Gravitational Molecular Hydro-Accretion:

A Novel Model Explaining Disparate Planetary Deuterium Ratios and the Plausible Origin of Earth's Water

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Abstract

• The primary delivery mechanisms tasked to explain the origin of Earth's water and deuterium ratios have been the wet and dry models. The wet model simply contends that Earth originally accreted water-rich material directly from the protoplanetary disc thus forming wet. The dry model assumes a hot Earth losing water to space, forming dry, and later receiving additional water via cometary and asteroidal bombardment.

• Deuterium, a hydrogen isotope, contains an additional neutron in its nucleus in contrast to hydrogen's one proton and electron. This isotope can chemically bond with hydrogen, deuterium, and oxygen atoms to create increasingly massive water molecules: H_2O, HDO, and D_2O respectively. Earth's oceans contain approximately one deuterium atom per 6,400 hydrogen atoms, a D/H ratio significantly less than those detected on the majority of comets and asteroids. Recent work shows asteroids to have conflicting elemental and isotopic properties as compared to Earth, suggesting current compositions of comets and asteroids are not uniquely suited as primary delivery mechanisms for terrestrial water.

• New research suggests a comet's present composition may not be an accurate analog to its ancient counterpart. A recent study now explains that during comet formation and shortly thereafter, the radioactive decay of ^{26}Al generates enough heat to force the interior temperatures above the melting point of water, permitting stratigraphic cometary differentiation and enrichment of near surface H_2O, as well as deuterium-rich HDO and D_2O near the core.

• Recent computational and experimental research conducted at temperatures between 138K and 900K, establishes that the adsorption of water onto olivine grains, which are among the most plentiful minerals in a protoplanetary disc, can cause a planet's mantle to contain multiple oceans worth of water, thus supporting a wet Earth formation.

• We present the Gravitational Molecular Hydro-Accretion model (GMHA), positing a succession of mechanisms explaining the origin of incongruent deuterium ratios found within our solar system, while additionally identifying the primary source of Earth's water. Furthermore, we illustrate that GMHA has already made one correct prediction regarding the deuterium ratio of Earth mantle samples, while several other predictions await testing.

Background

Figure 1: "Pillars of Creation", part of the Eagle Nebula
Credit: Jeff Hester, Paul Scowen (ASU), HST,, ESA, STScI, NASA

• Portions of molecular clouds like the "Pillars of Creation" found in the Eagle Nebula (Figure 1) containing mainly hydrogen and helium, can contract to create protoplanetary discs, new stars, and new planetary systems.

• The photograph shown in (Figure 2) is of star HL Tauri. Some 450 light-years away, this is the highest resolution photo ever taken of a young star and its protoplanetary disc. The dark rings are where planets, asteroids, and comets are most likely forming. This young star closely resembles the characteristics and dynamics of our own solar system around 4.6 billion years ago.

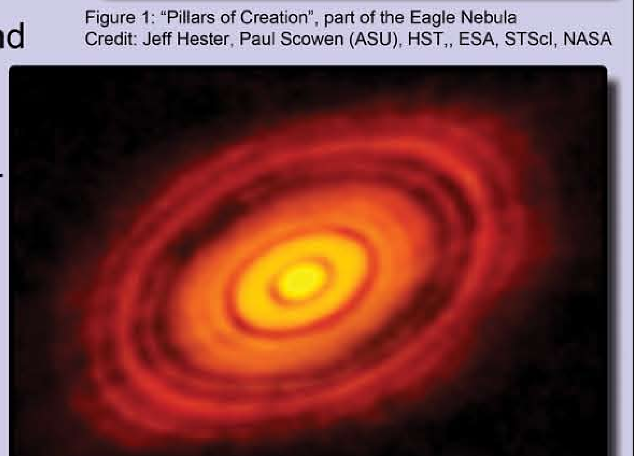

Figure 2: HL Tauri, highest resolution photo ever of protoplanetary disc
Credit: ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF).

• (Figure 3) depicts an artist's concept of comets, asteroids, and water vapor around the young, pre-main sequence T-Tauri star, TW Hydrae, and offers a closer visual context of what the accretion disc forming comets, asteroids, and planets during the birth of our own solar system may have looked like.

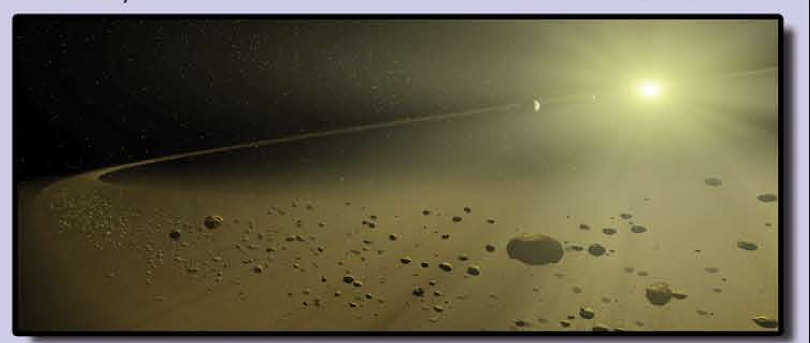

Figure 3: Artistic depiction of gas and water vapor aroung a young sun-like star
Illustration Credit: T. Pyle (SSC), JPL-Caltech, NASA

Background

• Amongst the water vapor, dust, and ice of an accretion disc, there exists a vast amount of the mineral olivine, which is one of the most abundant grains within a protoplanetary disc that can become hydrated, thus harbor water.

• An olivine meteorite known as a pallasite as shown in (Figure 4), depicts how these small mineral grains can accrete, grow, and become a large part of the matrix which forms asteroids and eventually planets.

Figure 4: Pallasite: Olivine meteorite
Credit: Mike Miller

• Deuterium, an isotope of hydrogen, can be a key to unlocking the mystery of how Earth originally received its water.

• As shown in (Figure 5), a typical hydrogen atom has only one proton in its nucleus and one electron in its electron shell. In the stable deuterium isotope, there is an additional neutron in the nucleus. When bonded with oxygen, three potential forms of water are possible, all of which have increasingly heavier masses:

1) H_2O (normal water)
2) HDO (semi-heavy water)
3) D_2O (heavy water)

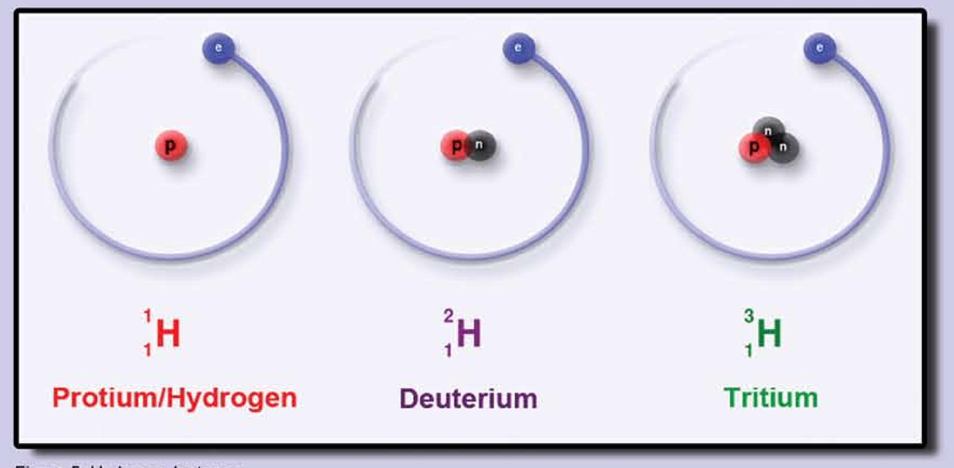

Figure 5: Hydrogen Isotopes
Credit: Wikimedia Commons

• If Earth's water was delivered mainly by comets and asteroids, their deuterium to hydrogen (D/H) ratios should closely match those on Earth however, they do not.

• In general, Earth's D/H ratio is much lower than the comets and asteroids that have recently been measured.

• Finding a mechanism explaining the disparate D/H ratios could potentially reveal the original source comprising the majority of Earth's water.

Results

• One hypothesis regarding how Earth's water was delivered points towards an early Earth being too hot to hold on to its water, thus its initial water would have boiled-off and the planet would have formed dry, receiving its water later via comet and wet asteroidal bombardment, while another hypothesis posits the Earth formed wet, accreting water as the planet grew. [1]

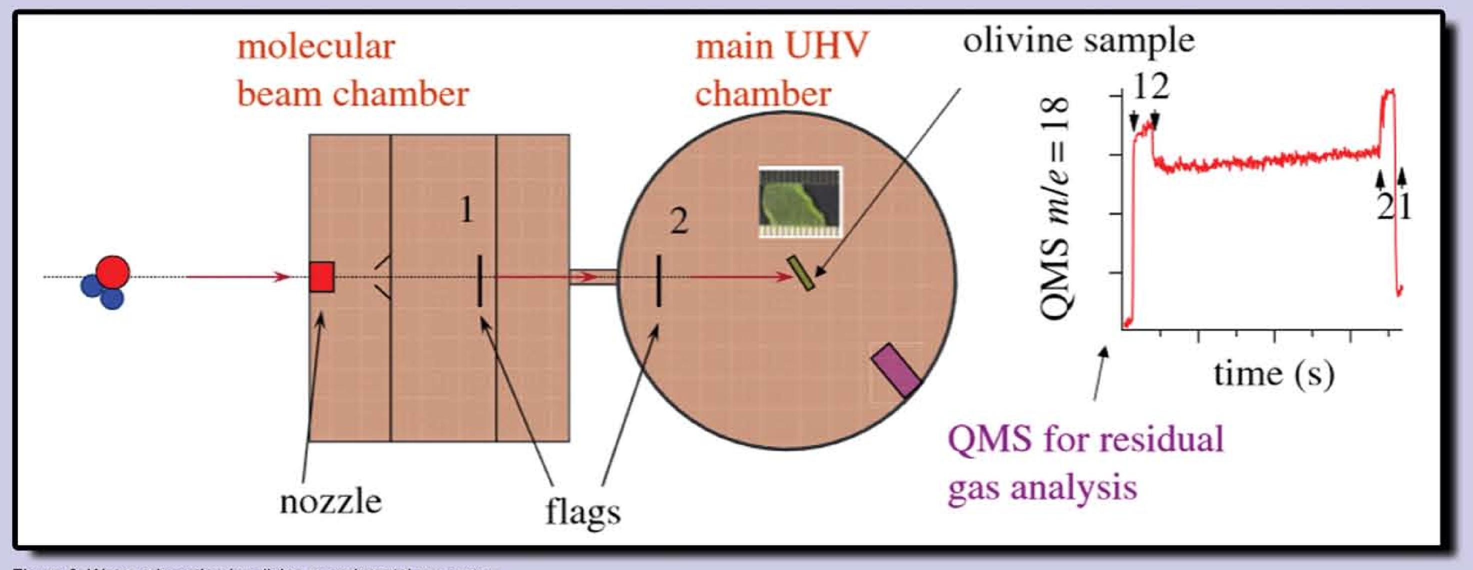

Figure 6: Water adsorption by olivine experimental apparatus
Credit: Vattuone et al. 2011

• Recent research now discounts asteroids as being the major source of Earth's water as they have inconsistent elemental and isotopic properties with Earth, thus limiting their contribution. [2] Recent experimental and computational research by MJ Drake [2] and subsequent work by Vattuone et al [4] as seen in (Figure 6) establishes that past adsorption of water onto olivine grains, some of the most abundant grains in an accretion disc, can form asteroids containing water-rich olivine crystals, (Figure 4) which ultimately form terrestrial planets such as Earth.

• The experiment (Figure 6) heats and cools an olivine surface between 138K and 900K, thus adsorbing, desorbing, and dissociating water on its surface, demonstrating that adsorption can be responsible for many Earth oceans worth of water held within our planet's deep mantle. [4]

• GMHA posits that today's comets and asteroids are not necessarily pristine examples of pre-solar material but rather could have been subject to change.

• According to a study published in *Nature*, this assertion may be correct as comets can be heated by supernovae, passing stars, collisions, ultraviolet damage, cosmic ray damage, and interstellar medium gas and grains, all of which can cause chemical reactions and sputtering devolatilization leaving today's comets anything other than a pristine pre-solar examples of cometary material. [7]

• Further evidence supporting GMHA's assertion that early comets could have contained low concentrations of surface deuterium via density stratification comes from additional recent research on cometary evolution suggesting that heat generated from primarily the radioactive decay of ^{26}Al could force interior temperatures above the melting point of water, which by extension would allow for cometary density stratification and light-water (H_2O) nearer the surface. [5]

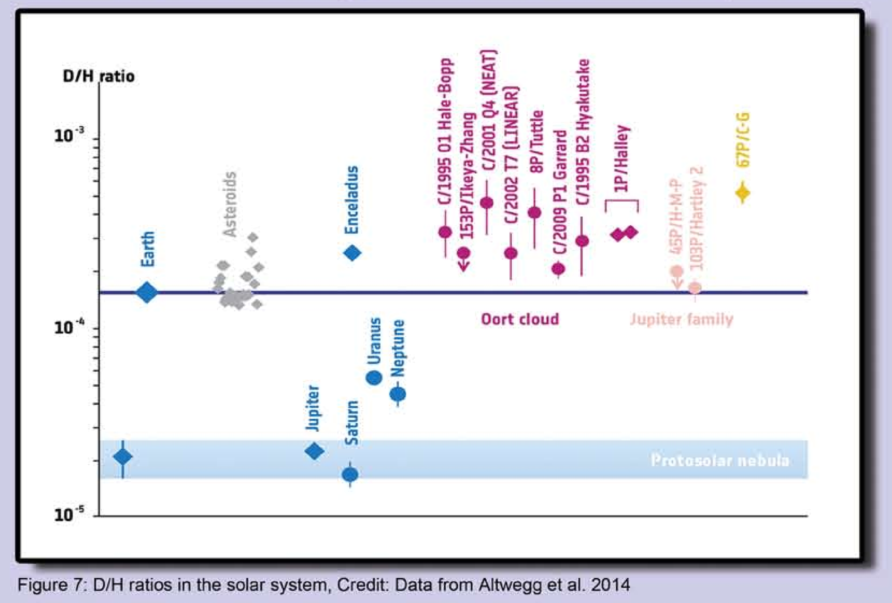

Figure 7: D/H ratios in the solar system, Credit: Data from Altwegg et al. 2014

• The most recent D/H measurements made of a comet was in 2014 when the European Space Agency (ESA) landed the Philae spacecraft on the surface of comet 67P/Churyumov-Gerasimenko and found that the D/H ratio was ~5.3×10^{-4}, more than three times greater than the ratio found on Earth of ~1.56×10^{-4}, (Figure 7) essentially ruling out comets (in their current form) as major water delivery mechanisms. [3]

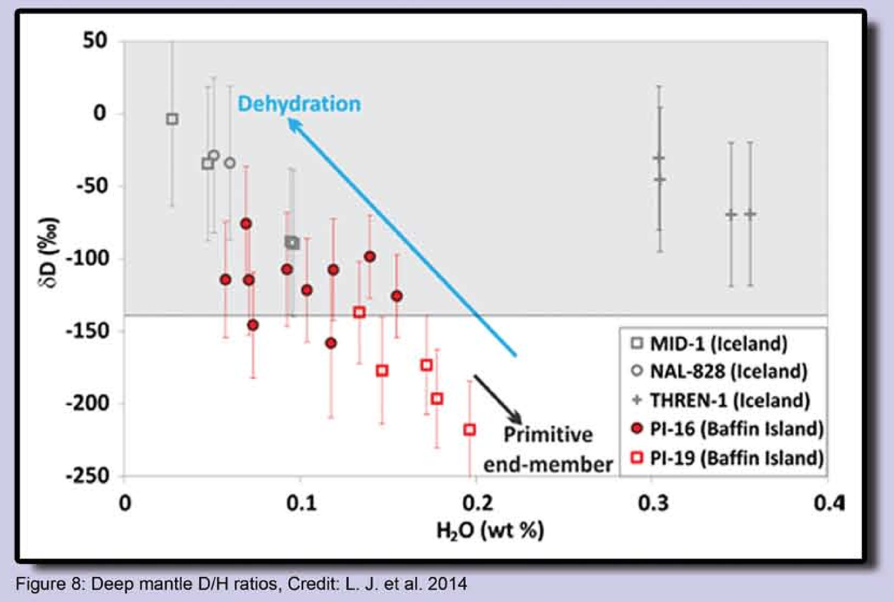

Figure 8: Deep mantle D/H ratios, Credit: L. J. et al. 2014

• In 2014, D/H ratios measured in olivine-bound melt inclusions in undegassed mantle-plume lava representing deep mantle water samples, yielded very low D/H ratios. (Figure 8)

• The melt inclusions PI-19 sampled from Baffin Island yielded the most negative δD out of all samples suggesting the more water-rich the deep mantle material is, the lower the deuterium concentrations.[6]

Conclusion

• Since early cometary density stratification now seems plausible as well as other mechanisms available to alter cometary and asteroidal surface compositions, it seems also reasonable that the D/H ratios we measure on comets and asteroids today, could have been lower in the past.

• If true, then the preferential sublimation of light-water (H_2O) originating from the surfaces of early comets and asteroids would likely have been the first volatiles adsorbed and accreted by olivine grains in the accretion disk, ultimately becoming part of the deep mantles of the terrestrial planets while the donating bodies not fully consumed by planetary formation processes would have enriched D/H ratios, like we see today.

• Since published research now suggests that comets and asteroids of current compositions do not match as primary water sources via direct bombardment, indirectly allows for cometary density stratification, and suggests olivine water adsorption as a likely mechanism for Earth forming wet, these allow the GMHA model to predict that primordial deep Earth mantle water should have a very low D/H ratio.

• In 2014, D/H ratios measured in olivine-bound melt inclusions in undegassed mantle-plume lava representing deep mantle water samples, yielded very low D/H ratios (Figure 8), allowing GMHA its first accurate prediction and further supporting the viability of the model.[6]

Future Work

• For GMHA to be a viable model of successive mechanisms explaining disparate D/H ratios, supporting adsorption of water onto olivine grains, wet model water accretion, and cometary density stratification, GMHA should be able to make four further predictions that warrant investigation:

1) D/H ratios in deep martian mantle material should be much lower relative to martian surface ratios, potentially similar to deep Earth mantle material since planetary formation was concurrent.
2) ^{18}O ratios should be higher on comets relative to Earth in general.
3) ^{18}O ratios should be lower in deep Earth mantle material relative to Earth's surface.
4) ^{18}O ratios should be significantly lower in deep martian mantle material relative to Mars' surface.

References

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