LULEÅ UNIVERSITY OF TECHNOLOGY

SOLAR SYSTEM PROJECT

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Are Comets the source of our water?

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Summary

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A simple introduction.

D (or HDO) ratio on Earth compared to Comet 67P/Churyumov-Gerasimenko: Are Comets the source of our water?

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2.1 Creation of asteroids and comets and their H/D Ratio

2.1.1 Creation of asteroids

In the Solar System, there are two main sources for asteroids and comets: the asteroid belt and the Kuiper Belt. The former is located between the terrestrial planets and the gas planets in a region that is often referred to as the snow line [1], while the latter is located further out than any of the known planets.
In the early states of the solar system, asteroids in the asteroid belt formed within the solar nebula. This process would not differ from the formation of the other planets were it not for the presence of Jupiter, the closest gas giant to the snow line. The gravitational forces and disturbances prevent the small planetesimals to form a planet. In addition to this, these disturbances could cause the asteroids to leave the asteroid belt and collide with other bodies in the solar system. [1]

2.1.2 Creation of comets

In the present solar system the comets encountered in the inner solar system usually originate from either the Kuiper Belt or the Oort cloud. However, it is likely that the comets were not originally formed there. For the formation of comets there are two plausible locations: either in the neighborhood of Uranus and Neptune or further out where the temperature was lower and the gravitational forces not as disturbing as in the vicinity of Uranus and Neptune. The low-density environment of the Oort cloud would not provide enough particles for the comets to form, so it is suggested that comets found in this region were formed somewhere else and then ejected into the Oort cloud. If comets were formed near Uranus and Neptune the comets would probably be absorbed by the planets or ejected onto hyperbolic trajectories rather than just being ejected into larger-distance orbits within the Oort cloud [2]. This leaves the most likely point of formation outside the orbits of Neptune and Jupiter [3].

2.2 Water distribution in the early states of the solar system and contribution to the formation of asteroids and comets

The early states of the Solar System with its hot inner core near the proto sun have mainly contributed to the fact that the only water-rich asteroids originally came from the outer asteroid belt and the Kuiper Belt. Up to 10 percent of their mass is water [4].
The possible areas where water particles can aggregate and therefore be found in bodies such as asteroids and comets as well as planets and planetary satellites are beyond the snow line that marks the area where H_2O only occurs as water ice and not as water particles or water vapor. Figure 1 shows the expected lifetime of pure and dirty ice grains depending on the grain size [5].

2.3 H/D ratio in comets and asteroids

The D/H ratio in comets and asteroids is linked to their formation region and therefore differs for various asteroids as well as comets from the Oort cloud and the Kuiper Belt and can be related to the D/H ratio in the solar nebula and the different planets. An overview of measured and estimated data is given in Figure 2
However, more recent observations of comet 103P/Hartley 2 have shown that it's H/D ratio is $(161 \pm 24) \times 10^{-6}$ and therefore significantly lower than estimated from previous measurements of other comets. This could be the case because the origin of 103P/Hartley 2 is not known for a certainty but it is believed that it could have originated in the Kuiper Belt, contrarily to a lot of other comets such as 1P/Halley who are widely believed to have originated in the Oort cloud. [7]

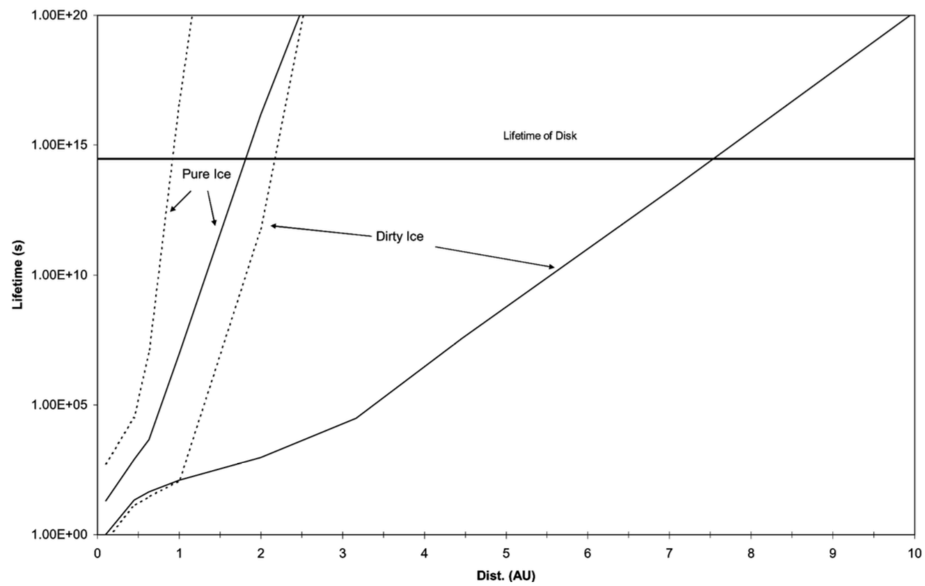

Figure 1: Comparison of lifetimes for pure and dirty ice grains. The dashed curves are for 0.1 μm grains and the solid curves are for 10 μm grains. The solid horizontal line shows a conservative upper limit to the age of the gas disk. [5]

For comets it has been suggested that the deuterium enrichment factor depends on the creation epoch of the comet which is different for Kuiper Belt comets and comets from the Oort cloud, due to different temperature scales and depends on the evolution of the solar nebula over time.
Using the enrichment factor f for water

$$f = \frac{1/2}{1/2} \frac{HDO/H_2O}{HD/H_2} \tag{1}$$

which quantifies the D/H ratio for a certain deuteriated species, in this case water. As mentioned above, the deuterium enrichment factor f depends on the temperature distribution of the isotopic exchange as well as the pressure distribution which is also temperature-dependent. The differential equation is given in Equation 2 [8]:

$$\partial_t f = \underbrace{k(T)P(A(T) - f)}_{\text{diffusion term}} + \underbrace{\frac{1}{\Sigma R} \partial_R (\kappa R \Sigma \partial_R f)}_{\text{exchange term}} \tag{2}$$

$A(T)$ is the fractation at equilibrium, P is the total pressure R is the heliocentric distance, $k(T)$ is the isotopic exchange, Σ is the gas surface density and κ describes the turbulent diffusivity which depends on the nature of the turbulence. Equation 2 can be split up in an exchange and a diffusion term, the former describes the dependency of the heliocentric distance while the latter describes the dependency on the temperature distribution.
This connection is displayed and compared with measurement data from various comets in Figure 3.
Meteorites with high D/H ratio are only those of the following two types: LL3 and carbonaceous chondrites. In both types, the insoluble organic matter shows elevated values of deuterium enrichment as well as clay minerals. The values obtained from the measurements of clay minerals can then be used to determine the D/H ratio of water because of the negligible isotopic fractionation between clay minerals and liquid water. [6]

D/H (10^{-6})	Species	Location	f	References
Galactic(6)				
20 to 50	H	Big-Bang (Theoretical)	-	Schramm, 1998
34 ± 2.5	H	Other Galaxy	-	Burles and Tytler, 1998
16 ± 1	H	Local Interstellar Medium	$\equiv 1$	Linsky *et al.*, 1993
110^{+150}_{-65}	H_2O	Hot Cores (HC)	7	Gensheimer *et al.*, 1996
1×10^{4} (10)	H_2O	Cold Interstellar Clouds (10 K)	625	Brown and Millar, 1989
$1^{+3}_{-0.2} \times 10^{3}$	OM(1)	HC in Interstellar Clouds (IC)	63	Pers. compilation(3)
$2^{+0.7}_{-1.8} \times 10^{4}$	OM(1)	Cold Interst. Clouds (<20 K)	1250	Pers. compilation(3)
950 ± 550	H_2O (Ice)	Cold Interst. Clouds (10 K)	60 ± 34	Texeira *et al.*, 1999
Proto Sun				
21 ± 5	H_2	Nebula 4.5 Gyrs ago	$\equiv 1$	Geiss and Gloeckler, 1998
Gaseous Planets(7)				
21 ± 8	H_2	Jupiter	$\equiv 1$	Lellouch *et al.*, 1996
26 ± 7	H_2	Jupiter	$\equiv 1$	Mahaffy *et al.*, 1998
15 to 35	H_2	Saturn	$\equiv 1$	Griffin *et al.*, 1996
$65^{+2.5}_{-1.5}$	H_2	Neptune	2.6	Feuchtgruber *et al.*, 1999
55^{+35}_{-15}	H_2	Uranus	2.2	Feuchtgruber *et al.*, 1999
Comets(7)				
310 ± 30	H_2O	Comet P/Halley	12.4	Eberhardt *et al.*, 1995
290 ± 100	H_2O	Comet Hyakutake	11.6	Bockelée *et al.*, 1998
330 ± 80	H_2O	Comet Hale-Bopp	13.2	Meier *et al.*, 1998a
2300 ± 400	OM(1)	HCN in Comet Hale-Bopp	92	Meier *et al.*, 1998b
Interplanetary Particles(7)				
91–4018	(?)(11)	IDP and AMM(12)	3.6–161	Pers. compilation(3)
Telluric Planets(7)				
149 ± 3	H_2O	Bulk Earth	6	Lécuyer *et al.*, 1998
16000 ± 200	H_2O	Venus (*Atmosph. in situ*)	640	Donahue *et al*, 1982
780 ± 80	H_2O	Mars (*Atmosph. in situ*)	31	Owen *et al.*, 1988
200–780	–OH	SNC (*Mars mantle*)	8–31	Watson *et al.*, 1994
LL3.0 and LL3.1 Meteorites(7)				
Interstellar compounds(8)				
730 ± 120	–OH	in Clays and Chondrules	29	Deloule and Robert, 1995
800–1100	OM(1)	in Kerogen - like in Matrix	32–44	Pers. compilation(3)
Protosolar water(9)				
88 ± 11	–OH	in Chondrules	3.5	Deloule *et al.*, 1998
Carbonaceous Meteorites(7)				
140 ± 10	–OH	Mean Statistical Value	5.6	Pers. compilation(3)
130<D/H<170 (66%)(2)				
380–620	OM(1)	Kerogen - like in Matrix	15–25	Pers. compilation(3)
(CM,CV,CR)(4)				
370 ± 6	OM(1)	Kerogen - like in Matrix	15–25	Halbout *et al.*, 1990
(Orgueil CI)(5)				
315–545	OM(1)	Amino Acids	12.5–22	Pizzarello *et al.*, 1991
185–310	OM(1)	Hydrocarbons and Carboxylic acids	7.5–12.5	Pizzarello *et al.*, 1991

Figure 2: D/H ratios of various objects in the solar system. [6]

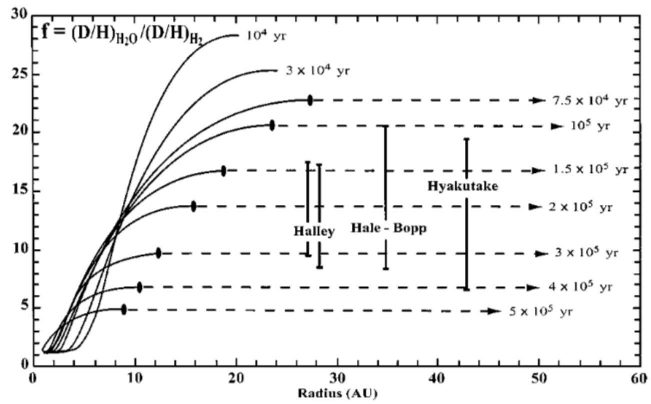

Figure 3: Calculated deuterium enrichment factor f in H2O as a function of the heliocentric distance R, at various epochs in years of the evolution of the nebula. Dots indicate the heliocentric distance where H2O condenses. Dashed lines correspond to the value of f in ices. D/H enrichments obtained in comets Halley, Hyakutake, and HaleBopp are shown for comparison. The location of comets is arbitrary. [9]

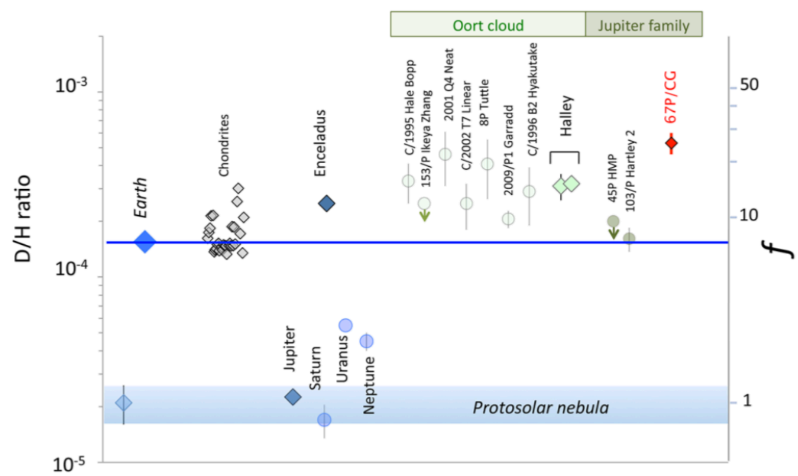

Figure 4: D/H ratios in different objects of the solar system. Diamonds represent data obtained by in-situ mass spectrometry measurements, and circles refer to data obtained by astronomical methods. [10]

2.4 Measurement data from 67P/Churyumov-Gerasimenko

67P/Churyumov-Gerasimenko is a Jupiter-family comet that probably originated in the Kuiper Belt. During the Rosetta Mission detailed measurements of the D/H ratio were conducted, resulting in a D/H ratio of $(530 \pm 70) \times 10^{-6}$, 3 times higher than the values found on Earth. Although 67P/Churyumov-Gerasimenko is expected to come from the same region of the Solar System as 103P/Hartley 2 (discussed in the previous section), they show significantly different values that suggest that the variety of Jupiter-family comets is greater than expected.

3 Water content of terrestrial planets after their creation

There is currently no perfect explanation of how the terrestrial planets gained water. The most common hypothesis is that water arrived later on those planets because the temperatures were too high. Therefore the planets accreted dry. This hypothesis is researched in this chapter together with the less famous hypothesis that the planets were accreted wet. For the latter one, also the possibility of holding on to this water is researched.

3.1 Formation of terrestrial planets in the early solar system

The terrestrial planets formed from the protoplanetary disk, a large, cold and slowly rotating cloud of gas and dust. The gas and dust sometimes collided due to gravitational forces. If the collisions where gentle enough the gas and dust would grow into a bigger object and eventually into a protoplanet. The gas consisted mostly of hydrogen, helium and oxygen, some of the hydrogen and oxygen combined to make water vapor [11, p. 523].

The amount of water vapor within 3 AU in the protoplanetary disk has been estimated at three earth masses [12] in 1994 and two earth masses [13] [14] in 2003. The mass of Earth is $5,9722 \pm 0.0006 \cdot 10^{27}$ g and the earth mass of all Earths oceans is $\pm 1,4 \cdot 10^{24}$ g. The amount of water inside the Earth is not exactly known, most estimations are around 10 Earth oceans with a extreme maximum of 50 Earth oceans [11, p. 523]. The water storage of Earth in minirals is about 5 - 6 Earth oceans [15].

If all four terrestrial planets accreted with 50 Earth oceans of water, then that would still only be 4,7% of the available water. There was probably enough water vapor in the early solar system to account for Earths oceans and the water on the other terrestrial bodies. The main problem is if the terrestrial bodies could hold on to this water during the formation of the protoplanets due to heat.

3.2 Water storage in terrestrial planets during formation

There are two main possibilities of water being stored, hydrated minerals and absorption onto grains. The water can be depleted by high temperatures and collisions. In this paragraph the storage is studied.

There are hydrated minerals observed in the mid-asteroid belt. Some were apparently heated to several hundred degrees Celsius. This is a confirmation that water was present at the early solar system and can be stored. The hotter an asteroid would have been, the less of these minerals are found. The chances of the terrestrial bodies holding on to water in hydrated minerals are pretty slim because the temperature of those planets were much higher than those of the asteroids [16].

There is also the possibility of water being absorbed by grains. Grains are small objects with a rough surface. The two forms of absorption that could have happened are physisorption and chemisorption [11, p. 523]. Physisorption is caused by the 'van der Waals force' which is $10 - 100$ meV $\approx 1,6 - 16 \cdot 10^{-21}$ J. Chemisorption involves a chemical reaction between the surface of the grain and in this case water. This force is stronger with $\approx 0,5$ eV $\approx 8 \cdot 10^{-20}$ J.

The effects of physisorption has been simulated by creating an Earth out of grains with a 100 times greater surface area than a spherical grain with the same volume. The finding were that with a temperature of 1000 K a quarter of Earths ocean could be absorbed. If the temperature would be 700 K than one Earth ocean would be absorbed and with 500 K three Earth oceans [17] [18].

If chemisorption is taken into account the force that keeps the water onto the grains will increase if there are multiple water molecules. How much it exactly contributes is unknown because tests are only performed at temperatures below 30 K. But it can be said that the force that keeps the water onto the grains will increase even at higher temperatures due to chemisorption [19].

As the grains collide with each other, some or all of the water will be lost depending on the impact. In the physisorption simulation they accounted for this, if two grains collided with a force greater than two times the total bond energy. In that case all water would be gone. If chemisorption was also taken into consideration the total amount of water that could be stored in the proto-Earth would increase [17] [18].

3.3 Water loss in terrestrial protoplanets

The early terrestrial planets probably melted one or multiple times while being accreted, probably from multiple major impacts, of which one created the moon. This means that there where magma oceans at some point in their lifetimes, before reaching their final solid state. [20].

These magma oceans could have played a key role in delivering volatile elements into the growing atmosphere through degassing. For this to happen the magma ocean should have been over saturated by these elements and there was no boundary layer for these elements [21, p. 128-129].

As the interior gained more heat the volatile elements broke down and formed bubbles that were being transported to the exterior. The melted material would become drier because most volatile elements would migrate to the atmosphere. Most of the big impacts would take away some of the Earths atmosphere but it could also bring other materials to Earth. The impacts would create more heat in the interior and the process of volatile elements out gassing continued until the interior was completely dry [21, p. 130-131].

Due to the heat there could not be any oceans on Earth, but the Earth was massive enough to keep most water vapor in the atmosphere. After the Earth cooled down this vapor could condense and become Earths first oceans. Through plate tectonics and volcanic activity more water could be transported from inside the Earth to the oceans [21, p. 130-131].

3.4 The current D/H ratio of terrestrial planets

The distribution of the D/H ratio through the solar system can be seen in figure 5. It's clear that how further away from the sun, the higher the D/H ratio. Mars has a D/H ratio which is 7 times larger and Venus has a D/H ratio which is 150 times larger. The latter one is a discrepancy because Venus is closer to the sun than Earth. It's possible that Venus got more water from comets from far way in the solar system. This confirms that the origin of water is from comets. Another explanation is that the ultraviolet radiation from the sun breaks water molecules into H and OH, the lighter gass will escape into space. It is possible that Venus lost an oceans worth of water but Earth did not because Earth was too far from the Sun for the instability to develop [22].

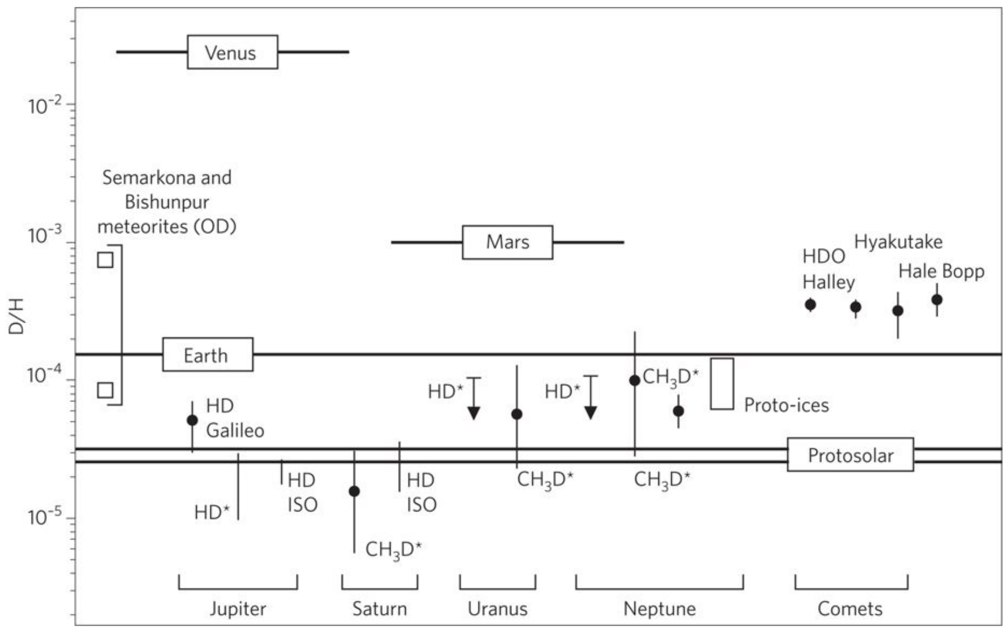

Figure 5: D/H ratio in the solar system [22].

4 The bombardment of Earth

There are differing trains of thought on the timing, how and where the Earth received its water. The possibilities where water could come from are either through internal reserves acquired during the accretion process or from extraplanetary sources after Earths development. These extraplanetary sources of water would have come from asteroids, comets and protoplanet collisions. The hypothesis that concerns these objects delivering water to a developed and dry Earth is referred to as the late bombardment hypothesis. The hypothesis that Earths water comes from extraplanetary origins is not flawless and has controversy. There is another hypothesis where the water was accumulated during the Earths accretion development. This hypothesis is referred to as the Accretion Model. These are the two base theories about the origin of Earths water. There are other theories which are derived from the base theory with changes. These hypotheses have evolved over time to account for previously unknown scientific data.

The late bombardment hypothesis has been addressed by different names such as Late Veneer, Late Bombardment Hypothesis, Late Accretion, and Late Heavy Bombardment: for consistency within this report, this hypothesis will be referred as Late Bombardment Hypothesis or LBH. The late bombardment hypothesis has variations that cover the various objects that could deliver water to the Earth as well as the influences of different planetary orbits. The various objects included are comets, asteroids and planetesimals. This hypothesis was first noted by Hopp[23] but not named as such in an article from Kimura et al. concerning the discrepancy in gold distribution [24]. However, another article from Maruyama [25] report that another article written by E. Anders [26] first came up with the theory. The start and progression of this theory concerns the siderophile elements and their distribution within the Earth. The elements include tungsten, ruthenium, gold, osmium, iridium, and more elements [27] [28] [29]. These reports on the different elements shows the gathering of data for this hypothesis. The late bombardment hypothesis has contending views on the origin of Earths water. The most popular to least popular opinions are asteroids, comets and then planetesimals. There are reports and articles [30] [31] [32] that highlight the differences between the sources as well as likelihood and the effects coming from the different sources. The most commonly discussed of these sources are the carbonaceous chondrite asteroids. The asteroids are the viewed as the most likely source of the Earths Water in the late bombardment hypothesis.

The hypothesis that states that Earth had contained water while formation was occurring is known as the Accretion Model. This theory also has other names such as Wet Earth and Cool Earth, for consistency and clarity. This hypothesis will further be addressed as Early Accretion Model, to distinguish itself from the previous hypothesis. This model has been proposed in opposition to the late bombardment hypothesis. This hypothesis was started because of the isotopic differences between Earth and extraplanetary objects. The hypothesis is based on the accretion of volatile elements and water in grains of dust and being able to retain them during the development of the planet. The developments in the hypothesis comes from showing that water can be absorbed into different materials at high temperatures of the accretion disc. There has been a study showing that olivine can be hydrated in high temperatures [33] [34]. A new article [35] discusses evidence that there was significant water before the collision that formed the moon, which is before the time period of the LBH. This hypothesis has not been as deeply researched as the late bombardment hypothesis has been.

The main two hypotheses are the late bombardment hypothesis and the early accretion model. The late bombardment hypothesis says that Earth was formed dry and received water and volatiles from extraplanetary sources. This model dismisses all claims from the early accretion model concerning the possibility of the Earth forming wet. The early accretion model does not preclude the late bombardment hypothesis, however does severely limit the amount of water accumulated from extraplanetary sources. There is agreement on our knowledge of detail of terrestrial planet formation and hydration is currently insufficient [36].

4.1 Main 2 - Late Bombardment Hypothesis

4.1.1 Section 1 - Comets

Par 1 - Intro
Par 2 - Calculations and probability for needed quantity to reach earth
Par 3 - Any other side notes or
effects on Earths composition
Par 4 - Controversy, short comings and failures
Par 5 - Conclusion

4.1.2 Section 2 - Asteroids

Par 1 - Intro -
Par 2 - Calculations and probability
for needed quantity to reach earth
Par 3 - Any other side notes or effects on Earths composition
Par 4 - Controversy, short comings and failures
Par 5 - Conclusion

4.1.3 Section 3 - Planetesimals

Par 1 - Varieties, starting locations, general compositions and ratios, hydration levels
Par 2 - Calculations and probability for needed quantity to reach earth
Par 3 - Any other side notes or effects on Earths composition
Par 4 - Controversy, short comings and failures
Par 5 - Conclusion

4.1.4 Section 4 - ABEL Model

Par 1 - Comparison to the other Late
Bombardment Hypothesis methods
Par 2 - Implications of the model
Par 3 - Controversy and shortcomings

4.2 Main 3 - Early Accretion Model

Section 1 Accretion Theory
Par 1 - Intro
Par 2 - Reiterate possibility of keeping water
Par 3 - Evidence for some accretion
Par 4 - Controversy, short comings and failures
Par 5 - Conclusion

4.3 Main 4 - Conclusion

Par 1 - Reiterate D/H Ratios
Par 2 - Which theories can account for the D/H Ratio
Par 3 - Try to reconcile the two theories
Par 4 - Conclusion

5 Earths atmosphere compared to comets & asteroids

D/H ratio and atmosphere ratios (like xenon and nitrogen)
Probably going to be deleted

6 Conclusion

7 Recommendations

What can we do/measure to get more information about the origin of water.

Create simulations of water being absorbed by grains that takes into account both physisorption and chemisorption at reasonable temperatures.

It is not clear if the giant collision that resulted in the formation of the moon led to a major loss of volatile elements or even contributed to it.

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