

WHY ISN'T THE EARTH COMPLETELY COVERED IN WATER? Joseph A. Nuth III¹, Frans J. M. Rietmeijer² and Cassandra Lee Marnocha^{1,3}, ¹Astrochemistry Laboratory, Code 691 NASA's Goddard Space Flight Center, Greenbelt MD 20771 USA (Joseph.A.Nuth@NASA.gov), ²Department of Earth and Planetary Sciences, MSC03-2040, University of New Mexico, Albuquerque, NM 87131-0001 USA (fransjmr@unm.edu), ³University of Wisconsin at Green Bay, Green Bay WI 54311 USA (MARNCL23@uwgb.edu)

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 [1]. The argument is typically phrased in terms of the chemical composition of the terrestrial mantle as compared to primitive meteorites that might represent the building blocks of the Earth [2] or to the isotopic composition of the Earth's oceans as compared to that of cometary water [3]. Both of these considerations yield important constraints on the problem. However, since both of these arguments have been thoroughly addressed elsewhere, we will not address them, but will instead look at additional lines of evidence that have not yet been as thoroughly explored. Specifically, we will examine what new information models of nebular accretion, planetary formation and the evolution of primitive bodies might add to the discussion.

Planetesimal Accretion: Weidenschilling [4] has published what we consider to be the best model for the formation of comets in a minimum mass 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 a more massive nebula, 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 applied a very simplified version of this general model to delineate the feeding zones for planetesimals that might have been accreted into the early Earth. Because many of these bodies began accreting well outside the snowline [5,6], they contain considerable quantities of water as ice grains, much like comets.

Planetesimal Heating and Runaway Accretion: The concentration of short lived radioactive elements initially available for incorporation into the terrestrial planets depends to a large extent on how they were added to the system. If injection of such material initiated the collapse of the nebula [7], or if they were simply present in the collapsing molecular cloud that

formed our solar system [8], 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 [7] however, 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 greatly enriched in ⁶⁰Fe and ²⁶Al require from a few hundred thousand to several tens of millions of years before reaching their maximum internal temperatures [9] and becoming totally dehydrated.



Figure 1. Earth may have been completely covered by oceans with virtually no dry land at all, had the Moon forming event not eliminated the initial atmosphere and hydrosphere while simultaneously drying some fraction of the crust and upper mantle.

While planetesimals heat slowly [10,11], planets form rapidly in a runaway growth process caused by the increased gravitational cross sections of larger planetesimals [12,13]. Terrestrial planets probably formed within 10 million years of nebular collapse [14] and core formation on Earth occurred less than 20 million years later [15]. In other words, the Earth

formed from 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, Earth may have formed with much too much water, rather than too little.

Where did all of the water go? Certainly in the later stages of planetary accretion, much of the water contained in a planetesimal would be released to the atmosphere as it collided with the planetary surface. Additional water vapor and other volatile species would be released from the planetary interior due to widespread volcanism. One would therefore suspect that a terrestrial planet in the late stages of accretion would have a thick, water-vapor-laden atmosphere that should undergo some loss back to space. However, 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 [16,17,18]. In addition, the 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 Earth.

Discussion: We do not have samples of the population of planetesimals that accreted to form the terrestrial planets in our modern meteorite collection [19]. Such planetesimals would have lost their ice and much of their water of hydration several billion years ago. The residual dehydrated body that began with more ice than dust and thus contained a smaller radioactive heat source than might produce the large scale melting and differentiation of Ceres, Vesta and other asteroids would also be much more fragile than such solid rocks. Collisional processes would gradually reduce the surviving number of these fragile bodies to an insignificant fraction of the asteroid population.

Comets still impact the Earth today and the frequency of such impacts must have been higher in the first billion years of Solar System history [20]. Comets therefore must have contributed some fraction of the water currently on the modern Earth. However, it is possible that a significant hydrosphere and a very wet atmosphere already existed on Earth prior to the Moon forming event, due to the accretion of ice laden planetesimals. Up to 3% water can be dissolved in the modern terrestrial mantle at equilibrium [3] and even more water could have been present "in transit" as water worked its way up through the mantle from the deeper planetary interior. The early Earth might therefore have had quite a large complement of water. It is quite possible that we have been asking the wrong question. Rather than seek to account for the large mass of water on the modern Earth, we should be looking to explain how even larger quantities were lost.

One might also ask what the modern Earth would have been like if the Moon-forming event had never occurred. The Earth's surface is already 75% ocean. Had the early Earth not lost its original wet atmosphere, hydrosphere and some fraction of the water dissolved in its upper mantle, the entire surface of the Earth might have been covered by water. This might have had some impact on the development of what passes for intelligent life on our planet.

Conclusions: Because planetesimals in the early solar system accreted from a wide feeding zone, and because these bodies 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 encounter with the proto-Earth, many of those bodies that accreted should have contained reasonably large quantities of ice. More than enough water should have been available to account for several modern oceans, especially when one includes the contributions from the decreasing, but continuous infall of comets to modern times. We should really be asking how all of the initial water was lost from the Earth, and what effect might such large quantities have had on the geochemical differentiation of the Earth prior to the Moon forming event.

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