Origin of water in the terrestrial planets

Michael J. DRAKE

Lunar and Planetary Laboratory, University of Arizona, Space Sciences Building, P. O. Box 210092, Tucson, Arizona 85721–0092, USA
E-mail: drake@lpl.arizona.edu

Abstract–I examine the origin of water in the terrestrial planets. Late-stage delivery of water from asteroidal and cometary sources appears to be ruled out by isotopic and molecular ratio considerations, unless either comets and asteroids currently sampled spectroscopically and by meteorites are unlike those falling to Earth 4.5 Ga ago, or our measurements are not representative of those bodies. However, the terrestrial planets were bathed in a gas of H, He, and O. The dominant gas phase species were H_2, He, H_2O, and CO. Thus, grains in the accretion disk must have been exposed to and adsorbed H_2 and water. Here I conduct a preliminary analysis of the efficacy of nebular gas adsorption as a mechanism by which the terrestrial planets accreted "wet." A simple model suggests that grains accreted to Earth could have adsorbed 1–3 Earth oceans of water. The fraction of this water retained during accretion is unknown, but these results suggest that examining the role of adsorption of water vapor onto grains in the accretion disk bears further study.

INTRODUCTION

We take water for granted. Earth demonstrably has water (Fig. 1). Using the Gamma Ray and Neutron Spectrometer (GRS) instrument aboard the Mars Odyssey spacecraft, Boynton et al. (2002) have found elevated H abundances that are most plausibly interpreted as vast water ice sheets at least 1 m thick and buried under a thin layer of dust polewards of about 60° of latitude in both hemispheres of Mars (Fig. 2). And, of course, the residual polar caps are water ice. Carr (1996) presents evidence for widespread water erosion on Mars. Further, Baker et al. (1991) present photogeological evidence for a boreal ocean on Mars. The D/H ratio of Venus is about 100 times that of Earth's oceans (Donahue and Pollack 1983). We do not know Venus' original water abundance and isotopic composition because Venus appears to have lost most of its water in a way that strongly fractionated the D/H ratio. One plausible explanation is preferential loss of H relative to D through UV photodissociation of H_2O at the top of the Venusian atmosphere caused by solar UV light. Mercury and the Moon appear to be bone-dry, possibly due to volatile loss in giant impacts (Taylor 2001), though both may have water ice trapped in permanently shadowed craters around their poles (Harmon 1997). Asteroids appear to be both hydrous and anhydrous bodies, with the hydrous bodies being concentrated towards the outer part of the Main Belt (Gradie et al. 1989), and McSween (1979) presents compelling evidence for aqueous alteration in some carbonaceous chondrites.

There is, however, no consensus on the origin of water in the terrestrial planets. Suggested sources include comets, hydrous asteroids, phyllosilicates migrating from the asteroid belt, and hydrous minerals forming in the inner solar system and accreting directly to the terrestrial planets. I examine each of these hypotheses below. There are potential problems with all of these sources. I propose that adsorption of water molecules from the gas in the accretion disk directly onto grains prior to their accretion into planetesimals and, eventually, planets may have been the source of some or all of the water present in Venus, Earth, and Mars 4.5 Ga ago.

SOURCES OF WATER

The origin of water in the terrestrial planets is intimately associated with the nature of their "building blocks." There are two end-member possibilities. One possibility is that temperatures were too high in the inner solar system for hydrous phases to exist in the accretion disk, so the terrestrial planets accreted "dry" (Boss 1998). Water and probably organics were delivered from exogenous sources (e.g., comets, meteorites) after the terrestrial planets had formed. In this case, all terrestrial planets should have had the same source of water, unless the delivery process was stochastic and dominated by one or a few large impacts of hydrous objects.

Fig. 1. The Atlantic Ocean on Earth. A view of the Copacabana Beach from the Sugar Loaf Mountain, Rio de Janeiro, September 2004. The Meteoritical Society's meeting was held at a hotel at the far end of the beach.

At the other extreme is the possibility that the terrestrial planets accreted "wet," with anhydrous and hydrous silicate phases among the material accreted to the growing planets (Drake and Righter 2002). In this view, planetary water has an indigenous origin. In this case, all terrestrial planets probably also had the same source of water, unless hydrous phases were stable at the orbit of, say, Mars but not closer to the Sun.

Distinguishing between these end-members, and even variants of one, requires an understanding of the abundance of water and the oxygen and hydrogen isotopic composition of water in the terrestrial planets. Unfortunately, we do not know the original abundance and isotopic composition of water on Venus because of the solar UV water dissociation loss mechanism. It is possible that we do not know the intrinsic isotopic composition of water on Mars because Mars lacks plate tectonics and Martian meteorites may simply be sampling water delivered subsequent to planetary formation, although Leshin-Watson et al. (1994) argue to the contrary—that SNC meteorites provide evidence for an intrinsic Martian mantle D/H ratio up to 50% higher than Earth's mantle. So we must look to the best-studied planet, Earth, for clues. But first, let us look at the pros and cons of various proposed sources of water.

Comets

Comets were long considered the leading candidate for the origin of water in the terrestrial planets. This hypothesis was attractive for two reasons. First, it is widely believed that the inner solar system was too hot for hydrous phases to be thermodynamically stable (Boss 1998). Thus an exogenous source of water was needed. Second, the Earth and other terrestrial planets underwent one or more magma ocean events (Righter and Drake 1996; Li and Agee 1996; Righter and Drake 1997; Walter et al. 2000) that some authors believed would effectively degas the planets of any existing water.

We now know that there are elemental and isotopic reasons why at best 50% and most probably a very small percentage of water accreted to Earth from cometary impacts (Drake and Righter 2002). Figure 3 compares the isotopic composition of hydrogen in Earth, Mars, three Oort Cloud comets, and various early solar system estimates. It is immediately clear that 100% of Earth's water did not come from the Oort Cloud comets. D/H ratios in Martian meteorites do agree with cometary values, but that may simply reflect the impact of comets onto the Martian surface in a non-plate tectonics environment that precludes recycling.
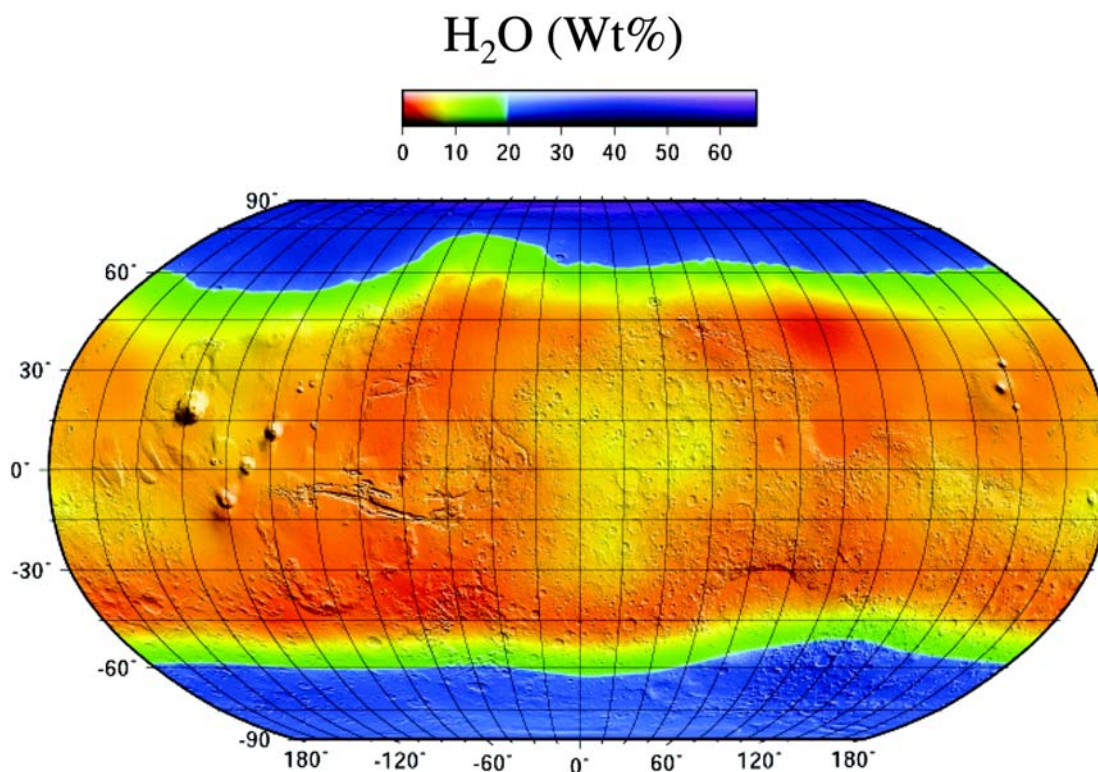
Fig. 2. Distribution of water ice on Mars, inferred from the Mars Odyssey Gamma Ray Spectrometer instrument (Boynton et al. 2002). Ice sheets at least 1 m thick are covered by a thin layer of dust polewards of approximately 60° of latitude in both hemispheres.

So what limits the cometary contribution to Earth's water? Consider, for example, that perhaps Earth accreted some hydrous phases or adsorbed water, and some amount of additional water came from comets. Indigenous Earth water could have had D/H ratios representative of the inner solar system, i.e., low values because of relatively high nebular temperatures, perhaps like protosolar hydrogen ($2–3 \times 10^{-5}$, Lecluse et al. 1994), in which case a cometary contribution of up to 50% is possible. Alternatively, indigenous Earth water could have had D/H ratios representative of a protosolar water component identified in meteorites ($\sim 9 \times 10^{-5}$, Deloule et al. 1995), in which case there could be as little as a 10–15% cometary contribution (Owen and Bar-nun 2000).

There are caveats to using cometary D/H ratios to limit the delivery of cometary water to Earth. First, we do not know if the Oort Cloud comets Halley, Hale-Bopp, and Hyakutake are representative of all comets. Certainly, they are unlikely to be representative of the Kuiper Belt objects, the source of Jupiter-family comets, as the Oort Cloud comets formed in the region of the giant planets and were ejected, while Kuiper Belt objects have always resided beyond the orbit of Neptune. Second, D/H measurements are not made of the solid nucleus, but of gases emitted during sublimation. Differential diffusion and sublimation of HDO and H_2O may make such measurements unrepresentative of the bulk comet, as the D/H ratio would be expected to rise in diffusion and sublimation,

as has been confirmed in preliminary laboratory experiments on pure water ice (Weirich et al. 2004). Lower bulk D/H ratios would increase the allowable amount of cometary water. Intriguing experiments on mixtures of water ice and TiO_2 grains by Moores et al. (2005) suggest that D/H ratios could be lowered in sublimates. Third, the D/H ratios of organics and hydrated silicates in comets are unknown, although that situation may be rectified by analysis of samples returned by the Stardust mission. Note, however, that D/H ratios up to 50× Vienna Standard Mean Ocean Water (VSMOW) have been measured in some chondritic porous interplanetary dust particles (CP-IDPs) that may have cometary origins (Messenger 2000), and higher aggregate D/H ratios of comets would decrease the allowable cometary contribution to Earth's water.

Delivery of water from comets can also be evaluated in light of other cometary geochemical data. For instance, for an assumed Ar/H_2O ratio of 1.2×10^{-7} in the bulk Earth, comets like Hale-Bopp with an approximately solar ratio of Ar/H_2O (Stern et al. 2000) would bring in 2×10^4 more Ar than is presently found in the Earth's atmosphere (Swindle and Kring 2001), if 50% of Earth's water—the maximum amount permitted by D/H ratios—were derived from comets. It is unclear if this measurement of comet Hale-Bopp is applicable to all comets. Ar/O ratios of <0.1 × solar and <0.08 × solar have recently been reported for comets LINEAR 2001 A2 and
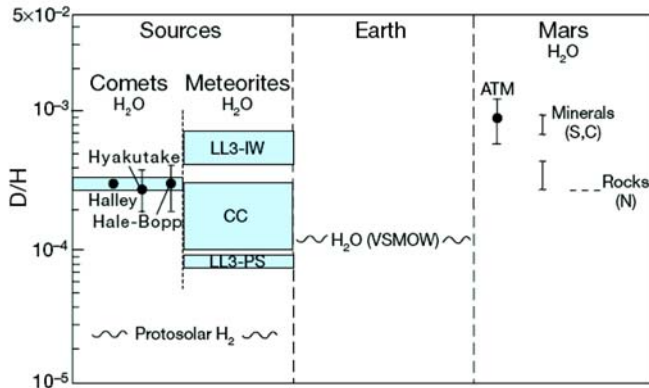
Fig. 3. The D/H ratios in H_2O in three comets, meteorites, Earth (Vienna Standard Mean Ocean Water [SMOW]), protosolar H_2, and Mars. CC = carbonaceous chondrites, LL3-IW = interstellar water in Semarkona, LL3-PS = protostellar water in Semarkona. After Drake and Righter (2002).
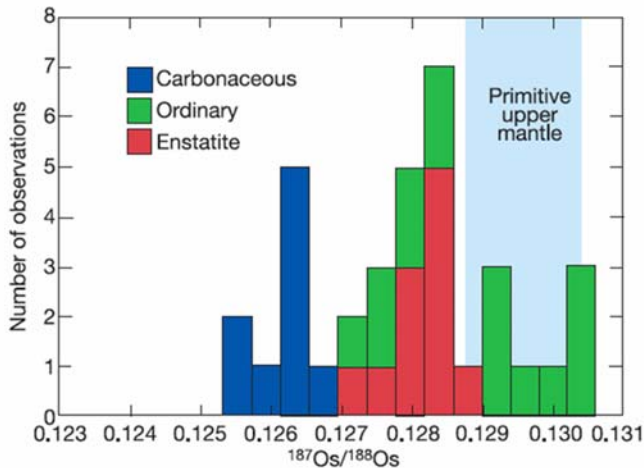

Fig. 4. $^{187}Os/^{188}Os$ ratios in carbonaceous, ordinary, and enstatite chondrites, and in the Earth's primitive upper mantle (PUM), are distinct and are diagnostic of the nature of the Earth's "late veneer." Mars is not plotted because the uncertainty in its initial $^{187}Os/^{188}Os$ ratio is larger than range of the x-axis. After Drake and Righter (2002).

LINEAR 2000 WM1 (Weaver et al. 2002). However, the true Ar/O ratios in comets would have to be at least three orders of magnitude below solar in order to be consistent with the Ar abundance of the Earth's atmosphere.

Another approach to estimating the contribution of cometary materials to Earth's water budget can be made by considering the implications for the abundances of noble metals and noble gases. Dauphas and Marty (2002) show that the total mass of cometary and asteroidal material accreting to Earth after core formation is $0.7–2.7 \times 10^{25}$ g and that comets contribute <0.001 by mass or $<0.7–2.7 \times 10^{22}$ g. Given that the minimum mass of water in the Earth (one Earth ocean) is 1.4×10^{24} g, comets can contribute less than 1% of Earth's water.

Asteroids

Asteroids are a plausible source of water based on dynamical arguments. Morbidelli et al. (2000) have shown that up to 15% of the mass of the Earth could be accreted late in Earth's growth by collision of one or a few asteroids originating in the Main Belt. However, there are strong geochemical arguments against a significant contribution of water from asteroids, unless one postulates that Earth was hit by a hydrous asteroid unlike any falling to Earth today, as sampled by meteorites. One cannot prove this hypothesis wrong, as it could involve a single, unique event.

However, if asteroidal material falling to Earth 4.5 Ga ago was the same as that which falls today, one can effectively rule out asteroids as a source of water. The reason involves the Os isotopic composition of the so-called "late veneer," the material that may have contributed the highly siderophile elements (HSEs) that are present to within 4% of chondritic proportions at about 0.003 of chondritic absolute abundances (see Fig. 1 of Drake and Righter 2002). Note that the term "late veneer" is misleading but is firmly entrenched in the literature. A veneer is a surface coating, yet the "late veneer" of HSEs must be well mixed into at least the upper mantle of Earth and perhaps the entire silicate mantle.

Of current meteorite falls, only carbonaceous chondrites have significant amounts of water (Drake and Righter 2002). Enstatite and ordinary chondrites are anhydrous. The late addition of water must be accompanied by other chemical elements such as Re and Os. Rhenium and Os are two HSEs that are linked by beta-decay, $^{187}Re = ^{187}Os + \beta$, thus Os isotopes can be used as a constraint on Earth's bulk composition. Earth's primitive upper mantle (PUM) has a significantly higher $^{187}Os/^{188}Os$ ratio than carbonaceous chondrites, effectively ruling them out as the source of the "late veneer" (Fig. 4). The PUM $^{187}Os/^{188}Os$ ratio overlaps anhydrous ordinary chondrites and is distinctly higher than anhydrous enstatite chondrites.

The identification of anhydrous meteorites with the "late veneer" (Walker et al. 2002) effectively rules out asteroidal material being the source of Earth's water. There is one caveat, however. Thermal processing of asteroids was occurring 4.5 Ga ago. One cannot exclude the possibility that ordinary chondrites once contained water and those falling to Earth today have lost it by metamorphism, even though water was still present 4.5 Ga ago. However, the preservation of aqueous alteration products in some carbonaceous chondrites (McSween 1979) suggests that loss of water from initially hydrous asteroids is unlikely to proceed to the anhydrous limit.

Phyllosilicates

Ciesla et al. (2004) have proposed that the terrestrial planets received their water by inward migration of

phyllosilicates from the asteroid belt, where they clearly exist. This hypothesis accepts that the region of the accretion disk where the terrestrial planets reside was too hot for hydrous phases to exist. This hypothesis appears subject to the same objection as other asteroidal sources of water. It seems unlikely that phyllosilicates could be decoupled from other minerals and transported into the inner solar system. Thus, the Os isotopic composition of PUM is a constraint in this case as well.

However, a variant on the hypothesis may be worth exploring. Inward migration of phyllosilicates is postulated to occur in an environment where nebular gas was still present and temperatures were too high for hydrated minerals such as phyllosilicates to be thermodynamically stable. Thus, if a way could be found to migrate phyllosilicates either by themselves or embedded with other minerals such that their contribution to the Os isotopic composition of PUM was insignificant, dehydration of phyllosilicates could enhance the water vapor content of the region of the terrestrial planets. Perhaps some of the phyllosilicates were accreted to the terrestrial planets as Ciesla et al. (2004) propose without perturbing the Os isotopic composition of PUM, but the majority of water carried in by them was adsorbed onto grains already present in the region of the terrestrial planets and incorporated into the terrestrial planets as they grew as discussed below (Drake 2004; Stimpfl et al. 2004).

COULD THE TERRESTRIAL PLANETS ACCRETE "WET"?

The solar system formed as a result of the collapse of a large, cold, slowly rotating cloud of gas and dust into a disk that defined the plane of the solar system. The terrestrial planets grew in this accretion disk. Hydrogen, helium, and oxygen dominated the gas, in which the dust was bathed. Some of that hydrogen and oxygen combined to make water vapor. If thermodynamic equilibrium was attained, Lecluse and Robert (1994) estimated that there were about three Earth masses of water vapor in the accretion disk inside of 3 AU. Subsequent spectroscopic work has led to a downward revision of the carbon abundance by 30% (Palme and Jones 2003) and the oxygen abundance by 40% (Lodders 2003). Thus, it now appears that there were about two Earth masses of water vapor in the accretion disk inside of 3 AU. There are arguments associated with the photodissociation of CO, the dominant C-bearing gas in the accretion disk, that suggest the water abundance could have been modestly higher than the value calculated from simple equilibrium thermodynamics (Clayton 2004). The mass of the Earth is 5×10^{27} g. The mass of one Earth ocean is 1.4×10^{24} g. The extreme maximum estimate for the amount of water in the Earth is about 50 Earth oceans (Abe et al. 2000), with most estimates being 10 Earth oceans or less. For example, an estimate based on the water storage potential of minerals in the silicate Earth is about 5–6 Earth oceans (Ohtani 2005). Thus, the mass of water available

to the terrestrial planets exceeded the mass of water accreted by a factor of about 12 if all four terrestrial planets initially had 50 Earth oceans of water. This excess represents a minimum in that the water vapor content of the accretion disk inside 3 AU could exceed 2 Earth masses, and it is unlikely that all four terrestrial planets received 50 Earth oceans. There is also the possibility of enhancing the available water vapor reservoir by inward migration of ices (Krot et al. 2004) and phyllosilicates (Ciesla et al. 2004).

The question is the fate of this water vapor. Let us accept for the purposes of discussion that it was too hot inside 3 AU, even as the accretion disk cooled, for hydrous minerals to form. Could water vapor be adsorbed onto grains before the gas in the inner solar system was dissipated? This question requires knowledge of grain volume distribution, fractal dimensions of grains, temperature (which affects the velocity with which molecules impact grains and hence the molecules' "stickiness"), competition between water molecules and others (H_2 is the dominant gas molecule, followed by He), and retentiveness after adsorption (can a molecule be knocked off the grain by impact of another molecule?). This question also requires knowledge of whether the molecules are adsorbed by low energy physisorption, or higher energy chemisorption. Physisorption and chemisorption span the range of energies from van der Waals forces around 5 kJ/mol through strong hydrogen bonding around 100 kJ/mol, just slightly weaker than covalent bonds. Various types of O-H bonds span this range of energies (Jeffrey 1997).

Physisorption

Stimpfl et al. (2004) have examined the role of physisorption by modeling the adsorption of water at 1000 K, 700 K, and 500 K using a Monte Carlo simulation with a grid of 10,000 adsorption sites. The composition of the nebular gas was 99.98 wt% H_2 and He, with an H_2O/H_2 ratio of 5.4×10^{-4} (Lodders 2003). All of the gases (H_2, He, and H_2O) interacted with the surface, but only H_2O could be adsorbed (Stimpfl, personal communication). An iterative process allowed the surface to reach steady state saturation at each temperature. Water molecules not only interact with the substrate by means of weak bonds (~5 kJ/mol) but also establish hydrogen bonds with other water molecules present in a monolayer (de Leeuw et al. 2000). Stimpfl et al. (2004) took this cooperative behavior into account by increasing the bond energy proportionally to the number of nearest neighbors (max. allowed = 4). The energy of the incoming molecules was computed using the Maxwell-Boltzmann probability distribution. Simple "sticking" rules were applied. Incoming water molecules stuck to the surface if their kinetic energy was lower than 5 kJ/mol. If any molecule collided with a molecule already occupying a site, the resident molecule was dislodged only if the incoming molecule had an energy exceeding two times the total bond energy of the bonded molecule. Stimpfl et al. (2004) allowed only for the
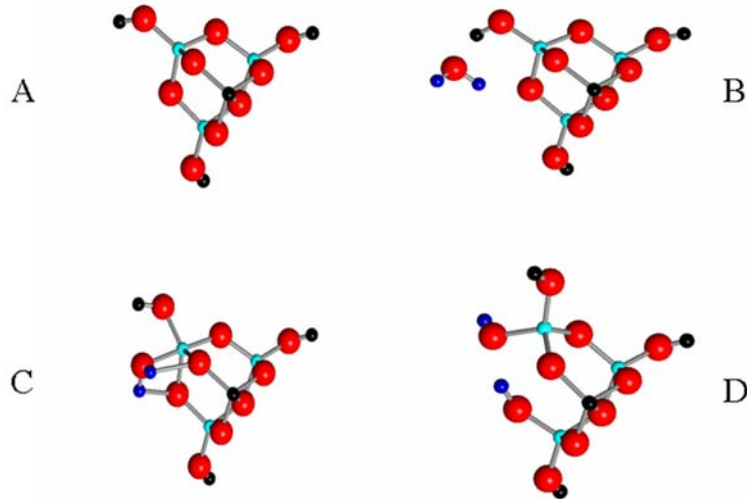
Fig. 5. Results of ab initio calculations at 0 K, in which the Gibbs free energy of Si-O-H clusters is minimized and then an H_2O molecule is introduced (Gibbs, personal communication 2004). Silicon is pale blue, oxygen is red, original hydrogens are black, and hydrogens attached to the introduced water molecule are dark blue. a) The Gibbs Free Energy (G) of a Si-O-H assemblage is minimized. b) A water molecule is introduced in the vicinity of the minimum G Si-O-H assemblage. c) A thermodynamically unstable early bonding of the water molecule with the Si-O-H assemblage. d) The final minimized G state.

adsorption of one monolayer, neglected porosity and surface roughness, considered water to be an infinite reservoir, and assumed that all the particles interacting with the surface were water molecules.

Stimpfl et al. (2004) "exploded" the Earth into 0.1 m spheres of volume equal to Earth, initially ignoring the fractal nature of these particles. The results were disappointing. Only 0.25% of an ocean of water could be adsorbed at 1000 K, 1% of one Earth ocean could be adsorbed at 700 K, and only 3% at 500 K.

However, grains in the accretion disk were not spherical, but fractal. They were also not of uniform volume. Thus, the available surface area for adsorption is vastly greater than that of a sphere of corresponding volume. If the surface area of the fractal grain was 100 times that of a sphere of corresponding volume, then one quarter of an ocean of water could be adsorbed at 1000 K, one Earth ocean could be adsorbed at 700 K, and three Earth oceans could be adsorbed at 500 K.

Of course, there are issues of retention of water as the grains collide and grow to make planets. Stimpfl et al. (2004) note that some of this water will be lost due to high collisional velocities, especially after the grains grow to a radius >10 cm. However, it is clear that volatiles are not completely outgassed even in planetary-scale collisions. For example, primordial [3]He, far more volatile than water, is still outgassing from Earth's mantle 4.5 Ga after an almost grown Earth collided with a Mars-sized body, which gave origin to the Moon.

Other processes may counter the tendency for loss of water. For example, the temperature at any given heliocentric distance in the accretion disk decreases as a function of time. Lower temperatures may favor water being chemisorbed, a process involving higher bond energies than ~5 kJ/mol and

hence making water more retentive. I address chemisorption next.

Chemisorption

Calculations of chemisorption of water onto accretion disk grains at realistic nebular temperatures have not been performed. However, Gibbs has conducted ab initio calculations on the docking sites of H onto SiO_2 polymorphs (e.g., Gibbs et al. 2004). Gibbs (personal communication) has also conducted ab initio calculations at 0 K, in which the Gibbs free energy of Si-O-H clusters is minimized and then a H_2O molecule is introduced. Dynamical visualization shows that, after passing through several metastable bonding states and when the minimum Gibbs free energy is achieved, strong bonds (>>5 kJ/mol) can be formed between the water molecule and the Si-O-H cluster (Fig. 5). If this strong bonding behavior persists to realistic nebular temperatures, retention of adsorbed water during the later violent stages of accretion is enhanced. This is an active area of current study by Gibbs.

MAJOR UNSOLVED QUESTIONS

We have just started examining the idea that the terrestrial planets could have obtained much or all of their water by adsorption onto grains directly from gas in the accretion disk, and many major issues remain to be resolved. Below I list some of the most important.

1. The D/H ratio of the nebular gas is inferred from spectroscopic measurements of CH_4 in the atmospheres of Jupiter and Saturn to be $2.1 \pm 0.4 \times 10^{-5}$ (Lellouch et al. 2001), much lower than VSMOW. Spectroscopic or

direct measurements of solar D/H ratio cannot be made because practically all of the Sun's deuterium has been burned to make ^{3}He. If the nebular D/H ratio really is as low as implied by the Jovian and Saturnian atmospheres, a mechanism to raise the D/H ratio of nebular gas from solar to VSMOW is needed.

2. It is likely that the D/H and Ar/O ratios measured in cometary comas and tails are not truly representative of cometary interiors. As noted earlier, D/H ratios in laboratory experiments can increase or decrease with time due to differential diffusion and sublimation, depending on the physical nature of the starting material (Weirich et al. 2004; Moores et al. 2005). Depending on the siting of Ar in comets, Ar/O ratios may also be similarly affected. The Deep Impact mission may resolve this issue by exposing fresh cometary interior material for spectral analysis with ground-based and space-based high spectral resolution spectrometers.

3. The key argument against an asteroidal source of Earth's water is that the Os isotopic composition of Earth's primitive upper mantle matches that of anhydrous ordinary chondrites, not hydrous carbonaceous chondrites. But are the parent bodies of the ordinary chondrites anhydrous? Could ordinary chondritic meteorites be derived from the metamorphosed outer parts of hydrous asteroids, in which case impact of a bulk asteroid could deliver water? It is probable that spacecraft spectral examination of very deep impact basins in S-type asteroids will be needed to address this question.

4. A related question is why there are any anhydrous primordial bodies in the solar system if adsorption of water from gas in the accretion disk was an efficient process, as preliminary calculations suggest it might have been.

5. The timing of loss of gas from the accretion disk in the region of the terrestrial planets is unknown. For adsorption to be efficient, nebular gas must have persisted long after the initial aggregation of grains into planetesimals. The timing of loss of gas from the accretion disk will be intimately connected to the currently unknown mechanism of loss.

IMPLICATIONS

The idea that planetary water could have been obtained by adsorption of nebular water onto grains in the accretion disk and retained during planetary accretion remains unproven because quantitative studies have just begun. In that sense, my Leonard Medal Address is risky but provocative because early results (Stimpfl et al. 2004) indicate that the idea has promise. If some or all of Earth's water was obtained by adsorption, then there are number of interesting implications.

Stimpfl et al. (2004) showed that, while it is plausible to adsorb 1–3 Earth oceans of water at temperatures of 500 K to 700 K, the efficiency of adsorption of water increases as temperature decreases. Thus, the process should have been more efficient further from the Sun than closer to the Sun. Thus, it is likely that Mars, Earth, and Venus all accreted some water by adsorption, with Mars accreting the most, both because of its greater distance from the Sun and the lower energy of collisions during accretion because of its smaller final mass. (A caveat—Mars' small size might be the result of higher energy collisions because of the gravitational pumping of relative velocities of planetesimals by Jupiter.) Mars accreting more water than Earth is consistent with Mars' enrichment in volatile lithophile elements (Dreibus and Wänke 1985). Even Mercury may have accreted some water by this mechanism, even though there is no evidence for water at its surface today. Therefore, the current differences in the apparent water abundances among the terrestrial planets are probably the result of both different initial inventories and subsequent geologic and atmospheric processing.

It is widely believed that the Moon formed in a giant impact (Canup and Asphaug 2001). Drake and Righter (2002) noted that the identical oxygen isotopic composition of Earth and Moon (Wiechert et al. 2001) imply that the impactor was made of the same material that formed Earth. If the Earth accreted "wet," then so did the impactor. Today the Moon appears to be devoid of water, at least to depths of approximately 500 km, as sampled by mare basalt glasses (Delano 1980). Thus, the fact that the Moon is bone-dry today must be a consequence of the physics and chemistry occurring during the extreme environments experienced by the ejecta following the giant impact. On a much smaller scale, tektites are anhydrous even though most formed during impacts into hydrous granitic terrain (Fudali et al. 1987; Brett and Sat 1984).

If the terrestrial planets were initially hydrous, there are important implications for the late stages of accretion and primordial planetary differentiation. Water depresses the liquidus and solidus of magmas (see Fig. 8 of Righter and Drake [1999] for a summary diagram for peridotite). For a water-saturated peridotite, that depression can be as much as 700 °C to 1000 °C, depending on pressure. While it is unlikely that the terrestrial planets accreted enough water to have water-saturated magmas, "wet" accretion implies much deeper planetary magma oceans than would be the case for ahydrous planets for the same impact energy.

There is another interesting consequence for the evolution of planetary redox states if the terrestrial planets accreted "wet." Okuchi (1997) showed that when Fe-metal and water were compressed to 75 kbars and heated to 1200–1500 °C, iron hydride formed. Thus, planetary cores should contain H, and OH should be left behind in the molten silicate. As more metal was delivered to the planet while it accreted, more H would be extracted into the core and more OH would be liberated in the silicate. Thus, planetary mantles should become progressively oxidized with time, perhaps explaining the high redox states relative to the iron-wüstite buffer.

It remains possible that the "late veneer" may really be of

asteroidal origin. If so, it has the composition of ordinary chondrites and cannot be the source of water delivered after the bulk of the terrestrial planets accreted. Late addition of up to 5 wt% asteroidal material is consistent with dynamical simulations (Morbidelli et al. 2000), though the "late veneer" appears to represent less than 1 wt% of the mass of the Earth. However, Dauphas et al. (2004) use Ru and Mo isotopic systematics to argue against this possibility and argue for homogeneous accretion. They note that most Mo in the Earth's mantle is delivered while core formation is occurring because Mo is moderately siderophile, while essentially all Ru must be delivered after core formation because it is highly siderophile. Thus, their isotopic systematics must record the first 99% of accretion (Mo) and the last 1% of accretion (Ru). The fact that the silicate Earth falls on the cosmic Mo-Ru correlation argues that the bulk of the Earth and the "late veneer" accreted from the same Mo-Ru isotopic reservoir.

Finally, the evidence that the Earth and other terrestrial planets accreted "wet" has implications for the first appearance of liquid water oceans. There is intriguing evidence for widespread water on Earth and Mars within about 100 Myr of the nucleosynthesis of ^{129}I. Earth and Mars preserve reservoirs with distinct ^{129}Xe/^{132}Xe ratios. The isotope ^{129}Xe is produced through the decay of now extinct ^{129}I (t1/2 = 16 Myr). After 5–7 half-lives, radiogenic daughter ^{129}Xe from the decay of ^{129}I cannot be detected. It is difficult, although not impossible, to fractionate I from Xe by purely magmatic processes (Musselwhite and Drake 2000). However, water is far more effective at fractionating I from Xe (Musselwhite et al. 1991) because I dissolves in liquid water (it is a halogen) while Xe bubbles through. If accretion ceased while ^{129}I still existed and any magma ocean solidified, liquid water could become stable at planetary surfaces. Iodine (including still extant ^{129}I) dissolved in a liquid water ocean would react hydrothermally with any crust. Recycling of ^{129}I into the mantles of Earth and Mars would lead to their mantles having excess ^{129}Xe. The distinct ^{129}Xe/^{132}Xe ratios in different reservoirs in Earth and Mars can be developed by outgassing of the mantles, coupled with atmospheric stripping in the case of Mars (Musselwhite 1995; Musselwhite et al. 1991). Thus, it is possible that Venus, Earth, and Mars all had liquid water oceans shortly after their magma ocean epochs.

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