quantitatively. Water-rich and water-poor asteroids overlap in the asteroid belt, suggesting that the snowline separating water-vapor from water-ice was located between 2 and 3 AU when these asteroids accreted (2–4 My after "time-0", defined as the time of accretion of calcium aluminum inclusions: 4.567 Gy ago). As explained in the reviews by Alexander et al. and O'Brien et al., it is likely that water-rich asteroids formed beyond Jupiter and were subsequently implanted into the asteroid belt. We don't know very well where Jupiter formed (due to planet migration its original location is not necessarily the current one), but if water-rich asteroids formed beyond its orbit the snowline was probably *beyond* the asteroid belt, possibly somewhere between 3 and 5 AU. Can disks be so hot to have a snowline there? As explained in the review by Hartman et al., a passive disk heated only by the central star would not be hot enough. It was thought that protoplanetary disks are viscous and therefore that the Keplerian sheer in the disk generates frictional heating; thus, a massive, high-opacity disk was expected to have its snowline even beyond 5 AU. But modern models suggest that disks are much less turbulent than previously expected, stellar accretion being driven by angular momentum removal in disk-winds at the surface of the disk rather than viscous dissipation. If this is the case, the disk would be almost as cold as a passive disk. So, which source of heat could place the snowline initially beyond 3 AU is unknown. A second problem is that, as the disk loses mass, it is likely to cool off. So, the snowline, even if originally beyond 3 AU, should migrate towards the Sun, reaching a distance comparable or even smaller than 1 AU in the mid-plane before the disk becomes optically thin. As ice dust and pebbles drift radially due to aerodynamic drag (see the review by Paardekooper and Johansen) all planetesimals down to 1 AU or so, including *all* asteroids and many of the planetary embryos precursors of the Earth, should have accreted substantial amounts of water. Signs of water alteration exist in all meteorites, even the driest, but the amount of water inferred is much less than that expected for planetesimals formed beyond the snowline (Alexander et al. review). Radioactive heating can erase water alteration features (Monteux et al. review), but the recorded peak temperatures are not high enough to explain the limited water alteration of water-poor meteorites, if the original planetesimals had been water rich. So, the cosmochemical analyses suggest that the disk throughout the asteroid belt was indeed cold when asteroids formed (some water could be accreted), but it remained nevertheless water-depleted relative to solar abundance. The problem can be solved if Jupiter formed quickly, before the disk cooled. When the mass of Jupiter exceeded 20–30 Earth masses, the flux of icy pebbles was interrupted beyond Jupiter's orbit. Thus, the bodies inwards of the orbit of Jupiter could accrete very little water, even if the temperature dropped below ice-stability values (Morbidelli et al. 2016).

Recent cosmochemical analyses (Kruijer et al. 2017) argue that Jupiter exceeded 20–30 Earth masses within the first My of Solar System history. This conclusion is derived from the observation that meteorites cluster in two distinct isotopic reservoirs (the carbonaceous and the non-carbonaceous groups) and that this separation was already present when the parent bodies of iron meteorites formed, i.e. no later than 1 My from "time-0". Because water-rich meteorites are carbonaceous chondrites, this supports the aforementioned idea that water-rich planetesimals could form only beyond Jupiter. A problem, though, is that not all carbonaceous chondrites are water rich (see Alexander et al.) and this is not understood so far.

If one accepts that water-rich planetesimals existed originally only beyond Jupiter, the possible sequences of subsequent events are described in the review paper by O'Brien et al.. The giant planets experienced two major phases of evolution: when they were still embedded in the gaseous protoplanetary disk they grew in mass and also migrated (although the amount of migration they suffered is still not quantified) acquiring a compact resonant orbital configuration; after the removal of gas, they experienced a final dynamical instability that broke the original resonant chain and brought the planets to their current orbital configuration. The terrestrial planets were still at the stage of planetary embryos (probably with a mass comparable to the mass of Mars) when the gas disappeared and completed their formation in a much longer timescale (tens of My). O'brien et al. identify the planetesimals in the giant planet region with water-rich asteroids and the planetesimals beyond the orbit that Neptune occupied at the end of the gas-phase (roughly 12–15 AU) with comets. Notice however that Alexander et al. argue that water-rich asteroids could only be the planetesimals between the orbits of Jupiter and Saturn, observing that Titan has the same N-isotope composition of comets (i.e. distinct from asteroids) and supposing a radial gradient of N-isotopic composition throughout the disk. Although well taken, this consideration should be retained with the caveat that Titan formed in the circumplanetary disk of Saturn, which might have had different thermal conditions (hence possibly composition) from those of the protoplanetary disk at the same location.

As described in the review by O'brien et al., while growing in mass and/or migrating, the giant planets scatter away the planetesimals from their neighborhood. Some planetesimals are ejected or sent in the outer disk, others are sent towards the Sun. Of these, a fraction is captured into the asteroid belt (thus becoming the water-rich asteroids we see today), others acquire more eccentric orbits that intersect those of the protoplanetary embryos in the terrestrial planet region. The simulations, calibrated on today's population of water-rich asteroids, predict that the Earth accreted about 1–2% of its mass from these bodies. Assuming that these bodies carried 10% water by mass and neglecting losses (thanks to the capability of the magma ocean to absorb water—see Ikoma et al.—and to the relative inefficiency of collisions in devolatilizing the planet—see Schlichting and Mukhopadhyay), this would correspond to 1000–2000 ppm of chondritic water in the Earth. As discussed in Peslier et al., the terrestrial water budget is estimated to be between 600 and 36000 ppm. So, numbers are in the same ball-park, with the exception of the high-end estimates of Earth's water content, that require huge amounts of water partitioned in the core. The D/H ratio of the Earth's water matches the chondritic mean value confirming that water-rich asteroids are the most likely source. An important caveat, though, is made in the review by Alexander et al. The D/H ratio measured in chondritic meteorites is probably the result of the interaction between an original water with low D/H ratio (intermediate between the solar and terrestrial values) and a D-rich organic material. This is not a problem as long as the Earth accreted only chondritic-like material. But if the Earth accreted also asteroids with a larger water/organic ratio than recorded in chondrites (for instance bodies with large ice reservoirs in their interior), the final D/H ratio of the accreted water should be sub-terrestrial. We know that there are asteroids rich in ice still today in the belt. Ceres, the major body in the asteroid belt, is one of them (see Grasset et al. review); the so-called main-belt comets are others. It is unknown what the D/H ratio of these ices are. If measurements in Ceres are not foreseeable in a realistic future, for main-belt comets the prospects are more favorable, because these objects degas when they pass near perihelion. Both NASA and ESA have received proposals for space missions to these objects, but so far none has been selected despite the undisputable scientific interest in characterizing isotopically these bodies, as ESA/Rosetta did for comet 67P.

The dynamical models also show that the Earth is not a singular planet. All terrestrial planets have been affected by the bombardment of water-rich asteroids during their growth. This is in agreement with the indications, reviewed in the Greenwood et al., that Venus and Mars had originally water budgets comparable to the Earth's. Mercury, closer to the Sun, could have received comparably less water than the other planets, although there is no sharp difference in the model predictions.

Still according to models, comets would have entered into the game of water delivery during the giant planet instability phase, sometime after the disappearance of the gas from the protoplanetary disk. It's expected that the Earth accreted only 7×10^{-6} of its mass from comets. This is in remarkable agreement with the estimates from the abundances of Argon and Xenon in the Earth's atmosphere, and the concentration of these gases measured in comet 67P by ESA/Rosetta (see Alexander et al.). This tiny amount of cometary material would have brought to the Earth less than 1% of the Earth's water, i.e. a negligible amount.

Models and observations agree not only for what concerns the total water amount and its origin; they also agree concerning the water delivery chronology. In the models (see again O'Brien et al.), the terrestrial planets form from a system of planetary embryos. The latter formed from local material so they are expected to have been totally dry. The first merging events among embryos therefore should have started to build dry terrestrial planets but then water-rich planetesimals scattered from beyond Jupiter's orbit became available in the terrestrial planet region. The accretion of some of these objects progressively built up the water's budgets as the terrestrial planets were growing towards their final mass. On the geochemical side (see reviews by Peslier et al. and Schlichting and Mukhopadhyay) there is evidence that Earth's early accretion history was volatile poor and that water was not incorporated in the Earth in significant quantities until the planet had grown to $\sim$60–90% of its current size. Models and geochemical considerations also agree that water was accreted throughout Earth's formation and not solely during the late veneer (see the review by Schlichting and Mukhopadhyay). The late veneer is defined as the accretion of material that occurred after the end of core formation; because the Moon-forming giant impact necessarily led to the growth of Earth's core, traditionally the late veneer is identified with the tail of accretion occurred after the Moon forming event. The mass of material accreted during the late veneer is constrained to be $<1\%$ of the Earth's mass by the concentration of the highly siderophile elements (HSE) in the terrestrial mantle. This mass would be insufficient to deliver the terrestrial water budget. Moreover, the isotope composition of some of the HSEs (e.g. osmium, ruthenium) exclude that the late veneer was dominated by water-rich (i.e. carbonaceous chondritic) material (Drake and Righter 2002; Dauphas et al. 2004). Finally, terrestrial volatile elements of comparable condensation temperature show different levels of partial depletion in the terrestrial mantle, correlated with their affinity to partition in metal, i.e. being trapped into the core. This implies that volatile accretion occurred while the Earth's core was still building up (Wood et al. 2010).

The presence of water on Earth prior to the Moon-forming event can explain the presence of water in the Moon (see Greenwood et al.). In fact, all models of Moon-forming events predict that at least a fraction of the lunar material came from the proto-Earth; so the Moon would have inherited part of the Earth's water. In the recent "synestia" model (Lock et al. 2018) the giant impact produced an extended, hot and fast rotating silicate vapor atmosphere around the Earth, called synestia. The synestia was in rapid equilibration with the terrestrial magma ocean. Upon cooling, the synestia could not contract entirely towards the Earth's surface; because its angular momentum was high, part of it had to form a disk in orbit around the Earth. The Moon formed from such a disk. If the Earth was water rich at the moment of the giant impact, the synestia would have contained water vapor. Due to the high solubility of water in liquid silicate (see Ikoma et al.) it is likely that part of the water remained trapped in the condensing silicates and therefore in the final Moon (see Greenwood et al.).

Not just water, but most volatile elements have isotope compositions that are chondritic. This supports the view that carbonaceous chondritic asteroids dominated the whole terrestrial volatile budget. However, the existence of Ne and possible H with a solar isotopic composition in the deep mantle (see Schlichting and Mukhopadhyay) points that the process of in-gassing of volatiles from a primitive atmosphere (i.e. gas trapped from the protoplanetary disk) described in the review by Ikoma et al. played some role. The capability to build a primitive atmosphere and its pressure depend sensitively on the planet's mass. The existence of solar gases in the deep mantle suggests that the Earth reached a few Mars-masses through mutual merging events among embryos before the disappearance of the disk, again in agreement with some dynamical models, but the uncertainty on this mass estimate unfortunately remains large. There is no trace of this primitive atmosphere now on Earth. As discussed in the review by Schlichting and Mukhopadhyay the present day geochemistry of volatiles shows no evidence of strong hydrodynamic escape. This suggests that impacts played a major role during Earth's formation in removing the original solar gases and delivering the chondritic ones. The review also provides geochemical evidence from the ^{3}He/^{22}Ne ratio for multiple giant impacts on Earth, again in agreement with accretion models that indicate that most of the terrestrial mass came from merging events with other planetary embryos.

A great deal of progress has been done in understanding the origin and evolution of water on the Earth and the other bodies of the Solar System. Still, surprises are not over, as shown by the announcement of the discovery of a subglacial lake on Mars, which came too late to be included in the review chapters (see Orosei et al. 2018). Moreover, the discovery and characterization of an increasingly large number of extrasolar planet will provide new observational light on the actual habitability of other worlds and the distribution of water in protoplanetary disks will pass from the realm of models to that of observational evidence. These exciting results are foreseen in the next few decades, so the future of exobiology is brighter than ever.

This Topical Collection of review papers is dedicated to the memory of Prof. Yutaka Abe. Throughout his career Prof. Abe had a long list of outstanding contributions to the field. Sadly, the ISSI workshop that motivated this series of reviews was the last meeting that Prof. Abe attended. Unfortunately, Prof. Abe ran into medical complications during his return flight to Japan, and after a two-year struggle, he passed away on the first day of 2018.

Already in his student days (mid 1980s), Prof. Abe was highly recognized based on a series of papers on the generation of the atmosphere-ocean in the late stage of terrestrial planet formation. During these studies, he recognized the importance of atmosphere-hydrosphere and solid planet interactions to define the "habitable conditions" on a terrestrial planet. To explore such interactions, he used detailed knowledge of materials properties (melting relations, solubility of volatiles in the melts etc.) together with an elegant treatment of mass and energy transfer in the models of planetary formation and evolution. A particularly important notion coming from his works is the recognition of the role of the magma ocean (a molten silicate layer on a growing planet) to control the surface conditions of a terrestrial planet.

In addition to the generation of the atmosphere and ocean, he made great contributions to understanding of the stability of aqua-planets. In particular, he found the presence of a radiative-emission limit of wet atmospheres, which is generally known today as a condition that defines the inner edge of the "habitable zone". Through those studies, he also noticed that a difference in ocean mass and water transport brings about a qualitative change to the stability of the atmosphere of aqua-planets. He developed a new concept of the land planet such that water transport is dominated not by surface transport but by atmospheric circulation. In recent years, he clarified the stability of the climate of such land planets by performing 3D GCM simulations. Even after the onset of ALS, without reducing his research activity, he continued such studies until his premature death at the age of 58.

Another important contribution by Professor Abe is that he has trained so many brilliant students (and post-docs) throughout his career. This is truly remarkable in view of the fact that he needed to fight against ALS during his last ∼15 years. We are sure that not only his scientific papers, but also these lucky students/postdocs will keep his legacy in the planetary science community for years to come.

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