The Delivery of Water to Terrestrial Planets: Earth and Mars

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A. Morbidelli et al. – Source regions and timescales for the delivery of water to the Earth

and

J. Lunine et al. – The origin of water on Mars

Motivation

- Astrobiology – On Earth, life follows water
- Geochemistry – Many geological processes on Earth are modulated by water content (e.g. Grove et al. 2009 Nature)

Subduction zone volcanic arc magmas form at depth due to the water content of subducted slab rocks (Grove et al. Nature 2009)

More Importantly...

Historical Model – Late Veneer Scenario

- Comets deliver water from the outer solar system
- Posited since water content decreases as distance to the Sun decreases
- Innermost asteroid belt is already lower in water content than Earth (0.05-0.1% at ~2AU)

Most water must come at the end of the accretion phase since some water content will be lost during the accretion process.

Problems with the Late Veneer

- Deuterium-Hydrogen ratio in comet ices is twice that of the Earth
- Mantle oxidation suggests that water was present during early stages of formation
- A bit of a Goldilocks problem – too little water, and the oxidation can't be explained, too much and core-mantle element partitioning doesn't work

D/H ratio is very important and serves as the primary test of the model presented

Primary Questions

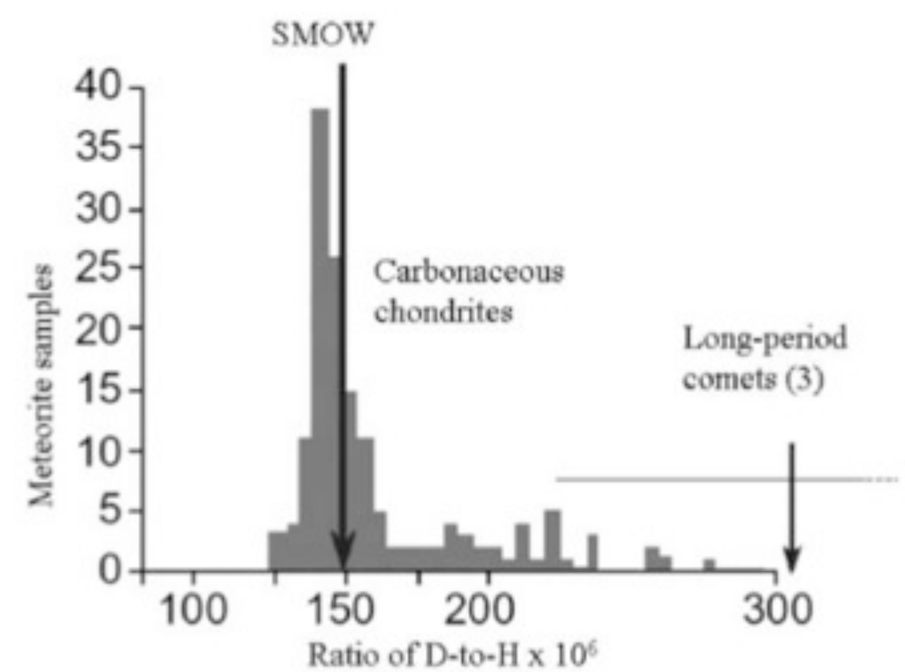
- Where did the Earth's water come from?
- When was the Earth's water delivered?

Elements

TABLE 1. Geochemical data for some volatile elements.

Object*	H_2O (ppm)	Ne (mol/g; $\times 10^{-13}$)	Xe (mol/g; $\times 10^{-16}$)	D/H ($\times 10^{-6}$)	$^{20}Ne/^{22}Ne$
Mantle†	80–800	–	–	145	13.2
Atm.+Sed.‡	280	5.00	1.1	153	9.80
Bulk§	360–1080	–	–	149 ± 3	–
C.C.#	1×10^5	160 – 250	300 – 500	128 – 180	8.9 – 9.6
Comets$	5×10^5	–	–	309 ± 20	–
Protosolar@	–	–	–	25 ± 5	13.8

*Atm.+Sed. stands for atmosphere and sediments (including the ocean) and C.C stands for carbonaceous chondrites. The abundances of water, Ne, and Xe in the mantle and in Atm.+Sed. are expressed as concentrations with respect to the total mass of the Earth.
†Kerridge (1985), Sarda *et al*. (1988), Deloule *et al*. (1991), Franchi *et al*. (1993), Cartigny *et al*. (1997, 1998).
‡Ozima and Podosek (1983), Marty and Humbert (1997), Lécuyer *et al*. (1998).
§Kyser and O'Neil (1984), Bell and Rossman (1992), Marty (1995), Marty and Humbert (1997), Lécuyer *et al*. (1998).
#Boato (1954), Mazor *et al*. (1970), Kerridge (1985), Robert and Epstein (1982).
$Jessberger *et al*. (1988), Meier *et al*. (1998), Bokelée-Morvan *et al*. (1998).
@Geiss and Gloecker (1998).



Executive Summary: Carbonaceous Chondrites have nice D/H ratio.
CC are 10% water, comets are 50%
Deep mantle rocks indicate proto-mantle D/H < 138E-6
Difficult to imagine it lower than current CC D/H – Not much water interior of CCs that would have a lower D/H ratio

Primary Model – Delivery Via Asteroid Belt Depletion

- Use a Mercury integrator model with simulation techniques of Wetherill & Chambers / Petit et al.
- Similar to Raymond et al. (2007) simulation
- Requires 10x current asteroid belt to be accreted by Earth. But, ~10^2-10^3x more asteroid mass in the past.

Very similar to Teresa's Raymond et al. paper
10^2-10^3 -- reconstruction of primordial surface density from material in planets, accretion of largest asteroids on timescale ~ with meteoritic solidification age.
Can't deplete via asteroid collisions -- fragile shells like vesta wouldn't survive -> scattering

Aside – Symplectic Integrators

- Simply refers to a mathematical property of the integrator
- Conserves the quantity dp∧dq (outer product) from Hamilton's equations
- As a result, conserves H, but with H(t) slightly perturbed from H(0)

That's a bunch of differential topology hoo-ha, but the upshot is that it conserves the energy of the system
ref: $dp = -\partial H/\partial q$, $dq = \partial H/\partial p$
symplectic from symplectomorphism

Initial Embryo Distribution

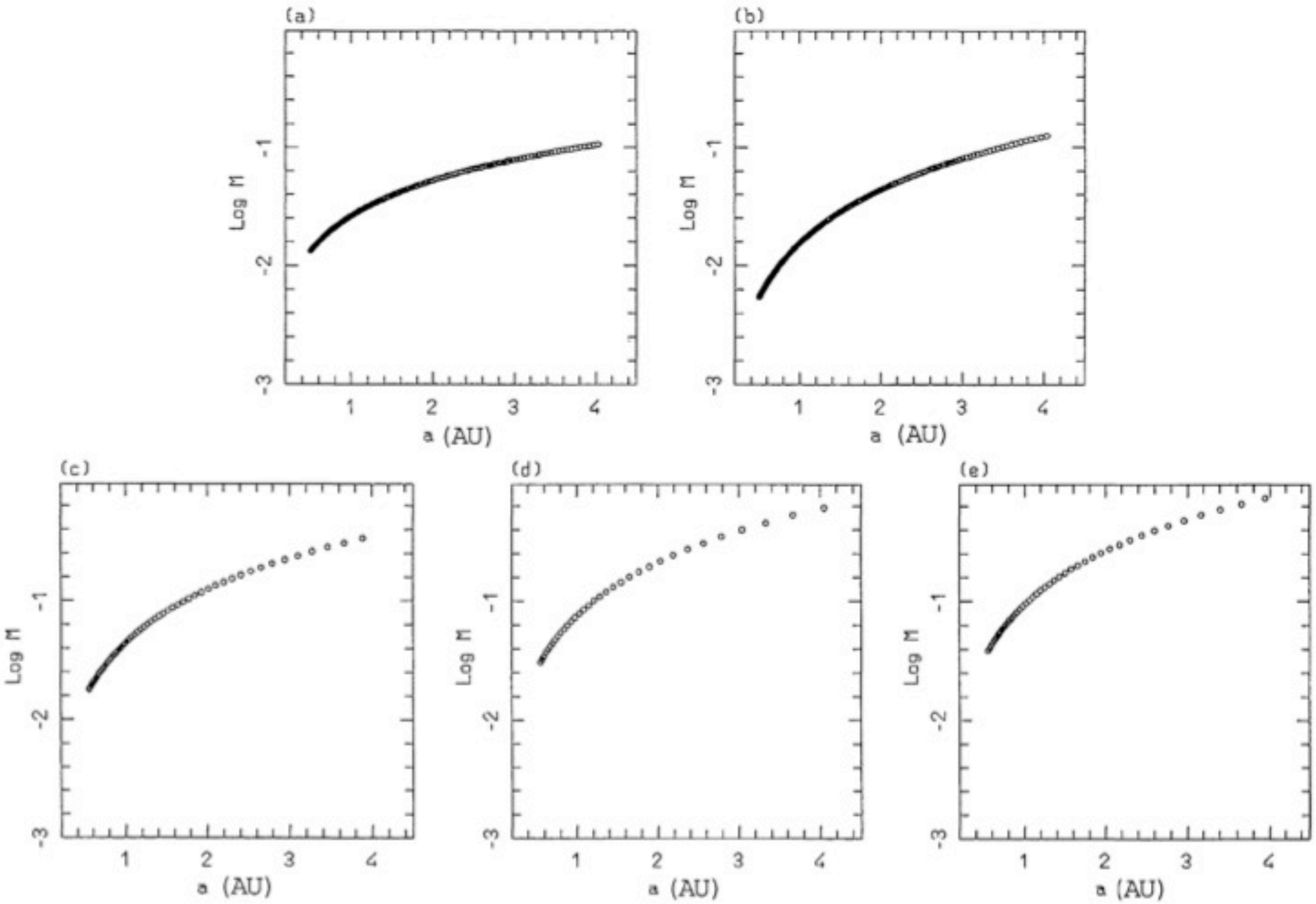


FIG 2. The initial mass distribution of the planetary embryos in the different simulations. M is expressed in Earth masses. The total mass is 6.6 $M_{\oplus}$ in (a) and (b), 5.0 $M_{\oplus}$ in (c), 5.5 $M_{\oplus}$ in (d) and 8.6 $M_{\oplus}$ in (e).

Simulation Snapshots

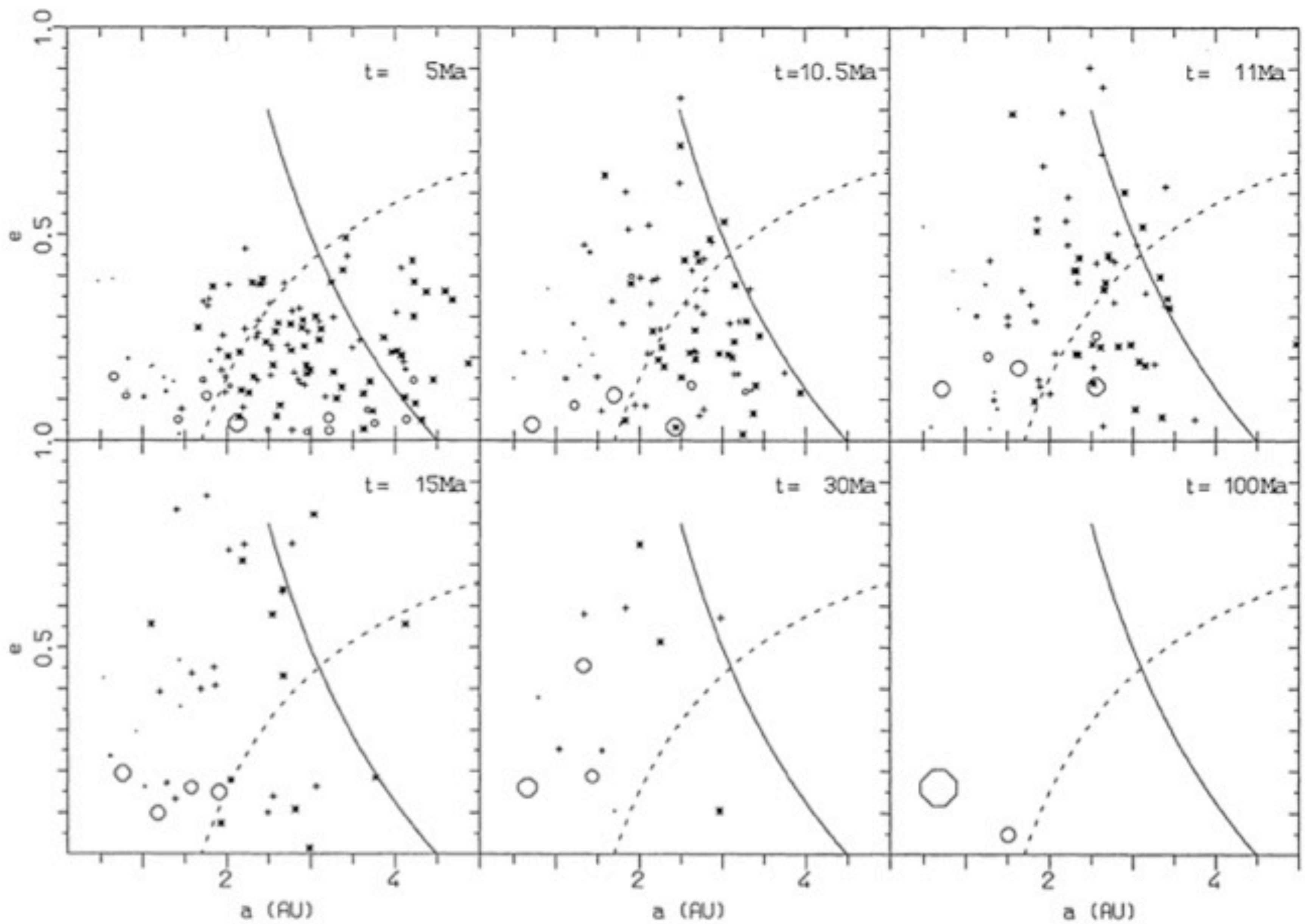


FIG. 1. Snapshots of the orbital distribution of the asteroids and of the planetary embryos. Asteroids are denoted by crosses if their initial semimajor axis was between 2 and 2.5 AU, and by asterisks if their initial semimajor axis was beyond 2.5 AU. The embryos are denoted by open circles, whose size is linearly proportional to their mass. Initially both embryos and asteroids have quasi-circular and coplanar orbits. The initial mass distribution of the embryos is shown in Fig. 2c. The solid and dash curves refer to $Q = 4.5$ AU and $q = 1.7$ AU and basically mark the boundaries of the present-day asteroid belt. A full-mass Jupiter is introduced in the simulation at 10 Ma. Notice that before 10 Ma the asteroids orbits are excited, but just a few asteroids are outside the boundaries of the present-day belt. Only a minority of those with initial semimajor axis beyond 2.5 AU reaches small semimajor axis. When Jupiter is introduced, the excitation becomes larger, and the belt is rapidly depleted. At 30 Ma there is just one asteroid out of 100 left in the belt, and at 100 Ma no asteroids are left. The complete depletion of the belt is an artifact of the limited number of integrated asteroids (100). In fact, Petit *et al.* (unpubl. data, 2000) find that seven asteroids out of 1000 stay in the belt at the end of the simulation. At 100 Ma, two terrestrial planets are left, in stable configurations. The largest planet has a mass equal to 1.39 $M_\oplus$ and a semimajor axis of 0.7 AU; we refer to this object as the "Earth". The smallest one has almost exactly Mars' orbit, but has a mass equal to half an Earth mass.

no asteroids out of 100 left, when using 1000, 7 left
black line - Q = 4.5 AU, dotted - q = 1.7 AU (present day asteroid belt)

Embryo Simulation Results

TABLE 2. Summary of the results of 11 simulations of Earth's accretion.*

Embros dist.	N (a >2.5 AU)	M (a >2.5 AU)	T at accretion	M at accretion
a	2	9%	68.5	100%
b	2	12%	82.9	85%
c	1	17%	34.0	96%
c	1	15%	65.3	68%
c	1	21%	46.8	90%
d	1	11%	121.1	78%
d	1	25%	0	–
d	3	47%	0	–
e	1	49%	0	–
e	1	36%	106.3	100%
e	1	35%	0	–

*The first column reports which panel of Fig. 2 shows the corresponding initial distribution of the embryos; the second column indicates the number of embryos originally located beyond 2.5 AU that are accreted by the Earth; the third column shows which fraction of the final mass of the Earth has been accreted from these presumably primitive embryos; the fourth entry gives the time (in millions of years) at which the last primitive embryo is accreted (when the time is 0 it means that the primitive embryo has played the role of "accretion seed"–see text for definition); the fifth column shows what fraction of its final mass the Earth has attained with the accretion of the last primitive embryo.

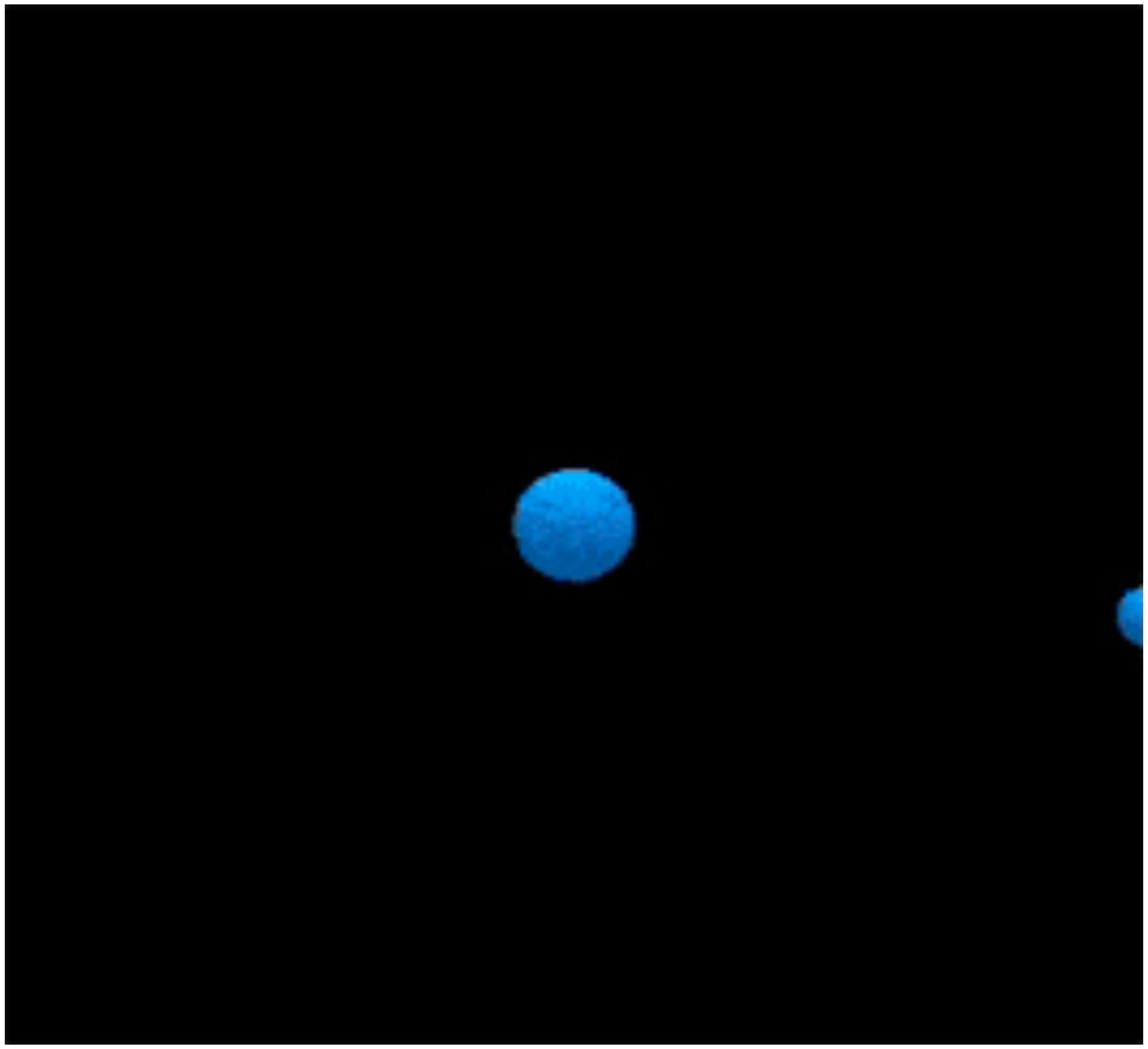
Col 2 is number of embryos accreted from beyond 2.5 AU (CC; water-rich)
Col 3 is % mass accreted from CC range
Col 5 is % mass accreted just prior to final accretion

Embryo Simulation Results

- Scattering-driven asteroid depletion gives a terrestrial D/H ratio and carbonaceous content via standard accretion
- Water delivery via >2.5 AU embryos occurs late, so chance of the water being retained increases

Killed two birds with one stone -- asteroid belt is depleted and the Earth gets water, all just from dynamics

Hit-and-Run Collisions



Animation by G.J. Taylor – Hawaii Institute of Geophysics and Planetology

This process is certainly not 100% efficient though.
Oblique collisions provide another possible way of decreasing efficiency...

Potential Problems

- Few impacts, so small-number statistics
- Differentiation
- Retention efficiency – unaddressed, but 10% mass from CC-like material with 10% water gives $10^{-2}M_{\oplus}$ delivered, ~50x more than the estimated water mass of early Earth

Differentiation was a big question mark. Ceres isn't, but Vesta is, so it doesn't appear to be simply mass.

Simulation of Asteroids

- Assumed to be negligible mass, and non-self-interacting (“test particles”)
- Calculate orbital elements for a few hundred, use them as tracers to determine what fraction of the total population would collide with Earth

Smaller than embryos, but use the results of embryo simulation

Asteroid Simulation Results

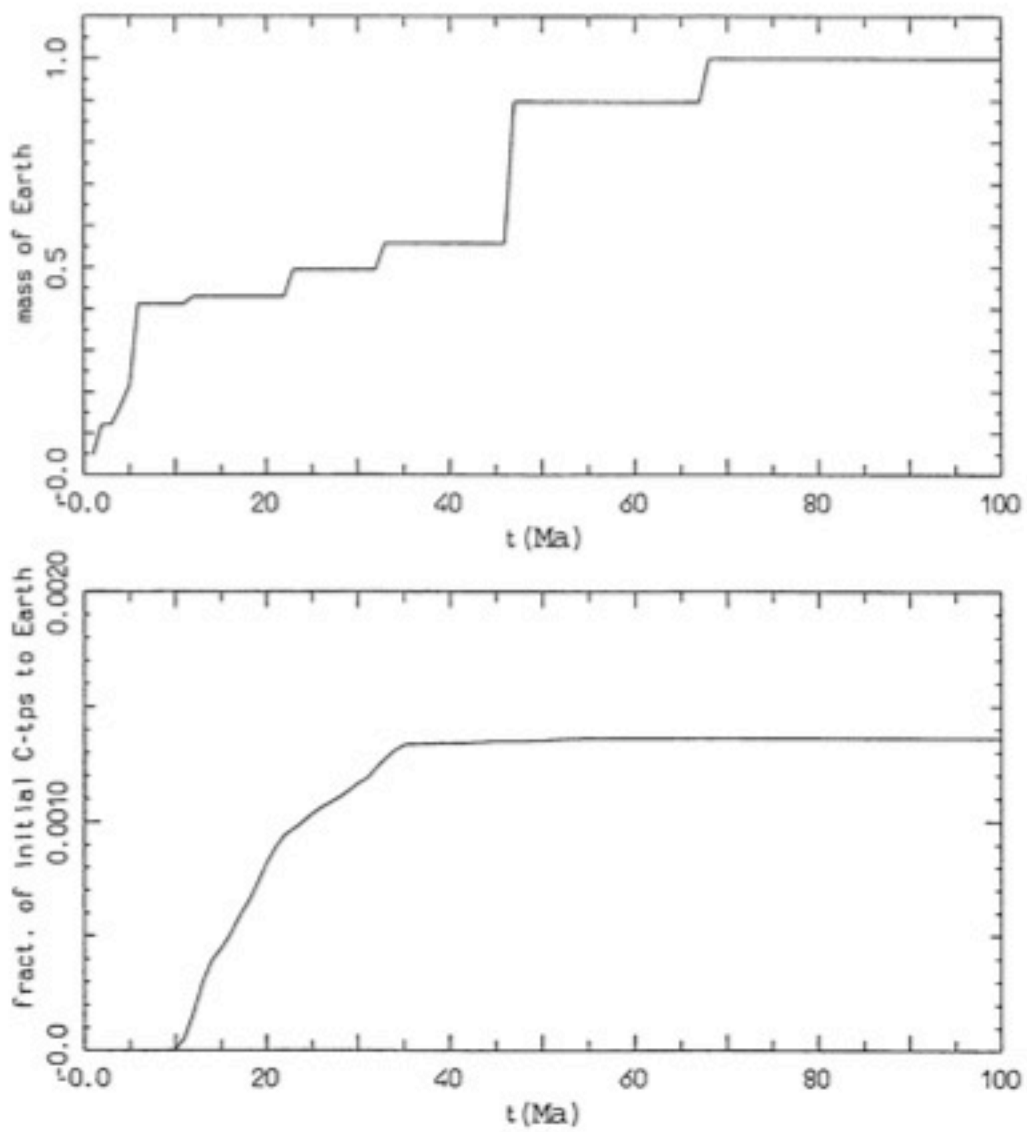


FIG 3. Top: The mass of the Earth as a function of time in the simulation shown in Fig. 1. The mass is normalized to the final mass. Bottom: The cumulative mean collision probability with the forming Earth (the $P(t)$ defined in the text) for the asteroids initially beyond 2.5 AU in the same simulation. Notice that the cumulative collision probability saturates at a time when the "Earth" has not yet accreted 60% of its final mass.

- Jupiter forms at 10 Ma, collision probability immediately goes up
- Collision probability stops increasing at ~50% total mass
- Assuming 100% efficiency, need $4M_{\oplus}$ beyond 2.5 AU

Using same statistical method for embryos yields same results as in Table 2 -- so seems like it's actually the different dynamics of small vs. larger bodies that causes the difference
4 earth masses beyond 2.5 AU is the high end of the current estimates.
Much of this water was likely lost in later giant collisions though

Other Possible Models

- Resonance sweeping, sweeping with gas drag, dust delivery
- Sweeping needs too much ($10M_{\oplus}$) mass
- Dust delivery requires very late depletion of the asteroid belt

Late depletion is contra-indicated by models as well as by Vesta

Sweeping With Gas Drag

- Sweeping with gas drag must happen between Jupiter formation and nebula dissipation
- Probably a small non-zero contribution, but not much since this time period is probably short

Jupiter formation to nebula dissipation time is probably quite short, plus bodies arrive too early

Water From Comets – Jupiter-Saturn Region

- Simulate comets as test particles using current solar system configuration and asteroid method from before
- Dominated by scattering from Jupiter and Saturn
- Authors argue that scattering “should be” insensitive to variations in Saturn’s position, but don’t demonstrate this

i.e. migration insensitive
it turns out we don’t care much about the last point, due to the next slide

Water From Jupiter-Saturn Comets – Results

- Jupiter-Saturn comets have very short (~10^5 yr) lifetimes
- Total amount of water delivered is only 2-20% of current Earth's water, and it arrives at ~10Ma, when the Earth is still small and young
- Likely can't provide significant retained water

Since they have such short lifetimes, they all scatter shortly after Jupiter forms (ie the 10Ma)

Water From Comets Beyond Uranus

- Total water contribution of ~10% of Earth's total, as an upper limit (100% efficiency, 100% water content)
- Most arrive quite late (10^6-10^8 yr), so retention of their water is more likely
- D/H ratio supports this, since long-period comet D/H ratios are 2x larger than the Earth's

Comets float around for 10^6-10^7 years before encountering a planet, after which time they are kicked out within several million years
half-life of trans-neptunians is 10^8 years AFTER first encountering it

Predicted Comet Water Contribution via D/H Ratio

- $F_C \leq (149-128)/(309-128) = 0.12$, i.e. 12% maximum contribution from comets
- Matches well with the model, which predicted an upper limit of 10% from Neptune-Uranus comets, and perhaps a few percent from the Jupiter-Saturn region

Difference between current and primitive values, divided by difference between cometary and primitive values

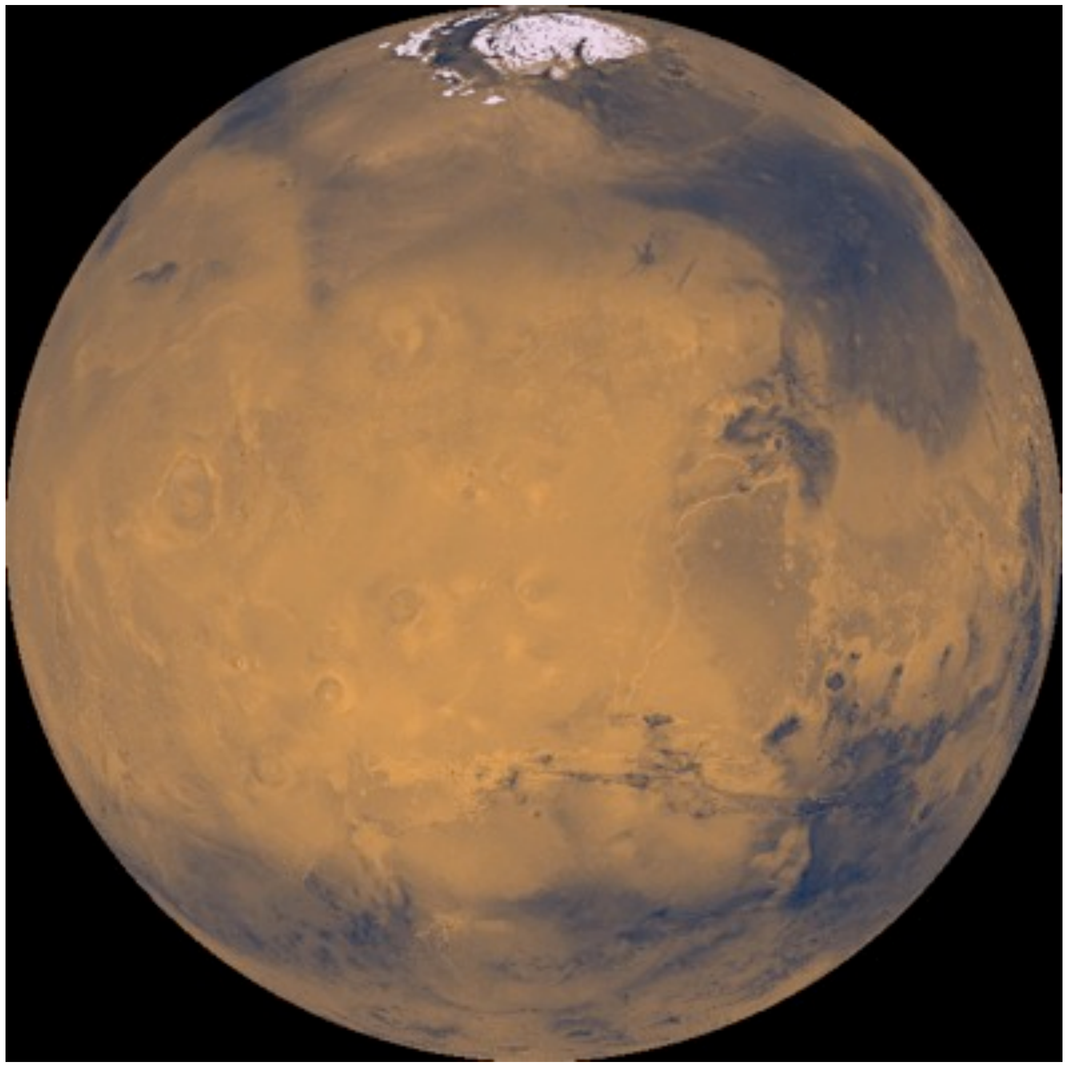
One Small Problem – An Excess of Neon

- The Earth has 8-10x more Ne than would be expected from chondritic materials
- Authors propose capture from solar nebula, then fractionation, followed by mixing with chondritic material, but don't really do the topic justice

Conclusions

- Earth accreted water throughout its history
- Initial dose from asteroids via gas drag
- Most comes from distant-formed embryos near the end of formation
- Around ~10% is delivered via comets in a late veneer phase, the only high D/H water

Mars – A Slight Contrast



- The current size of Mars means it cannot have suffered giant impacts
- Primary source of Earth's water (large embryos) thus doesn't apply

The Setup

- Analyzed same Mercury integrator runs from previous paper
- Determined none of the planets represents a "Mars" since they all have at least one large impact
- Calculate collision probabilities for asteroids and comets as before

Doesn't use gravitational focusing, as the Earth model from the first paper did.
That is, presumes Mars' small mass won't be enough to collect nearby things that aren't on collision courses.

Collision Probabilities

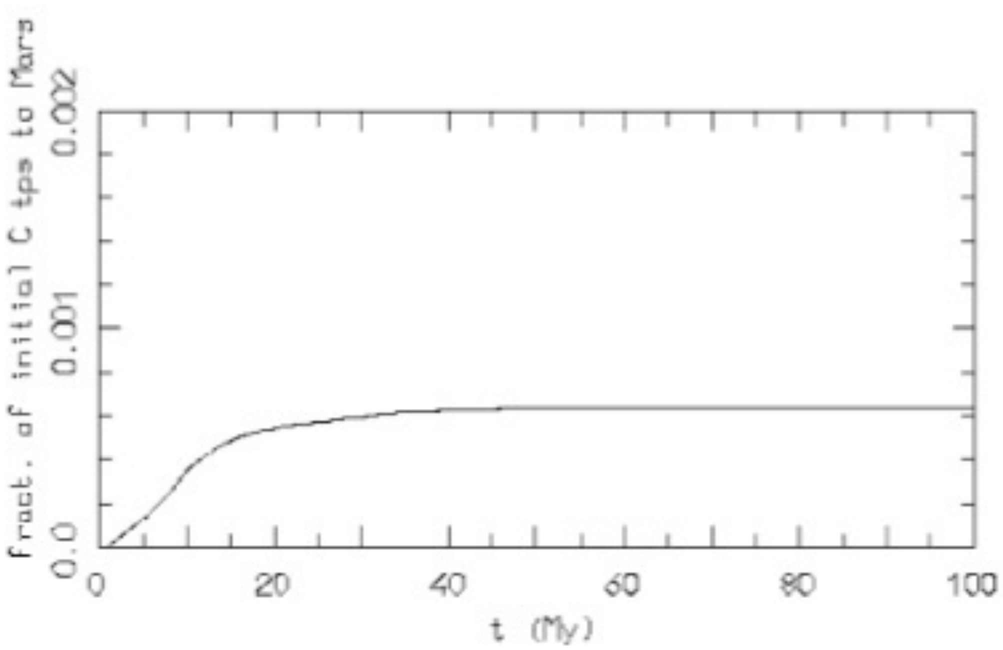


Fig. 3. Collisional history of water-laden asteroids (those bodies with initial semimajor axis between 2.5 and 4 AU), expressed as the cumulative fraction of such "C-type" asteroids accreted by Mars versus time in millions of years.

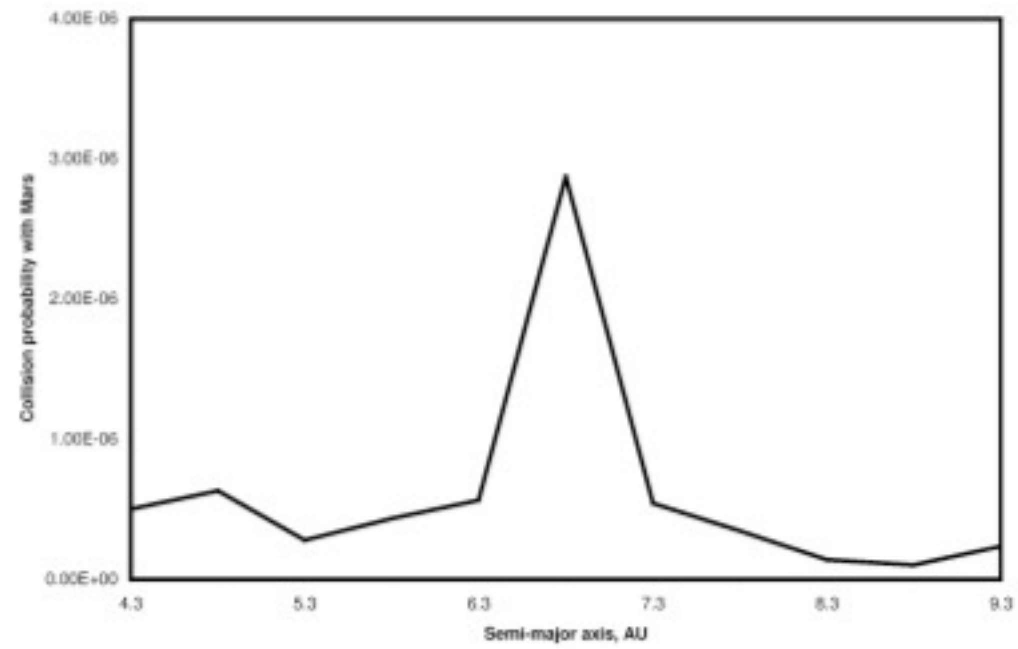


Fig. 4. Probability of collision with Mars of comets as a function of their initial semimajor axes. The calculation that generated the figure had semi-major axes binned in 0.5 AU intervals. Beyond 9.5 AU, the impact probability is taken to be constant; inward of that radius the impact probability is obtained as described in the text.

The Upshot

- Mars acquires more water from comets and small asteroids than the Earth does, but receives none from large embryo impacts
- Most accretes as a late veneer – early accretion would bind to core iron and leave too little to fractionate into the atmosphere D/H ratio we observe today

Scale heights of D and H water are different -- H water gets high enough to be dissociated and then escape. Causes overabundance of D in the atmosphere

Questions?

Another good paper: Raymond et al. 2007b