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Compound model using D/H ratio to explain water's origins of Earth-like planets

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ABSTRACT

The origin of water on Earth and other terrestrial planets remains one of the most important subjects of debate and controversy in Solar System formation science. Comets were long considered the most likely source of water, but chemical measurements in three comets indicated a maximum of 50 per cent on the cometary contribution to Earth's water. Other sources have been proposed and some of them became more prominent, such as local absorption onto grains and asteroids. However, no sole source of water provides a satisfactory explanation for Earth's water as a whole. In view of that, we created a compound model incorporating both the principal endogenous and exogenous theories, and investigate the implications with dynamical simulations of planetary formation and water delivery. Comets are also considered in the final analysis, as it is likely at least some of Earth's water has cometary origin. We analyse our results using D/H ratio as a discriminator, giving possible relative contributions from each source, focusing on embryos formed in the habitable zone of the main star. The goal is to identify the sources of terrestrial planets' water in the Solar System and expand it to extrasolar systems. We conclude that the compound model better explains the D/H ratio of Earth's water, as well as expected values of mass and water content for Earth-like planets.

Key words: Solar system: formation, Earth, planets and satellites: formation, astrobiology, methods: N-body simulations

1 INTRODUCTION

In its gaseous and solid forms, water is present in distant galaxies, among stars, in the Sun, in its planets and their satellites and ring systems, and in fcomets. In its liquid form, it has played an essential part in the appearance, development and maintenance of terrestrial life. The question of how terrestrial planets form and how they get water has been heavily discussed in the last few years. According to the most accepted theory of planetary formation, the protosolar nebula was hotter and denser toward its centre and cooler and less dense farther out (Encrenaz 2006). These gradients influenced the chemical composition of different regions of the early solar system, including the distribution of water. Close to the nebula's centre, high temperatures and pressures vaporised ice crystals and the light elements. The solar wind blew these materials toward the outskirts of the nebula, leaving mainly grains of rock behind to form the inner planets. Farther out, debris formed the carbonaceous chondrites that carry up to 10 per cent of their mass in water ice (Morbidelli et al. 2000). Beyond the giant planets, water condensed in large quantities and formed comets, which are up to 80 per cent of water (Jessberger, Kissel & Rahe 1989). Compared with these icy objects, Earth contains little water: only about 0.02 percent of its mass in its oceans, and somewhat more water sits beneath the surface. Nevertheless, Earth has substantially more water than could be expected at 1 AU from the Sun: the minimum value is 1 $O_\oplus$, the maximum value of 50 $O_\oplus$, and an expected value would be ~ 10 $O_\oplus$ (Drake & Campins 2006). Many models trying to explain Earth's water have been proposed over the years (*e.g.* Morbidelli et al. (2000), Raymond, Quinn & Lunine (2004), Stimpfl, Lauretta & Drake (2004), O'Brien, Morbidelli & Levison (2006)) basing on available evidence. Suggested sources can be divided into endogenous and exogenous, and include mainly water absorbed by dry silicate grains in the nebula, asteroids and comets. These different sources may be distinguished by their deuterium-to-hydrogen (D/H) ratio and others isotopic differences, and by predictions of their relatives amounts of water and mass (Lunine 2006). The following sub-sections describe the most

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Table 1. D/H ratio values for comets, nebula gas and Earth.

Body	D/H Ratio	Reference
Halley	$3.2 \pm 0.1 \times 10^{-4}$	Eberhardt et al. (1995)
Hyakutake	$2.9 \pm 1.0 \times 10^{-4}$	Bockelee-Morvan et al. (1998)
Hale-Bopp	$3.3 \pm 0.8 \times 10^{-4}$	Meier et al. (1998)
Nebula	$2.1 \pm 0.4 \times 10^{-5}$	Lellouch et al. (2001)
Earth	$1.49 \pm 0.03 \times 10^{-4}$	Lecuyer, Gillet & Robert (1998)

accepted sources for Earth's water, from which it is possible to get an indication of how any terrestrial planet can become aqueous.

1.1 Comets

Comets were long considered the most likely source of water for terrestrial planets in the Solar System. A cometary source was attractive because it is widely believed that the inner Solar System was too hot for hydrous phases to be thermodynamically stable (Boss 1998) and thus an exogenous source of water was needed (Drake & Campins 2006). Drake & Righter (2002) affirm that recent data, for elemental and isotopic reasons, limit the cometary contribution for Earth's water to 50 per cent, and the true value is probably nearer to 10–15 per cent. Measurements of the D/H ratio of water in three Oort Cloud comets are about twice the value of Earth's water and about fifteen times the value of the solar nebula gas (Table 1).

Gomes et al. (2005) calculated the cometary material delivered to Earth to be $\sim 1.8 \times 10^{23}$ g, which is about 6 per cent of the current terrestrial ocean mass ($O_{\oplus} = 1.4 \times 10^{24}$g). Based on noble gas ratios, Swindle & Kring (2001) argue that comets could not have supplied any significant fraction of Earth's water, unless it occurred in the first 100 Myrs of Earth's history, or came from comets unlike those coming from the Oort cloud today. However, Ipatov & Mather (2006) analysed the orbital evolution of Jupiter-family comets (JFCs), Halley-type comets (HTCs), and long-period comets, and the probabilities of their collisions with planets. They found the probability of collisions of former JFCs with the Earth was enough to deliver all the water to Earth's oceans during formation of giant planets.

There are some discussions as to which measured D/H ratio values in comets are representative of their real bulk composition. Since the primary source of information about comets continues to be studies of the coma, Schmidt, Brown & Lauretta (2005) argue that it is necessary to understand the relationship of the coma with the bulk ice. Weirich, Brown & Lauretta (2004) affirm that the D/H ratio would be expected to rise in diffusion and sublimation, and Schmidt et al. (2005) did an experimental study of comet sublimation in which was observed an upward trend in the D/H ratio in the evaporated material independent of the bulk composition.

Drouart et al. (1999) suggested that comets are likely to retain the isotopic composition they acquired when they formed and for that it is possible to use them to differentiate among different models of planet formation. Horner, Mousis & Hersant (2007) used observed comets properties to determine their formation regions. Using a deuterium-enrichment profile, which offers a relationship between D/H ratio incorporated in the water within planetesimals and their formation location in the solar nebula (Drouart et al. (1999), Mousis et al. (2000), Hersant, Gautier & Huré (2001)), they examined the possible effect that formation in different regions could have on the values of D/H ratio in comets today.

1.2 Asteroids

When a cometary contribution for Earth's water was contested by measurements of D/H ratio values, hydrated carbonaceous asteroids coming from the Primordial Asteroid Belt became a more likely source for terrestrial planets water. The D/H ratios of the individual carbonaceous chondrites range over the interval $1.2–3.2 \times 10^{-4}$ (Lecuyer et al. 1998), so that the D/H ratio of the terrestrial water is well within the chondritic values. Water-containing rocky planetesimals (*e.g.* Morbidelli et al. (2000), Raymond et al. (2004), Raymond, Quinn & Lunine (2005)) and/or icy planetesimals (*e.g.* Gomes et al. (2005)) can be delivered from outer regions (typically $> 2–3$ AU) because of gravitational perturbation of the giant planets. Morbidelli et al. (2000) have shown that up to 15 per cent of the mass of the Earth could be accreted late in Earth's growth by collision of one or a few asteroids originating in the Main Belt. Raymond et al. (2004) used simulations of late stage of planetary accretion, focusing on the delivery of volatiles to the terrestrial planets, to analyse the influence of a giant planet and they find an eccentric Jupiter produces drier terrestrial planets with higher eccentricities than a circular one.

Some geochemical arguments are against a large contribution of water from asteroids considering, for example, noble gases ratios and osmium isotopic composition in the Earth's Primitive Upper Mantle (Drake & Campins 2006). Righter, Drake & Scott (2006) studied the idea that Earth and perhaps other terrestrial planets are not made from familiar meteorite types, but instead from a material that is not currently represented in our collections.

1.3 Adsorption of Water on Grains

As an alternative to exogenous sources like comets and asteroids, there are endogenous sources that consider Earth's water could have came directly from the solar nebula, where terrestrial planets were being formed. Stimpfl et al. (2004) have examined the role of physisorption by modelling the adsorption of water at 1000 K, 700 K, and 500 K using a Monte Carlo simulation. Their results suggest that grains accreted to Earth could have adsorbed 1–3 Earth oceans of water and the efficiency of adsorption of water increases as temperature decreases. However, there are issues with retention of water as the grains collide and grow to make planets, as well D/H ratio discrepancy with terrestrial water, since the D/H ratio of the nebula is ~ 6 times smaller than Earth's water value. However Campins, Swindle & Kring (2004) pointed out that the process involved in planetary accretion, degassing and the evolution of a hydrosphere and atmosphere are complex and may have fractionated the chemical and isotopic signature of the source(s) of water. Genda & Ikoma (2007) proposed that the assumption that the D/H ratio of water on the Earth has remained unchanged for the past 4.5 Gyr must be reviewed, since the D/H ratio of water could have changed during the formation and evolution of the Earth's ocean.

In this paper, we tackle the question of the origins of terrestrial planets' water by incorporating all these principal proposed sources in an analytical model which is tested with numerical simulations. We are motivated by the idea that probably Earth's water had not just one source and it can be better explained via a combination of an absorbed component, a component of asteroids and a cometary component. Results are analysed using known D/H ratio values in order to identify possible relative contributions from each source.

Section 2 describes the compound model, which incorporates asteroids and local adsorption of water. Section 3 describes the initial conditions for numerical simulations and Section 4 presents the results of these. Section 5 discusses results adding analyses of a cometary contribution. Section 6 presents the conclusions of the whole work.

2 MODEL

The model realistically describes the beginning of late-stage planetary accretion and is based on available information for the Solar System. However, it is intended to be easily expanded for any planetary system. It incorporates an endogenous and an exogenous source of water and uses D/H ratio as a discriminator. The endogenous source is adsorption onto grains (Stimpfl et al. 2004) and the exogenous source is asteroids (Raymond et al. 2004), as defined in the previous section. Comets are considered in *a posteriori* analysis. The next sub-sections describe how mass, water and D/H ratio values are initially attributed.

2.1 Mass

We use a mass distribution model as in Raymond et al. (2004), where the mass is divided between embryos and planetesimals. We assume that oligarchic growth has taken place in the inner Solar System. A two-tiered surface density is used, which reflects an increase in surface density due to the condensation of water immediately past the snow line. Σ_1 and $\Sigma_{\rm snow}$ are the surface density at 1 and 5 AU, respectively.

$$\Sigma(r) = \begin{cases} \Sigma_1 \left(\frac{r}{1AU}\right)^{-3/2}, & r > snowline \\ \Sigma_{snow} \left(\frac{r}{5AU}\right)^{-3/2}, & r < snowline \end{cases} \quad (1)$$

2.1.1 Embryos

Each embryo mass is determined by a semi-major axis function. The previous phase to oligarchic growth (runaway phase) ends when the embryo has merged with every available planetesimal in its surroundings, leaving an annulus of cleared material in the solar nebula called the 'feeding zone'. The 'feeding zone' of a planetary embryo is an annulus with width comparable to the embryo's Hill radius (R_H) and radius a. The mass inside that is given by:

$$M = 2\pi a R_H \Sigma \quad (2)$$

where Σ is the surface density in solids given by the Equation 1. Replacing the Hill radius in Equation 2 and solving for M we can obtain the embryo mass at the beginnig of oligarchic growth, given by:

$$M_{embryo} = \left(\frac{2\pi\Sigma a^2}{(3M_\odot)^{1/3}}\right)^{3/2} \quad (3)$$

Simulations of the formation of embryos from planetesimals (Kokubo & Ida 2000) show that they typically form with separations of 5–10 mutual Hill radii defined as:

$$R_{H,m} = \left(\frac{a_1 + a_2}{2}\right)\left(\frac{M_1 + M_2}{3M_\odot}\right)^{1/3} \quad (4)$$

Planetary embryos are therefore spaced between 0.5–2.5 AU for a random number (between 5 and 10) of mutual Hill radii.

2.1.2 Planetesimals

Between the Snow Line (2.5 AU in the Solar System) and 4.0 AU we assume the mass in planetesimals, representing carbonaceous chondrites asteroids. The planetesimal mass is fixed at 0.01 $M_\oplus$ and $\sim$ 200 of them are distributed as $N \sim r^{-1/2}$, corresponding to the annular mass in a disc with surface density proportional to $r^{-3/2}$, according to Equation 1.

2.1.3 Giant Planet

One Jupiter-like planet is used to influence the accretion dynamics. It has the same position, mass, semi-major axis and eccentricity of Jupiter.

2.2 Water

The water content of planetesimals and planetary embryos in a given planetary system depends in a complex way upon a range of factors including the mass and evolutionary characteristics of the protoplanetary disc, overall metallicity of the molecular cloud clump from which the star is forming, and the positions, masses and timings of formation of the system's giant planets (Raymond et al. 2004). Here we use a biphasic model that considers the most recent theories about sources of water for terrestrial planets.

For embryos, we use an initial water content defined by an endogenous theory model (Stimpfl et al. 2004) that depends on the temperature gradient profile in the solar nebula. Fig. 1 shows the temperature gradient throughout the disc of material where the planets would form in the Solar System.

Exploring the co-relation between temperature and distance, and then the co-relation between distance and water content susceptible to be absorbed by embryos in the inner Solar System (Stimpfl et al. 2004), we have the equation:

$$W = 10a - 7 \quad (5)$$

where W is the water content absorbed (in $O_\oplus$) by terrestrial masses and a is the semi-major axis in AU.

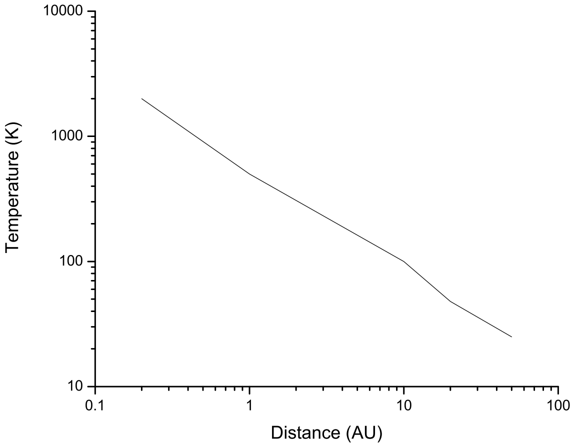

Figure 1. Temperature gradient in the solar nebula (Clark, 1998).

For the planetesimals we use a water content representative of carbonaceous chondrites (5 per cent by mass), as in Raymond et al. (2004).

2.3 D/H Ratio

In principle, it should be possible to determine the main sources and relative contributions to Earth's water if they have distinct chemical and isotopic signatures. Signatures that are used as discriminators include the D/H ratio, the ratio of noble gases and the isotopic composition of the highly siderophile element osmium. Among them, the D/H ratio discriminator is the one for which most data on different celestial bodies are available.

The D/H ratio of the solar nebula gas is estimated from observations of CH_4 in Jupiter and Saturn to be a low 2.1 ± 0.4 x 10^{-5} (Table 1, Lellouch et al. (2001)). Jupiter and Saturn likely obtained most of their hydrogen directly from the solar nebula.

The D/H ratios were measured from water in three comets - Halley, Hyakutake and Hale-Bopp (Table 1) - and they are all about twice the value for terrestrial water, and about fifteen times the value for the solar nebula gas. Carbonaceous chondrites have the highest water abundance of all meteorites and their D/H ratios range from 1.2 x 10^{-4} to 3.2 x 10^{-4}. These values are illustrated in Fig. 2.

Using these data, we are able to give the initial D/H ratio values for embryos and particles. Initially, embryos are considered to have some locally absorbed water (as described in previous sub-section) and this water receives a D/H ratio value like the protosolar nebula. Particles receive a median value (2.2 x 10^{-4}) among D/H ratio values of carbonaceous chondrites. In an *a posteriori* analysis, comets receive a median value (3.1 x 10^{-4}) over the three known values.

All the model's equations were implemented using the software MATHEMATICA to create the initial conditions files for the numerical simulations, as described in the next section.

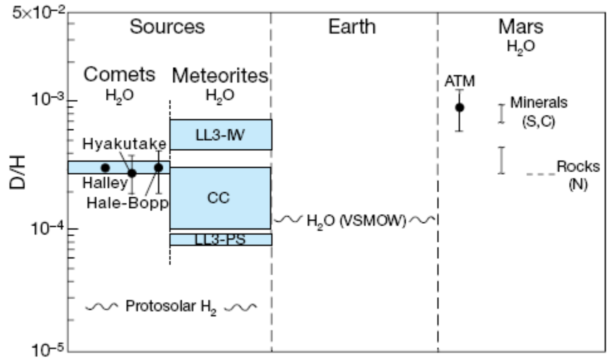

Figure 2. The D/H ratio in H2O in three comets, meteorites, Earth (Vienna standard mean ocean water - VSMOW), protosolar H_2, and Mars. 'CC' = carbonaceous chondrites, 'LL3-IW' = interstellar water in Semarkona, 'LL3-PS' = protostellar water in Semarkona. (Drake et al., 2006)

3 NUMERICAL SIMULATIONS

We run all the simulations for 200 Myrs (Raymond et al. 2004) using a modified version of Mercury (Chambers 1999). Mercury is a general-purpose software package for doing N-body integrations and we reprogrammed it to include water content. The hybrid integrator is used, which uses a second-order mixed variable sympletic algorithm when objects are separated by more than 1 Hill radii, and a Burlisch-Stoer method for closer encounters. We use a 5 days time-step. Collisions conserve linear momentum and do not take fragmentation into account. These simulation were run on desktop PCs, each taking about 1 month of CPU time on an 800 MHz machine.

We use three values of surface density at 1 AU (Σ_1), the minimum mass solar nebula (6 g/cm^2) expected for the inner Solar System, the maximum value expected (10 g/cm^2) , and an intermediate value (8 g/cm^2). Each surface density is simulated three times, with slightly different configurations. Fig. 3 sums up the initial conditions for one simulation. All the other simulations follow the same pattern, with embryos initially Moon to Mars sized. Fig. 4 shows some snapshots of one of the simulations.

4 RESULTS

Table 2 summarizes final embryos data of all simulations. The columns are name, surface density, simulation number, final semi-major axis, final eccentricity, final mass (in terrestrial masses), percentage of asteroidal mass, final water (in terrestrial oceans), percentage of asteroidal water and final D/H ratio of the surviving embryos.

The work of Morbidelli et al. (2000), as well as earlier authors (*e.g.* Wetherill (1996)), showed that planetary accretion is a stochastic process, especially if much of the mass is contained in a small number of large embryos (Raymond, Quinn & Lunine 2007). The content of water delivered to any given terrestrial planet, and its source region, can vary

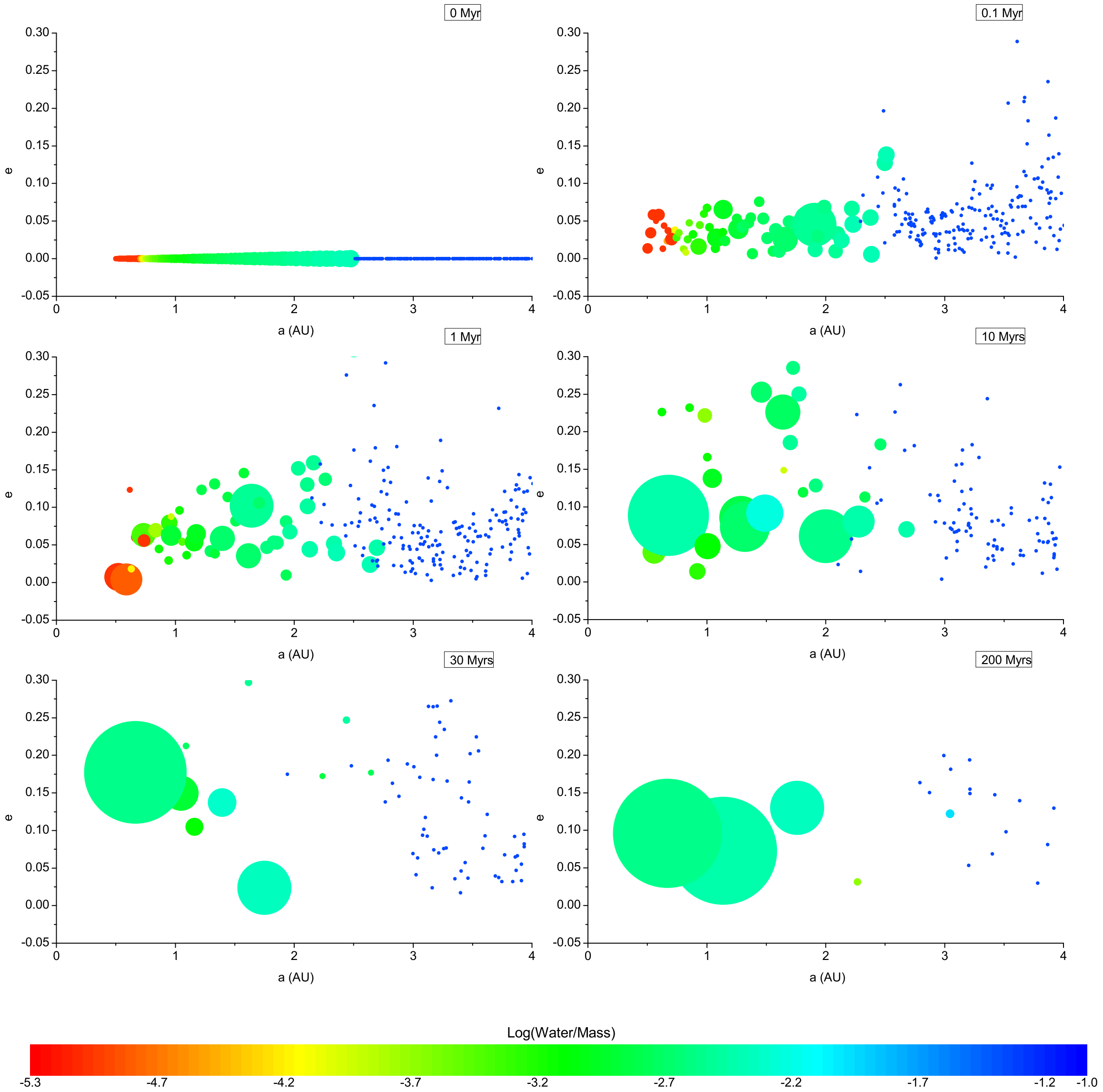

Figure 4. Snapshots for one of the simulations; surface density of 8 g/cm^2 at 1 AU.

widely. If this view is valid, then it implies that terrestrial planets around other stars may differ greatly in terms of water amounts, and the timing of formation and location of giant planets from one system to another could play an important role in this variation (Lunine et al. 2003). These simulations produce different configurations which supports this picture of potentially large variations in water abundance.

In the next sub-sections each main parameter, mass, water and D/H ratio, is analysed separately.

4.1 Mass

Fig. 5 shows the total mass, initial and final, of embryos and planetesimals in all the simulations. Considerable mass is lost in the simulations by ejections or collisions with star or the giant planet. That is due to cumulative perturbations of embryos and gravitational influence of the giant planet. Most of the restant mass is used to form proto-planets.

In all the following figures the surface densities are represented as shown in Fig. 6. Fig. 7 shows mass distribution in a x e graph. Larger embryos are concentrated between 0.5 and 1.5 AU, in lower eccentricities. Mass distribution peaks around 1.3 AU (Fig. 8) and it could represents a mass' equilibrium zone of the system, where planets are likely to form with more mass. If it happens, there would be implications

Table 2. Final data of survivors. [a]

Body	Σ_1	Sim	a_f	e_f	Mass($M_\oplus$)	$\%M_{Ast}$	Water($O_\oplus$)	$\%W_{Ast}$	D/H
EM53	6	1	1.2422	0.2820	0.0238	0	0.1605	0	2.10E-05
EM54	6	1	1.9297	0.2624	0.0475	0	0.3201	0	2.10E-05
EM25	6	2	0.6575	0.0310	0.5652	5.33	8.0421	80	1.79E-04
EM35	6	2	2.0172	0.1276	0.4703	4.27	8.4141	51	1.22E-04
EM37	6	2	1.1913	0.0311	0.5905	0	3.5568	0	2.10E-05
EM16	6	3	0.6472	0.1795	0.5424	0	0.7057	0	2.10E-05
EM49	6	3	1.2701	0.0631	0.6212	3.24	8.5152	50	1.21E-04
EM53	6	3	1.6453	0.0313	0.1944	0	2.0790	0	2.10E-05
EM67	6	3	1.7909	0.2576	0.0384	26.20	2.4267	88	1.96E-04
EM77	6	3	2.4302	0.1840	0.1200	25.12	7.5152	85	1.90E-04
EM33	8	1	1.4725	0.1197	0.1877	0	1.5848	0	2.10E-05
EM54	8	1	0.9237	0.2661	0.0523	19.22	2.5411	84	1.88E-04
EM58	8	1	2.4472	0.0117	0.0902	0	1.0075	0	2.10E-05
EM61	8	1	2.9343	0.1197	0.0478	0	0.6050	0	2.10E-05
EM64	8	1	2.6261	0.8908	0.0500	0	0.6954	0	2.10E-05
EM65	8	1	1.9094	0.0939	0.1703	11.80	6.3617	67	1.54E-04
EM6	8	2	0.6684	0.0961	0.7238	4.17	8.4873	75	1.71E-04
EM22	8	2	2.2660	0.0316	0.0482	0	0.0403	0	2.10E-05
EM41	8	2	1.1374	0.0728	0.7132	4.23	11.3468	56	1.33E-04
EM51	8	2	1.7585	0.1300	0.3598	5.59	7.0762	60	1.41E-04
EM57	8	2	2.2332	0.5756	0.0555	18.10	2.6511	80	1.81E-04
EM62	8	2	3.0464	0.1223	0.0592	16.97	2.7931	76	1.73E-04
EM36	8	3	1.4107	0.0438	0.5882	0	4.8500	0	2.10E-05
EM37	8	3	2.1633	0.4128	0.0309	0	0.1206	0	2.10E-05
EM47	8	3	2.1017	0.6323	0.0365	0	0.2449	0	2.10E-05
EM55	8	3	0.8039	0.1472	0.7190	1.40	5.2529	41	1.02E-04
EM68	8	3	2.1167	0.1941	0.2357	12.79	9.4650	68	1.56E-04
EM4	10	1	0.71	0.1492	0.9635	1.04	5.8516	36	9.36E-05
EM49	10	1	1.4076	0.0783	0.8596	4.68	14.2830	60	1.40E-04
EM60	10	1	2.6466	0.5187	0.0718	0	1.0508	0	2.10E-05
EM42	10	2	1.406	0.0279	1.2113	3.32	20.0818	43	1.06E-04
EM10	10	3	0.5015	0.1399	0.2756	3.65	2.2885	93	2.07E-04
EM44	10	3	1.2858	0.0608	1.2597	3.19	17.0530	50	1.21E-04
EM50	10	3	2.2788	0.0476	0.0595	0	0.5853	0	2.10E-05
EM65	10	3	2.3168	0.2354	0.1518	0	2.4830	0	2.10E-05

[a] Columns are: embryo name, surface density, simulation number, final semi-major axis, final eccentricity, final mass (in terrestrial masses), percentage of asteroidal mass, final water (in terrestrial oceans), percentage of asteroidal water and final D/H ratio of the surviving embryos.

for habitable planet formation around solar type stars, since this zone includes the habitable zone (HZ) of the Solar System (see Section 5 for more about HZ). It would imply that terrestrial planets are likely to be formed in the HZ of solar type stars with masses close to that of Earth. There is also a mass peak around 4 per cent of asteroidal mass (Fig. 9).

A disc with an increased surface density of solid material will form a smaller number of more massive terrestrial planets with larger water amounts than lower mass discs, due to stronger self-scattering among protoplanets (Raymond et al. 2004, 2007). That would explain why just the highest surface density value ($\Sigma_1 = 10 g/cm^2$) produced embryos with mass $> 0.8 M_\oplus$ and, generally, more water content. Most of the largest embryos are formed close to their initial position (Fig. 10) which suggests a correlation between bigger mass and lower migration.

4.2 Water

The final content of water will depend not only on asteroidal contribution but also on the water locally absorbed, before the simulations get started (as described in Section 2). Some embryos get lower water content than Earth's minimum limit (1 $O_\oplus$), but it is expected terrestrial planets get different mass and water amounts, as is seen in the Solar System nowadays. The system water is initially abundant (up to $\sim 450\ O_\oplus$) but with the mass loss (Fig. 5), also most of the water is lost. No embryo gets more water than the maximum expected for Earth (50 $O_\oplus$, Abe et al. (2000)).

Final water distribution can be seen in the colors of Fig. 8 and Fig. 9. Both embryos with most water in the system are around 1.3 AU and possess 4 per cent of asteroidal water. There is also water concentration between 0.5 and 1.5 AU, in lower eccentricities, as can be seen in Fig. 11. Fig. 12 shows also a strong correlation between water and low migration.

Embryos formed in the inner part of the system with

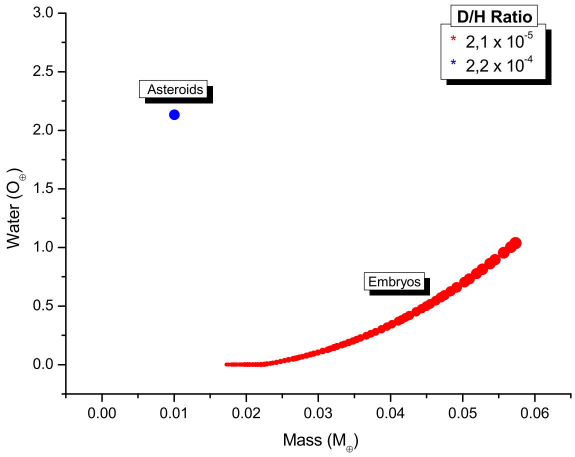

Figure 3. Initial conditions for one of the simulations; surface density of 8 g/cm^2 in 1 AU.

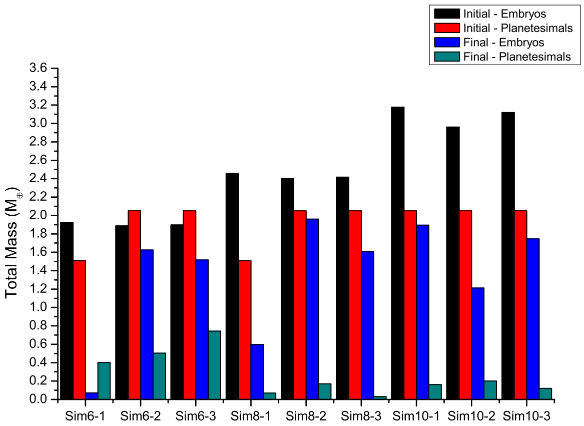

Figure 5. Initial and final total mass of embryos and planetesimals in all the simulations.

very low migration (Fig. 10) and high asteroidal percentage of water (*e.g.* **EM25**, $\Sigma_1 = 6g/cm^2$, simulation 2 and **EM10**, $\Sigma_1 = 10g/cm^2$, simulation 3) show that water delivery by ice bodies coming from beyond the snow line can be very efficient. That is confirmed also by other simulations, for example, Raymond et al. (2004) and Morbidelli et al. (2000).

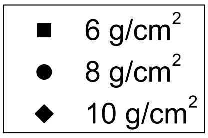

Figure 6. Legend for the following figures. Each symbol represents one surface density group in the simulations.

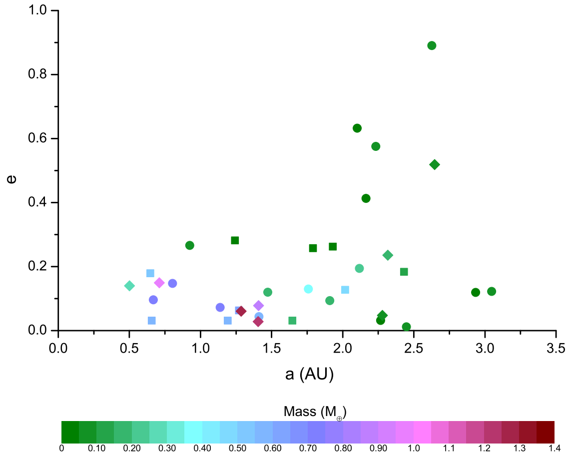

Figure 7. Final semi-major axis versus eccentricity showing mass distribution.

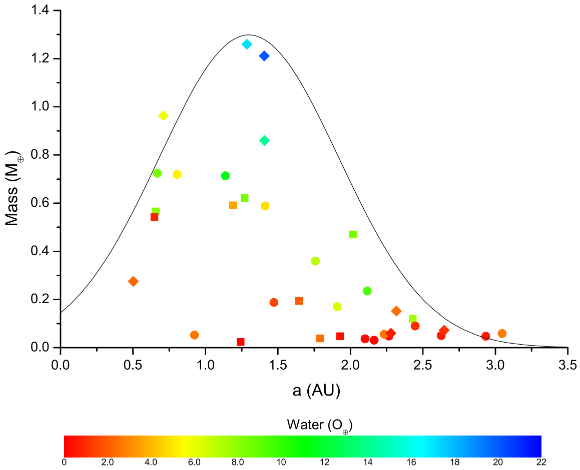

Figure 8. Final semi-major axis versus final mass showing water distribution.

4.3 D/H Ratio

The final D/H ratio of the surviving embryos is, in these simulations, completely related to the asteroidal water percentage. The percentage of asteroidal water to reach the Earth's water D/H ratio is given for Equation 6, with K representing the percentage of asteroidal water. The equation gives $K \sim 64$ per cent.

$$K\,(DH_{ast}) + (1-K)\,(DH_{neb}) = DH_{Earth} \tag{6}$$

where $DH_{ast} = 2.2 \text{ x } 10^{-4}$, $DH_{neb} = 2.1 \text{ x } 10^{-5}$ and $DH_{Earth} = 1.49 \text{ x } 10^{-4}$, the asteroidal D/H ratio used here, the nebular D/H ratio and the Earth's water D/H ratio, respectively.

Some of the surviving embryos acquire percentage of asteroidal water close to this value, but not with the exact one (Table 2). Fig. 13 shows final D/H ratio of survivors' water versus final mass. Colors show also the final water

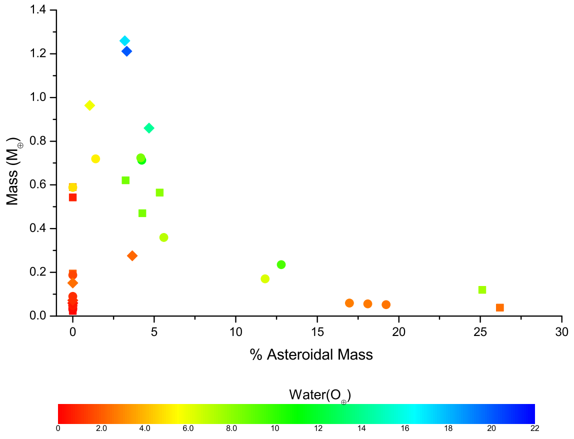

Figure 9. Final percentage of asteroidal mass versus final mass showing water distribution.

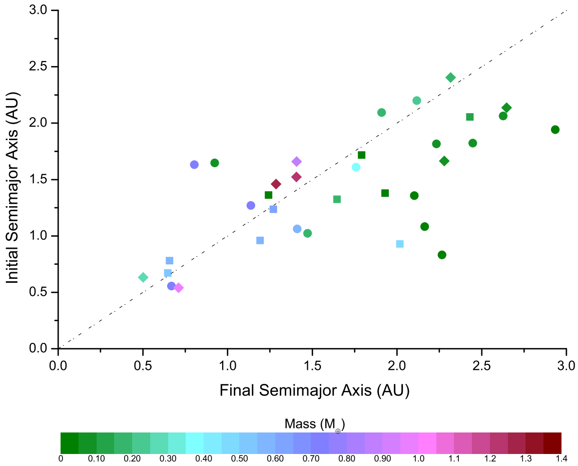

Figure 10. Final semi-major axis versus initial semi-major axis showing mass distribution.

content. What is remarkable is most of the embryos around the Earth's D/H ratio value have around 10 $O_{\oplus}$ of final water content, what is the amount of water expected for Earth (Drake & Campins 2006).

In the Table 2 we can see some embryos (**EM37**, $\Sigma_1 = 6g/cm^2$, simulation 2 e **EM36**, $\Sigma_1 = 6g/cm^2$, simulation 3) got more than half Earth's mass and considerable water content without asteroidal contribution. The D/H ratio of these embryos' water will be the same of the nebula gas, $\sim$ 6 x lower than Earth's water D/H ratio. Genda & Ikoma (2007) argue that the D/H ratio of Earth's water is not immutable, and likely higher today than it was primordially. In these cases, not only an asteroidal contribution but also a cometary contribution could be less important to complete Earth's water. Section 5 brings more discussions about the D/H ratio of embryos' water formed in the HZ of the simulated systems.

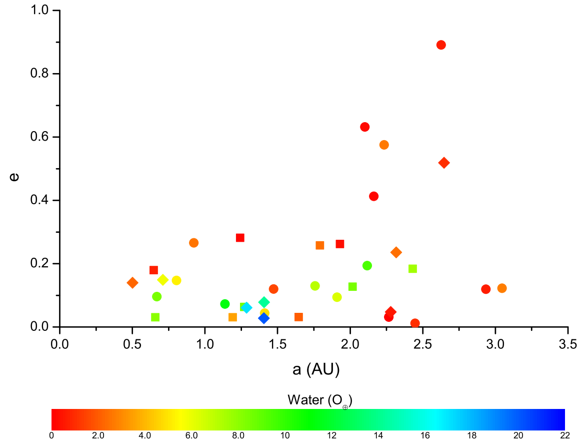

Figure 11. Final semi-major axis versus eccentricity showing water distribution.

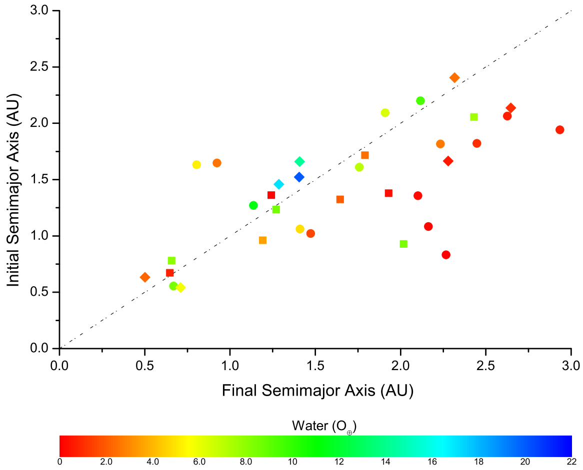

Figure 12. Final versus initial semi-major axis showing water distribution.

5 COMETS AND FINAL ANALYSES

A cometary contribution to Earth's water is not unlikely, although not expected as so relevant any more. Gomes et al. (2005) calculated the content of cometary material delivered at the Late Heavy Bombardment (LHB) as about 6 per cent of 1 $O_{\oplus}$. It is consistent with upper limits of cometary contribution calculated based in D/H ratio measurements by Morbidelli et al. (2000).

Table 3 summarizes embryos' data formed inside the HZ of the simulated systems, that extends from 0.9 to 1.5 AU (Raymond et al. 2007). It shows which percentage of cometary water would be necessary to increase the D/H ratio of these embryos' water to the Earth's value (excepting **EM54**, *8* g/cm^2, *simulation 1*, that has higher value). Final mass and water content were updated accordingly. It is possible to see from the table that adding 0.06 $O_{\oplus}$ of cometary water (with a cometary D/H ratio) according to

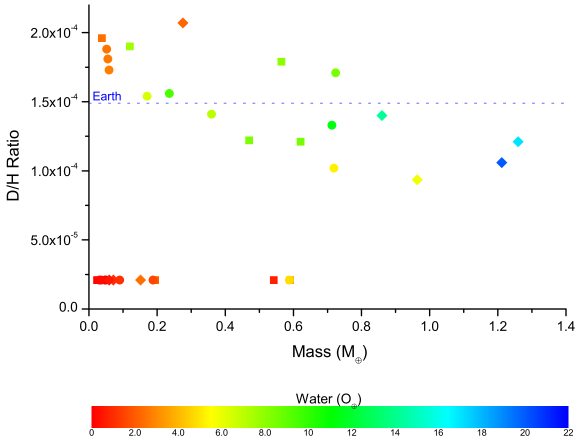

Figure 13. Final mass versus D/H ratio showing water distribution.

Gomes et al. (2005) would not change considerably the D/H ratio of most of the final embryos formed in the HZ of these simulated systems.

For embryos with none or very low water asteroidal percentage, more cometary water is needed (about 44 per cent, according to this model). Some studies consider that likely, ignoring a remarkable asteroidal contribution. Ipatov & Mather (2006) argue that, from a dynamical viewpoint, the probability of JFC's collide with Earth would be enough to complete Earth's oceans. Other studies (*e.g.* Owen & Bar-Nun (2001), Drake & Campins (2006)) based on noble gases ratios and osmium isotopic composition to show the possibility of low asteroidal contribution. In this case a cometary contribution up to 50 per cent would be possible. However, according to geochemical investigations, (Chaussidon 2007) it is unlikely that Earth has none or very low asteroidal contribution in its water.

Most of the rest of the embryos in Table 3 need about 5-15 per cent of cometary water to reach the D/H ratio of Earth's water. That involves an upper limited a little higher than some previous works (∼ 10 per cent by Morbidelli et al. (2000), up to 12 per cent by Deloule, Robert & Doukhan (1998)) but would be in accordance with by Owen & Bar-Nun (2000) (up to 15 per cent), giving relevance for locally absorbed water content.

6 CONCLUSIONS

We presented results of 9 numerical simulations, projected to investigate possible sources of terrestrial planets' water and possible relative contributions to Earth's water. We propose a compound model that incorporates the main recent theories of local absorption and asteroids, adding comets at final analysis. We base our research on the likely assumption that Earth's water had more than one source, and we use known D/H ratio measurements of different celestial bodies to discuss possible sources.

Final embryos have their mass, water content and D/H ratio analysed and compared with Earth's values. Bigger embryos with more water are concentrated around 1.3 AU, which is inside the HZ of the systems. Higher values of mass and water content are related with low migration. Embryos formed in the habitable zone of the systems are analysed considering a cometary contribution for their water. Some embryos formed with no asteroidal water contribution, and for these would be necessary about 44 per cent of a cometary contribution to make the D/H ratio of Earth's water.

In the simulations we assumed that all collisions were perfectly inelastic, and the water amounts of the resulted planet would be equal to the sum of the water amounts of the impacting bodies. As pointed out by Haghighipour & Raymond (2007), this is an assumption that sets an upper limit for the water budget of terrestrial planets, and ignores the loss of water due to the impact. The simulations presented are also low resolution and the results may not reveal detailed characteristics of the final planetary systems. However, as shown by Agnor, Canup & Levison (1999) and Chambers (2001), such integrations can produce the main general properties of the final assembly of the planetary bodies. Numerical simulations are always limited by the fact that the speed of computation simulations varies as N^2, where N is the number of involved objects (Haghighipour & Raymond 2007).

Despite its limitations, our study shows a compound model incorporating main theories produces expected results for water content and mass for terrestrial planets and better explains the D/H ratio of Earth's water, whereas any individual source of water fails. Such low-resolution small number of simulations do not prove a theory, but improve previous and recent studies about water origins for terrestrial planets. Results of the model and analyses basing in D/H ratio measurements show the most likely relatives contributions for Earth's water involves ∼ 35 per cent of absorbed water, 50–60 per cent of asteroidal water and 5–15 per cent of cometary water.

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Table 3. Data of survivors in HZ, with the percentage of cometary water to reach the D/H ratio of Earth's water.[a]

Body	Σ_1	Sim	a_f	e_f	Mass($M_\oplus$)	$\%M_{Ast}$	Water($O_\oplus$)	$\%W_{Ast}$	$\% W_{Comet}$
EM53	6	a	1.2422	0.2820	0.0238	0	0.2882	0	44
EM37	6	b	1.1913	0.0311	0.5912	0	6.3856	0	44
EM49	6	c	1.2701	0.0631	0.6215	3.24	9.9944	50	15
EM33	8	a	1.4725	0.1197	0.1880	0	2.8452	0	44
EM41	8	b	1.1374	0.0728	0.7135	4.23	12.4690	56	9
EM36	8	c	1.4107	0.0438	0.5891	0	8.7073	0	44
EM49	10	a	1.4076	0.0783	0.8598	4.68	15.0827	60	5
EM42	10	b	1.406	0.0279	1.2126	3.32	25.4522	43	21
EM44	10	c	1.2858	0.0608	1.2604	3.19	20.0153	50	15

[a] Columns are: embryo name, surface density, simulation number, final semi-major axis, eccentricity, mass, percentage of asteroidal mass, water, percentage of asteroidal water and percentage of cometary water to reach VSMOW.

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