WHY ISN'T THE EARTH COMPLETELY COVERED IN WATER?

Joseph A. Nuth III[1], Frans J. M. Rietmeijer[2] and Cassandra L. Marnocha[1,3]

[1]Astrochemistry Laboratory, Code 691 NASA's Goddard Space Flight Center, Greenbelt MD 20771 USA (Joseph.A.Nuth@NASA.gov)
[2]Dept. of Earth and Planetary Sciences, MSC03-2040, University of New Mexico, Albuquerque, NM 87131 - 0001 USA (fransjmr@unm.edu)
[3]University of Wisconsin at Green Bay, Green Bay WI 54311 USA (MARNCL23@uwgb.edu)

Abstract

If protoplanets formed from 10 to 20 kilometer diameter planetesimals in a runaway accretion process prior to their oligarchic growth into the terrestrial planets, it is only logical to ask where these planetesimals may have formed in order to assess the initial composition of the Earth. We have used Weidenschilling's model for the formation of comets (1997) to calculate an efficiency factor for the formation of planetesimals from the solar nebula, then used this factor to calculate the feeding zones that contribute to material contained within 10, 15 and 20 kilometer diameter planetesimals at 1 A.U. as a function of nebular mass. We find that for all reasonable nebular masses, these planetesimals contain a minimum of 3% water as ice by mass. The fraction of ice increases as the planetesimals increase in size and as the nebular mass decreases, since both factors increase the feeding zones from which solids in the final planetesimals are drawn. Is there really a problem with the current accretion scenario that makes the Earth too dry, or is it possible that the nascent Earth lost significant quantities of water in the final stages of accretion?

1. Introduction

There is considerable discussion about the origin of Earth's water and the possibility that much of it may have been delivered by comets either within the first several hundred million years or possibly over geologic time [Drake, 2005]. Typical models for the origin of the Earth begin by assuming the accumulation of some combination of chondritic meteorites (Javoy, 1995; Ringwood, 1979; Wanke, 1981), yet it is highly likely that the asteroids that went into the terrestrial planets are no longer represented to any significant extent in the present-day asteroid population (Nuth, 2008). The argument concerning the composition of the building blocks of the Earth is typically phrased in terms of the chemical composition of the terrestrial mantle as compared to that of primitive meteorites [Righter et al., 2006] or to the isotopic composition of the Earth's oceans as compared to that of cometary water [Righter, 2007]. Both of these considerations yield important constraints on the problem. However, we will demonstrate that a completely novel examination of the problem based on models of nebular accretion, terrestrial planet formation and the evolution of primitive bodies makes using any modern meteorite type as the basis for understanding the volatile content of the Earth inappropriate. Unfortunately, while this approach yields terrestrial planets with sufficient water to easily explain the Earth's oceans, it also introduces a new problem: How do we get rid of the massive excess of water that this model predicts?

The mechanism for the formation of the terrestrial planets has been the subject of considerable debate. Gravitational instabilities in a dusty disk (Goldreich & Ward, 1973; Youdin and Shu, 2002) may have been responsible for planetesimal formation on very rapid timescales compared to the lifetime of the nebula. On the other hand, collisional accretion of larger aggregates starting from primitive interstellar dust grains should also occur in the nebula (Blum, 1990; Blum and Wurm, 2000), and these aggregates could continue to evolve into kilometer scale planetesimals or even into proto-planetary scale objects. While it is not clear if dust and gas can be concentrated sufficiently to trigger the gravitational accretion (Cuzzi and Weidenschilling, 2006) of planetesimals or proto-planets, it is clear that some level of collisional accretion must occur in proto-planetary nebulae in order to at least make chondrule precursors and probably to make components of meteorite parent bodies, meters to tens of meters in diameter. Youdin and Goodman (2005) have suggested that turbulent shear instabilities might serve to concentrate mixtures of chondrules and dust to sufficient density for gravitational instabilities to directly form meteorite parent bodies. As these bodies grow from dust grains to larger sizes, they also drift inward due to gas drag and can be lost into the sun in about a century (Youdin, pers. comm.). This drift might also serve to bring ices to the terrestrial planet region from beyond the snowline, and could thus be a primary source of water that has not been accounted for in models of planet growth. The purpose of this effort is to investigate the potential for such a mechanism to deliver water to the terrestrial planets as they grow.

Weidenschilling [1997: Hereafter W97] published an excellent model for the formation of comets in a minimum mass solar nebula. In this model, because the growing icy agglomerates slowly decouple from the gas as they gain mass and become more compact, comets begin to form at nebular radii between about 100 - 200 A.U. and fully decouple from the gas at 5 to 10 A.U. having grown into planetesimals on the order of 10 - 15 km in diameter. In more massive nebulae, the feeding zone for materials incorporated into a growing planetesimal would be proportionally smaller and icy agglomerates that begin accreting at 200 A.U. might easily reach diameters of 10 - 15 km before leaving the region of the Kuiper Belt. We have tried to extend a very simplified version of this general model to delineate the feeding zones for planetesimals that might have been accreted into the early Earth.

In the sections that follow we will describe our very simple calculations of the feeding zones from which the planetesimals formed that aggregated into protoplanets at 1 A.U. We will discuss the results of these calculations in terms of their dependence on the mass of the solar nebula and demonstrate that if this accretion model is applicable to even some planetesimals, then the Earth may have accreted an enormous quantity of water, the majority of which must have escaped early in our planet's history. We will very briefly discuss reasons why meteorites in our modern collections are unlikely to represent the materials that accreted to form our planet 4.5 billion years ago, and how our modern sample is likely to differ from these more primitive materials. We will also discuss possible alternative scenarios for the accretion of the proto-Earth, and how these scenarios might change our conclusions.

2. Methods

Weidenschilling (W97) published what we consider to be one of the best models for the formation of comets in a low-mass nebula. The model is based on the simple accretion of nebular solids and the effect that increased mass has on an object in orbit about the sun in a gas filled nebula. Specifically, tiny solids are initially very closely coupled to the gas. As accretion proceeds, a growing body begins to orbit independently and decouples from the gas. However, while the local gas and dust is partially supported by gas pressure, requiring a lower velocity to maintain its position in the nebula, a growing dusty snowball soon begins to drift inward without the support of the surrounding gas. This drift brings the accreting planetesimals into contact with fresh materials across a broad feeding zone, and continues until the body has grown to a size where its orbital velocity is no longer significantly affected by gas drag. Weidenschilling's (W97) purpose was to identify the radial dimensions of the nebula that produced the comets that were scattered by the giant planets into the Oort Cloud. It is our intention in this work to extend Weidenschilling's results to determine the composition of the population of planetesimals at 1 A.U. from which the terrestrial planets may have formed.

Using Weidenschilling's results together with Hayashi's model for the solar nebula (Hayashi, 1981), based on the minimum mass solar nebula, we were able to construct a simple model maintaining the nebular structure used in both authors' works. Hayashi's model provides equations for the surface density of gas, rock, and solids as a function of annular distance. The surface density for rock (ρ_r) is given as $7.1\ r^{-1.5}$ g cm^{-2} and the surface density for solids (ρ_s) as $30\ r^{-1.5}$ g cm^{-2}. These equations also apply to the assumptions of surface density at 30 AU used in Weidenschilling's model. Assuming that the composition of the nebula does not change as we increase nebular mass, then the "surface density" phase coefficient for rock or solids in higher mass nebulae is easily calculated by increasing each by the same factor by which one wishes to increase the nebular mass. These surface density coefficients are used to calculate the mass of either rock or solids (ice plus rock) between two given points via the following equation:

$$\textbf{Total Mass (g)} = 4\pi Q\,[r_b^{1/2} - r_a^{1/2}][1.496 \times 10^{13}]^2 \qquad (1)$$

where Q is the phase coefficient for a given nebular mass in units of g cm^{-2}, $[1.496\text{x } 10^{13}]^2$ converts(A.U.)^2 to cm^2, r_b is the annular distance in A.U. at which the planetesimal begins accreting material, and r_a is the annular distance at which the planetesimal ends its accretion (presumably merging into a larger body).

Weidenschilling (W97) used numerical methods to calculate that a planetesimal must start at about 200 AU in order to grow to 15 kilometers by the time it drifts in to 5 - 10 A.U. Using the solid surface density coefficient ($\rho_s = 84$) for Weidenschilling's model, as well as his stated "start" and "end" points, we calculate that a planetesimal must travel through 2.494 x 10^{30} grams of material in order to accrete to 15 km. This equates to an accretion efficiency of ~1.41 parts in 10^{12} depending on the density assumed for the accreting planetesimal. This "accretion rate" is used throughout our calculations such that: planetesimal mass (in g) = total mass of solids and/or rock between r_b and r_a /1.41 x 10^{12}, or

$$\textbf{Mass (g)} = (4\pi Q\,[r_b^{1/2} - r_a^{1/2}][1.496 \times 10^{13}]^2)/1.41 \times 10^{12} \qquad (2)$$

Note, we have assumed a density of 1.0 g/cc for all planetesimals. Determining approximate percentages of rock and ice found in a planetesimal was dependent on the starting and ending radii in reference to the snowline (which in this very simple model we have assumed to remain at 5 A.U.). Planetesimals beginning and ending accretion inside the snowline will be completely dry and 100% rock. Planetesimals that begin to accrete beyond the snowline and ending their accretion within the snowline must have the total mass (e.g., rock) from the snowline to the end point calculated, as well as the mass of solids (e.g., rock and ice) calculated from the starting point to the snowline. Again, using the surface density coefficients allows us to "separate" the mass of rock and ice accreted beyond the snowline from the pure rock accreted within, and thereby calculates approximate percentages for each.

Several important points must be made concerning our use of Weidenschilling's results before we begin to discuss our own. First, Weidenschilling reported extensive results from numerical simulations that explicitly took into account a wide range of factors such as the sticking of grains to a growing body. We have lumped all of these effects into an efficiency factor and have used this same efficiency factor to represent the accretion of both icy dust (outside the snowline) and dry rock (inside the snow line). This is obviously an oversimplification of a very complex and poorly understood process. Second, other processes may have created planetesimals in the solar nebula such as gravitational instabilities or large-scale vortices. Our study only examines the results of hierarchical accretion. Third, we assume that the snowline represents a discontinuity between a mixture of dry dust and hydrous gas inside the line and a mixture of dry gas and icy dust on the outside of this sharp divide. This obviously neglects the bodies that may have accreted to ten-meter or even kilometer scales outside this divide, yet drifted inward to some extent due to gas drag or gravitational interactions. Finally, we have assumed that the position of the snowline (at 5 A.U.) does not migrate as we increase the mass of the nebula, but instead remains fixed no matter how we change the mass of the system.

The effects of each of these simplifications will be examined below, after we have presented the results of our calculations. However, we contend that the effects of many of these factors would not tend to favor the accretion of rock over ice into planetesimals at 1 A.U. and that the uncertainties in nebular conditions, particularly in the mass of the nebula itself, are sufficiently large that our simplified calculations are an appropriate first step in examining the potential incorporation of ice and water into the progenitors of the terrestrial planets.

3. Results

From Weidenschilling's work [W97] we calculated an efficiency factor for the accretion of primitive planetesimals based on the final diameter of the body, the density of nebular solids (including ice) and the total mass of the nebular disk. We first validated this efficiency factor by using it to reproduce other examples of accretion calculations shown in Weidenschilling's (W97) paper. We then used this efficiency factor to calculate the size of the initial feeding zone for planetesimals that had grown to 10, 15 and 20 km in diameter by the time they reached 1 A.U. as a function of nebular mass. In other words, assuming that 10, 15 and 20 km sized planetesimals were present at 1 A.U., were still drifting inward but were available to be incorporated into growing protoplanets, where did these bodies begin to accrete? The results of our calculations are presented in Table 1 where we show the nebular radius where accretion begins as a function of the diameter of the planetesimal at 1 A.U. and the mass of the solar nebula. In all cases we assumed that the snowline is located at exactly 5 A.U. As can be seen from Table 1, the size of the planetesimal feeding zone and the percentage of ice in the final planetesimal are strong functions of the nebular mass and the size of the planetesimal itself: higher mass planets in lower mass nebulae contain much more ice.

We based our calculations on the total nebular mass expressed in units of the Hayashi Minimum Mass Nebula [Hayashi, 1981, Hayashi et al., 1985] and for each nebular mass we calculated where aggregation must begin in order to produce the planetesimal size of interest based on the accretion efficiency discussed above. We note that Weidenschilling [W97] used a value 2.8 times the Hayashi Minimum Mass in his model of comet formation, and more recently, Desch [2008] has estimated that the primitive solar nebula must have been at least 25 times the Hayashi Minimum Mass, but with a somewhat steeper slope (e.g. less mass in the outer regions of the nebula), thus more centrally concentrating the material available for planet formation. In this scenario, the snow line may be as close as 2.8 A.U. from the protosun. We decided to adopt the more conservative 5 A.U. position for the snow line in this work, and still only in the most massive nebulae do the smallest planetesimals at 1 A.U. contain pure rock. All planetesimals 10 km in diameter and larger contain a significant fraction of ice.

4. Effects of Our Assumptions on the Results

As noted above we made a number of simplifying assumptions in our calculations that could affect our results. First, we assumed that the snowline remains at 5 A.U. no matter the mass of the nebula. However, since any likely accretion scenario for the Solar Nebula would have a mass considerably larger than the Hayashi Minimum Mass, the snowline for more massive nebulae would occur closer to the proto-sun. This would tend to increase the number of planetesimals containing ice and increase the ice content as a fraction of planetesimal mass for small bodies at 1 A.U. In fact Desch (2008) calculated that the snowline for a nebula 25 times the Hayashi Minimum Mass would occur at 2.5 A.U., well inside the outer asteroid belt. Under these conditions, some outer main belt asteroids would certainly contain significant quantities of ice in their interiors.

Second, we assumed that we could extend the results of Weidenschilling's (W97) numerical calculations from the Outer Planets region to the Terrestrial Planets region and that the efficiency for particulate aggregation would remain unchanged. We find that reasonable changes in the efficiency factor used in these calculations do not change our basic results that smaller planetesimals at 1 A.U. accreted in more massive nebulae contain more rock while larger bodies in lower mass nebulae contain much more ice. Certainly the detailed results are modified with changes to this factor; however, the uncertainty in the actual mass of the Solar Nebula is more important in determining the ice content of the planetesimals than is the exact value of the accretion efficiency factor employed in the calculations. We also use the same factor for the accretion of both icy and anhydrous dust. The relative sizes of the particles and the velocities of the collisions appear to be more important than the exact composition of the accreting material, but the modest experimental results that we have to date indicate that collisions between icy particles are more likely to result in sticking than are collisions between dry rocks and pebbles. Our calculations therefore may overestimate the efficiency of forming ice-free planetesimals.

Third, we assumed that the snowline represents a sharp compositional boundary in the nebula. Accretion entirely inside the snowline will never incorporate ice into the planetesimal under this assumption. However, in the current solar system there are numerous examples of short period comets making many passes inside the orbit of the Earth, and subsequent apparitions of these comets demonstrate that they continue to retain at least some water vapor over thousands of years. Comets are even known to make several passes through the solar corona without complete loss of the ice in their interiors. The early nebula between 1 and 10 A.U. was certainly more opaque to solar radiation than our modern solar system and was more densely populated by icy planetesimals. Our assumption of a sharp discontinuity in the availability of small icy bodies inside the snowline that might be incorporated into planetesimals, even ones formed by turbulent accretion or gravitational instabilities, certainly favors the formation of ice-free planetesimals.

On each occasion where we made an assumption to simplify our calculations while still using the basic results of Weidenschilling (W97), we tried to consistently err on the side of producing the largest fraction of ice-free planetesimals possible. In spite of our obvious bias in favor of such dry dusty bodies, we nearly always produced a population of ice-rich planetesimals at 1 A.U.

Alternative Accretion Models

Weidenschilling's (W97) manuscript describing his model for planetesimal (comet) aggregation acknowledges that as the total mass of the Solar Nebula increases, additional factors, such as gravitational instabilities and other collective effects could increase the efficiency of accretion.

In another treatment of the formation of the terrestrial planets Kokubo and Ida (2000) find that the formation of proto-planets occurs as a two stage process. Runaway accretion first produces a mixed distribution of planetesimals and proto-planets (Kokubo and Ida, 1995). The proto-planets initially grow rapidly at the expense of the planetesimal population (Kokubo and Ida, 1996) until a small number of proto-planets have formed in the nebula. These proto-planets then grow much more slowly, entering the "oligarchic growth" stage (Kokubo and Ida, 1998) where the larger proto-planets actually grow more slowly than smaller ones. In this scenario, proto-planets with masses of 10^{26} g are formed within about 500,000 years at 1 A.U. (Kokubo and Ida, 2000) and thereafter maintain rough separations greater than 5 Hill radii from one another as they continue to accrete planetesimals from their surroundings. These proto-planets form rapidly from young planetesimals that have not had sufficient time to lose any ice that may have been sequestered within, and such proto-planets are sufficiently large that they should retain a reasonable fraction of their accreted volatile complement.

The oligarchic growth stage from proto-planet to planet is a result of the larger bodies accreting materials from their immediate vicinity. While casual readers of these papers might believe that because these proto-planets incorporate materials from only a very narrow range of heliocentric distance, this must imply that the proto-planet that eventually grew to become the Earth could only incorporate rocky material. This impression is incorrect for two reasons. First, the initial distribution of planetesimals from which the population of proto-planets evolved was shaped by gas drag as the planetesimals accreted from the disk. Thus the population of planetesimals from which a proto-planet at 1 A.U. accreted should have been similar to that shown in Table 1.

Second, although the models of Kokubo and Ida (2000) span only a very narrow ring within the nebula ($\Delta a = 0.02 - 0.09$ A.U.) the boundary conditions (see their section 3.2) that they apply to these calculations assume a free flow of planetesimals through the model annulus. In other words, as proto-planets grow from the population of planetesimals within an annulus, the model assumes a balance between the inward loss of planetesimals due to gas drag and those that flow into the accretion zone from the outer nebula such that the surface density of the accreting annular disk remains constant. Thus, while the growing proto-planets remain stationary in this scenario, the planetesimal population from which they accrete continuously flows in toward the sun due to gas drag. Again the ice to rock ratio shown in Table 1 would apply to this population.

Finally, there is the possibility that some planetesimals could form on very short timescales due to turbulent-gas-driven gravitational instabilities. In turbulent eddies the local conditions for gravitational instability can be met (Johansen et al., 2006; 2007). The numerical simulations by Johansen et al. show the formation of Ceres-mass planetesimals in a few orbital periods. Also, chondrule-size particles can be concentrated in the low-vorticity regions of the disk (Ormel et al., 2008) and this can allow the formation of 50-100 km planetesimals on a short timescale due to the self-gravity of the chondrule clump. In both cases, the short timescales will prevent any significant radial migration. These mechanisms could easily produce relatively dry proto-planets if all of the components within the gravitational instability had equilibrated within the snowline.

While such processes would aggregate all of the mass of an individual planetesimal or proto-planet within a short timescale and from a very narrow range of heliocentric distances, the composition of such bodies will depend on the composition of the material that one would expect to be present at 1 A.U. while the composition of the proto-Earth would depend on the fraction of planetesimals that form via gravitational instabilities. Gravitational instabilities are unlikely to be the dominant process forming comets in the outer nebula as both the degree of MHD driven turbulence and the surface density of the disk are too low for efficient operation of this accretion mechanism. This argues that collisional aggregation processes that formed ever larger solid bodies that drifted sunward due to gas drag probably dominated in this regime (W97). If such processes dominated in the outer solar system, there is no reason to believe that this mechanism did not also operate at least to some extent in the inner solar nebula. In contrast, there are meteorite samples from asteroids that contained very little water, even at the time of their formation. As almost any sized body ending accretion near 3 A.U. would contain some ice if formed via the collisional-aggregation, gas-drag scenario, this provides evidence for the role of turbulent accretion or gravitational instabilities in the production of some planetesimals.

We can make the simple approximation that planetesimals formed via gravitational instabilities at 1 A.U. always consist of rocky materials. If half of all planetesimals at 1 A.U. formed via this mechanism, then the ice fraction of materials accreting to form the proto-Earth shown in Table 1 would be reduced by a factor of 2. However, as gas drag mediated migration of meter-to-kilometer scale planetesimals will always occur to some degree, some fraction of the larger planetesimals formed via gravitational instabilities will contain ice that drifted inward within bodies that began to accrete beyond the snowline. While small bodies eventually lose their volatiles in the inner nebula, rapid gravitational accretion could trap considerable fractions of this ice in larger, more robust planetesimals before it was lost. Therefore unless all planetesimals at 1 A.U. formed via gravitational instability and unless there were no small bodies present at 1 A.U.

that began accretion beyond the snowline to be incorporated into these planetesimals, then the proto-Earth would have accreted considerably more water than is assumed in models that begin with planetesimals of chondritic composition.

5. Implications of the Results

Young Planetesimals Were Wet

Because many of these bodies began accreting well outside the snowline [Lunine, 2006; Ciesla and Charnley, 2006], they contain considerable quantities of water as ice grains, much like comets. However, can this water be retained to be incorporated into the growing Earth? In a dense nebula, the light of the protosun is unlikely to drive the loss of volatiles from a small planetesimal within the snowline as our sun does today. Instead, volatile loss was more likely controlled by the internal heat generated within the planetesimals via radioactive decay or by accretional impact. For small planetesimals that coalesce from even smaller bodies in similar orbits, impact energy is likely to be localized and relatively insignificant on the global scale. Such collisions resulted in planetesimals that we call comets when they now arrive from the outer solar system, and are unlikely to result in extensive volatile loss in the inner solar system.

The concentration of radioactive elements initially available for incorporation into the terrestrial planets depends to a large degree on how they were added to the system. If injection of such material initiated the collapse of the nebula [Wadhwa et al., 2006], or if they were simply present in the collapsing molecular cloud that formed our solar system [Chabot and Haack, 2006], then all planetesimals would accrete from roughly the same mix of material. If the short-lived radioactive elements were injected into the nebula at some time after nebular collapse [Wadhwa et al, 2006], then later formed planetesimals could contain higher fractions of these heat sources than planetesimals formed from the less radioactive solids in the molecular cloud core, and these younger bodies would therefore evolve faster than those formed earlier. However, even small (5 km) planetesimals that are enriched in ^{60}Fe and ^{26}Al require from a few hundred thousand to several tens of millions of years to reach their maximum internal temperatures [Das and Srinivasan, 2007] and become totally dehydrated. If such bodies contained substantial quantities of water as ice, then heating would be slower due to the reduced concentration of radioactive heat sources, and the slow loss of volatiles would allow these planetesimals to sweat, thus efficiently losing heat from their interiors.

While planetesimals heat slowly [LaTourette and Wasserburg, 1998; Huss et al., 2006], protoplanets form rapidly in a runaway growth process caused by the increased gravitational cross sections of larger planetesimals [Wetherill and Stewart, 1989; 1993]. It has been suggested that terrestrial planets may have formed within 10 million years of nebular collapse [Jacobsen, 2003; Jacobsen et al., 2009] and that core formation on the Earth occurred less than 20 million years later [Nichols, 2006]. In other words, the Earth may have formed from very young planetesimals that had not yet had a chance to lose any significant quantity of ice or water of hydration due to radioactive decay driven heating. In this scenario, a proto-Earth may have formed directly from the planetesimals whose ice content is listed in Table 1. This would result in a planet with much too much water, rather than too little. Given other considerations, the rocky fraction of the planet would most likely need to be comparable to the present mass of the Moon or Mars, and so the proto-Earth may have been nearly twice as massive if much of the incoming ice remained trapped within the growing protoplanet, on its very wet surface, or within its massive, water - rich atmosphere.

Composition of Planetesimals

The composition of the rocky component of the planetesimals formed via gas-drag mediated accretion should be roughly chondritic. There is no mechanism for metal-silicate fractionation to operate on the dust grains and boulders that would be accreted via this mechanism. Although the overall composition of the planetesimals formed in this scenario bear more resemblance to what we currently call comets than to modern asteroids, for reasonable values of the nebular mass, the majority of the water accreted into these planetesimals originates in the inner solar system within a few A.U. of the snowline. For this reason, the planetesimals would not be expected to have the high D/H ratios or any significant content of volatile organic materials found in modern Kuiper-belt or Oort cloud comets.

As both the refractory composition of the planetesimals and the isotopic composition of the water would be "normal" when compared to typical models for the formation of the Earth, the only real compositional difference between the scenario described above and current models for the origin of the terrestrial planets is in the total quantity of water that might have been accreted.

While current models often require the delivery of water at the end of the accretion process, this scenario requires the loss of water from the proto-Earth to be compatible with the composition of the modern Earth.

We do not have samples of the population of planetesimals that accreted to form the terrestrial planets in our modern meteorite collection [Drake and Righter, 2002]. Such planetesimals would have lost their ice and much of their water of hydration several billion years ago [Nuth, 2008]. The residual dehydrated body that began with more ice than dust and thus contained a smaller radioactive heat source than that which produced the large scale melting and differentiation of Ceres, Vesta and other asteroids would also be much more fragile than such solid rocks, much like loosely compressed sandstone. Collisional processes over the lifetime of the solar system would have gradually reduced the surviving number of these fragile bodies to an insignificant fraction of the asteroid population. It is therefore very likely that we do not have any representative samples of the planetesimal population that contributed to the formation of the terrestrial planets in our modern meteorite collections.

Loss of Volatiles from the Earth

We expect that large quantities of water may have been lost from the growing proto-Earth due to impact induced heating, especially considering the lower escape velocity of the less massive, but rapidly growing protoplanet. We must also assume that the rocky terrestrial interior would remain at least fully saturated by water dissolved within the rocks and magma. In fact, given the overburden and likely difficulty of escape to the surface, we would expect that water vapor would become supersaturated within the proto-planet, and that any terrestrial proto-planet in the late stages of accretion would have a thick, water-vapor-laden atmosphere that should undergo some loss of water back to space. In the case of the Earth it is likely that this entire atmosphere, as well as any nascent hydrosphere, was lost during the impact of the Mars-scale body that formed the Moon [Cameron and Benz, 1991; Canup and Asphaug, 2001; Canup, 2004]. In addition, such a large impact would dehydrate a significant fraction of the terrestrial mantle as well as virtually all of the material from the impactor that might fall back onto the surface of the Earth. The Late Heavy Bombardment would have further dehydrated the terrestrial crust and uppermost mantle due to impact induced heating. Meanwhile the planetesimals impacting the Earth at this late stage would have had 500 million years since their accretion to lose a large fraction of their own volatile content, probably resulting in a net loss of water from the Earth.

If runaway growth morphed into oligarchic growth and only formed proto-planets in size ranges somewhere between Ceres and the Moon, then it may be much easier to explain volatile loss during the growth of the Earth. Because the initial proto-planets would be small, they would more easily lose volatiles that reached the surface than would a 90% finished Earth. In addition, a large number of collisional aggregation events are required to increase the mass of the Earth to its present value (~6 x 10^{27}g) starting from a population of much smaller objects (~10^{26}g). Each of these events would strip away any nascent hydrosphere on the colliding proto-planets, and could partially dehydrate the interior of the resultant body. However, if the interior of the growing proto-Earth remained near saturation (~3% water by mass) throughout the accretion process, the resulting planet would have many times more water than is needed to form the current hydrosphere (<0.025% of the Earth by mass). In fact, the above statement would still be true even if 95% of the water contained in all of the saturated proto-planets that accreted to form the Earth were lost in the growth process.

Water on the Newborn Earth

Comets still impact the Earth today (e.g., Tunguska) and the frequency of such impacts was higher in the first billion years of Solar System history [Chyba, et al., 1994]. Comets therefore must have contributed some fraction of the water currently on the modern Earth. But we submit that a significant hydrosphere and a very wet atmosphere already existed on the proto-Earth prior to the Moon forming event, due to the accretion of ice laden planetesimals. Since up to 3% water can be dissolved in the modern terrestrial mantle at equilibrium [Righter, 2007] and even more water could have been present "in transit" through the mantle and crust as water worked its way up to the surface from the deeper planetary interior, we see no possible alternative but to accept that the early Earth had quite a large complement of water and may have been a bit more massive than expected when the moon forming collision occurred.

One might ask what the modern Earth would have been like if the Moon-forming event and the Late Heavy Bombardment had never occurred. The Earth's surface is already 75% ocean even though water comprises much less than 0.1% of the Earth's total mass. Had the early Earth not lost its original wet atmosphere, hydrosphere and some very large fraction of the water dissolved in its upper mantle, the entire surface of the Earth might today be covered by water to depths of at least several hundred miles, assuming that natural atmospheric erosion would have eliminated a substantial fraction of the initially accreted ice. Even with the moon forming event and Late Heavy Bombardment, the interior of the planet should still be rich in dissolved water and hydrogen: dissolved hydrogen could certainly be plentiful in the Earth's core, and most mantle magmas should be fully saturated in water.

Water Equilibrates Oxygen Isotopes in the Earth-Moon System

If the proto-Earth and the "Mars-size impactor" were both equilibrated bodies containing significant reservoirs of liquid water prior to impact, the energy of the collision would vaporize any oceans on the surfaces of the bodies while simultaneously equilibrating the isotopic composition of both bodies in the debris cloud surrounding the Earth. This is consistent with the models of Pahlevan and Stevenson (2007) who demonstrated a viable mechanism for equilibrating the oxygen isotopic compositions of the Earth-Moon system via exchange reactions mediated by a moderately long lived disk. Such a disk and its isotopic exchange efficiency would be greatly enhanced by increased water content in the proto-Earth. Depending on the accretional loss of water during the initial accretion of both bodies, there could be several tenths of an Earth mass of water vapor in this cloud. Although most of this water would be lost from the system due to the high temperature of the debris disk, this same high temperature would ensure the equilibration of the silicates in the cloud. If the oceans of the larger proto-Earth dominate the contribution to this disk, then the silicate particles and SiO vapor in the debris cloud will be equilibrated with the Earth before the cloud coalesces into the Moon.

6. Conclusions

Some planetesimals in the early solar system accreted from wide feeding zones and took a long time to heat to sufficiently high temperatures to lose the volatiles and ices they initially contained. Models for the formation of the terrestrial planets suggest that planets grew by the aggregation and growth of proto-planets that themselves grew quickly via runaway accretion from planetesimals in narrow feeding zones. Because these planetesimals had not yet had time to warm to the stage where they would lose a large fraction of their water and volatiles prior to their aggregation into proto-planets, many of those bodies that accreted should have contained reasonably large quantities of ice. The initial composition of the Earth contained more than enough water to form the modern hydrosphere depending on the position of the snowline, the fraction of planetesimals formed via gravitational instabilities or turbulent aggregation and the overall mass of the solar nebula. Even with substantial accretional loses and atmospheric erosion during the series of giant collisions between proto-planets that formed the terrestrial planets, more than enough water should have been available on and within the Earth to account for several modern oceans, especially when one includes the contributions from the decreasing, but continuous infall of comets to modern times.

We do not need to wonder where the Earth's water came from; it clearly arrived with the planetesimals accumulated by the proto-Earth during the accretion process. Instead we should be asking how all of the initial water was lost from the Earth and what the consequences of these possible loss mechanisms are. Modeling the formation of the Earth and the other terrestrial planets from modern (dry) meteoritic matter, even carbonaceous meteorites, is not appropriate, and is certainly inconsistent with results one gets by following a planetesimal from its origin beyond the snowline, into the accreting planet. What effect might such large quantities of water have had on the geochemical differentiation of proto-planets, or of the Earth prior to the Moon forming event? Could a more massive but water filled proto-Earth better account for the properties of the Earth-Moon system during and after the giant collision with a Mars sized body (e.g., Pahlevan and Stevenson, 2007)? No one has yet investigated such possibilities: There is much more work still to do.

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Table 1

Radius of Feeding Zone and Percentage of Ice in the Final Planetesimal as a Function of Nebular Mass and Planetesimal Diameter

	Total Nebular Mass (Hayashi Minimum Mass Nebula)					
	1	10	20	30	40	50
Planetesimal Diameter (km)	Distance from the Proto-Sun where Aggregation Begins (A.U.)					
10	122	8.1	5.8	5.05	4.71	4.52
15	1068	25.2	12.1	8.81	7.36	6.55
20	5594	85.2	31.2	19.11	14.17	11.56
	Percentage of Ice in the Final Planetesimal (%)					
10	74	52	27	3	0	0
15	76	69	62	55	47	40
20	76	73	70	67	64	61