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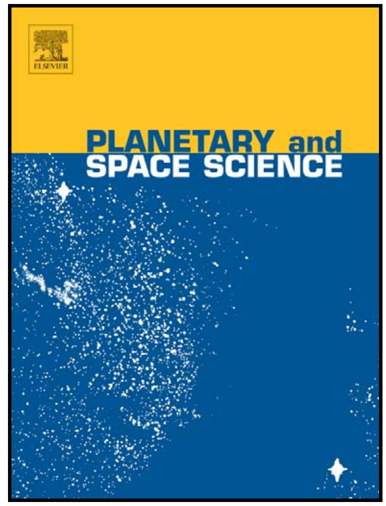

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J. Horner, O. Mousis, J.M. Petit, B.W. Jones

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Differences between the impact regimes of the terrestrial planets: implications for primordial D:H ratios

J. Horner[1], O. Mousis[2,3], J.M- Petit[3] and B. W. JONES[1]

[1]Astronomy Group, Physics & Astronomy, The Open University, Milton Keynes, MK7 6AA, UK

[2]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA

[3]Université de Franche-Comté, Observatoire de Besançon, Institut UTINAM, CNRS/INSU, UMR 6213, 25030 Besançon Cedex, France

e-mail: j.a.horner@open.ac.uk *Phone: +44 1908 653229* *Fax: +44 1908 654192*

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Abstract

It is often assumed that the terrestrial worlds have experienced identical impact regimes over the course of their formation and evolution, and, as a result, would have started life with identical volatile budgets. In this work, through illustrative dynamical simulations of the impact flux on Venus, the Earth, and Mars, we show that these planets can actually experience greatly different rates of impact from objects injected from different reservoirs. For example, we show scenarios in which Mars experiences far more asteroidal impacts, per cometary impactor, than Venus, with the Earth being intermediate in value between the two. This difference is significant, and is apparent in simulations of both quiescent and highly stirred asteroid belts (such as could be produced by a mutual mean-motion resonance crossing between Jupiter and Saturn, as proposed in the *Nice* model of the Late Heavy Bombardment). We consider the effects such differences would have on the initial volatilisation of the terrestrial planets in a variety of scenarios of both *endogenous* and *exogenous* hydration, with particular focus on the key question of the initial level of deuteration in each planet's water budget. We conclude that each of the terrestrial worlds will have experienced a significantly different distribution of impactors from various reservoirs, and that the assumption that each planet has the same initial volatile budget is, at the very least, a gross over-simplification.

Key words: Terrestrial planets, isotopic abundances, impacts.

1) Introduction

The nature of impacts in our Solar System is something that is of great interest to astronomers, geologists, and the general public alike. Which objects pose the greatest threat to the Earth? Where did the terrestrial planets acquire their water? What killed the dinosaurs?

Over the years, our understanding of the impact regime on the Earth has evolved in fits and starts – in fact, it is only really in the last fifty or sixty years that the idea that impacts are anything of a threat has been accepted! Traditionally, the Earth was viewed as a peaceful, tranquil place, unchanging and unthreatening. Over the early 1900s, this view slowly shifted, with the acceptance of processes such as plate tectonics and mass extinctions replacing the paradigm of constant peace and safely. Finally, thanks to the work of a few scientists (such as Gene Shoemaker), the craters on the Earth's surface were accepted as being impact features, and impacts were confirmed as being both a current concern and an important part of the history of our planet. Since this realisation, many authors have carried out studies of the impact flux on the Earth, attempting to determine which groups of objects pose the greatest threat, and trying to explain peculiarities of the impact history constructed for the Earth from the study of craters here and on the Moon. Less work, however, has been carried out to examine the differences in impact regimes experienced by the different terrestrial planets, with a common assumption being that Venus and Mars have experienced the same general impact history as the Earth. In this work, we attempt to address this question, and to see what similarities, and what differences, there are between the impact fluxes raining down on these three worlds.

A tool which can tell us many things about the formation of the inner Solar System is the study of the ratio between deuterium and hydrogen in water. Recent modelling work (Drouart *et al*., 1999; Mousis *et al.*, 2000; Mousis, 2004; Horner *et al*., 2007, 2008) suggests that the D:H ratio in the water within icy bodies will vary as a function of their formation distance from the Sun. In brief, because water falling into the solar nebula from beyond was highly enriched in deuterium when compared with the infalling molecular hydrogen[1], a reversible gas phase reaction between these two nebula components leads to a slow but steady reduction in the deuteration of the water. Once the temperature of the nebula drops, the water freezes out, halting the reaction and fixing the D:H value. As the nebula cools over time, the areas furthest from the Sun, which are initially the coldest, are the first to experience water freezing out in this way, fixing the D:H value acquired in the gas phase, with the "ice-line" moving inward over time. In other words, this means that the closer to the Sun a body formed, the lower the D:H ratio within its water would be. Across the Solar System, the resulting value changes dramatically, as one moves through the regions in which asteroidal and cometary bodies would have formed.

A field in which knowledge of the D:H ratio in water is particularly important is the study of the atmospheres of the terrestrial planets, Venus, the Earth, and Mars. In that work, examination of the current D:H is used to study a variety of planetary properties, from the hydration history of Venus (Donahue, 1999; Lécuyer *et al.,* 2000), to the structure of the early Martian atmosphere (Solomon *et al.*, 2005). However, all these studies require knowledge of the *original* D:H ratios on these planets – values that are currently unknown. Despite this, a large amount of work has been done on the deuterium budgets of these worlds, often involving complicated models of atmospheric physics.

[1] Geiss and Reeves (1981) have shown that ion-molecule reactions occurring in the ISM likely explain the high enrichments values observed in the meteoritic organic macromolecules (Robert *et al.*, 1979; Robert & Epstein, 1982). Subsequently, a number of highly enriched deuterated species, including HDO, have been detected in the ISM (Turner, 2001), and an abundant literature has been devoted to the theory of the isotopic chemistry in this medium (see Bockelee-Morvan *et al.*, 1998 and references therein).

The fact that different escape rates would be expected from the atmospheres of the planets for hydrogen and deuterium complicates the matter, as do isotope-sensitive processes on the surfaces of the planets in question. In fact, it is strikingly obvious that the deuteration on each planet at the current day is quite different to the native value. The bulk of authors who study the behaviour of deuterium on these worlds make the simplifying assumption that the original values were the same for the three worlds (so, for example, assuming that the initial level of deuteration in Martian water was identical to that of the Earth) (Krasnopolsky *et al.*, 1998; Lécuyer *et al.*, 2000; Gurwell, 1995). Such assumptions allow the authors to use the modern values as a tool to aid their understanding of the various physical processes through which the values can be changed.

In the absence of data, the assumption that the original D:H ratios within the water on Venus and Mars were the same as the original terrestrial value is an obvious simplification to make, particularly since it allows various studies of these bodies to be carried out. However, while such studies are doubtless valuable, it is far from obvious that the three planets would have had identical initial levels of deuteration. Indeed, given our growing understanding of the chaotic nature of planetary accretion, together with the effects of late giant impacts and the late heavy bombardment (LHB), it seems more likely that the planets would obtain their volatiles from a variety of different reservoirs, and would therefore have acquired water with a wide variety of D:H values. Such variation between the amounts of water delivered to the terrestrial planets from various sources has, in fact, been identified before. Levison *et al.*, (2001) carried out dynamical simulations to examine the idea that Uranus and Neptune's formation led to the proposed cataclysm known as the Late Heavy Bombardment. Their results, highlighted in figure 4 of that work, suggest that Mars would have experienced more impacts from objects in the Uranus-Neptune region, per asteroidal impactor, than any of the other terrestrial planets. Although that work was based on a very small sample of potential impactors (600 bodies in total, spread between the asteroid belt, the Jovian Trojan family, and in the Uranus-Neptune region, with collision rates on the terrestrial planets estimated using Öpik's equation (Öpik, 1951)), and despite the fact that it examined just one possible scenario for Solar system evolution, it provides a strong indication that the terrestrial worlds would have experienced greatly disparate hydration regimes, at least for that component of their water sourced from beyond the orbit of Mars. This conclusion is supported by the work of Lunine *et al.*, (2003), who examine the question of the origin of Martian water. The authors consider the scenario in which the bulk of the water provided to the Earth is sourced by a small number of collisions between the Earth and planet-sized embryos, rich in water, sourced from the asteroid belt (Morbidelli *et al.*, 2000). In order to explain the current mass of Mars, the authors propose that the planet must have experienced no such giant collisions, and so would be expected to form solely through the accretion of smaller bodies. Essentially, the authors propose that the rare and stochastic nature of such collisions during the late stages of planet formation could lead to proto-Mars experiencing no such event during its evolution, whilst the larger Earth experienced at least one, or even a few. Mars' volatiles, then, would have been contributed by the ongoing background flux of asteroidal and cometary impacts during its formation, while the contribution of those reservoirs to the Earth's hydration would have been swamped by the bulk of material delivered in collision with such embryos. This would clearly lead to a greatly different origin for the bulk of that planet's hydration when compared to the Earth. Although recent work (Andrews-Hanna, Zuber & Banerdt, 2008) has provided evidence that Mars has experienced at least one giant impact over the course of its evolution, the work of Lunine *et al.*, once again highlights the fact that caution must be taken when attempting to equate the primordial levels of deuteration on the other terrestrial planets to that of the Earth.

In this work, we aim to build upon these earlier studies, which examined very specific scenarios of terrestrial planet hydration. A series of more general simulations involving a variety of simple, but plausible, populations of potential impactors covering a wide range of possible formation scenarios were carried out in order to examine the similarities and the differences between the impact flux upon the terrestrial worlds. This allowed us, in turn, to examine the effect such differences would have on the degree of deuteration experienced by those planets. In section two, we introduce the various scenarios which are currently used to explain the volatilisation of the terrestrial planets, before detailing the dynamical simulations carried out to assess the impact regimes in section three. In section four, we present a detailed discussion of how the differences between the impact rates on the terrestrial worlds would affect their volatilisation history, with a particular focus on the D:H values in their water, while in section five, we state our main conclusions.

2) Scenarios for planetary hydration

Two main models exist for the hydration of the terrestrial planets: in the *endogeneous* water scenario, the water originates from the region of the solar nebula in which the planet is forming; whilst in the *exogeneous* water scenario, it originates from regions beyond that planet's feeding zone. In the endogeneous case, the source of water was therefore local, coming from the same feeding zone as the rocky material making up the terrestrial planet in question, and was concomitantly accreted to the planet in the form of hydrated silicates, in which water can survive well within the ice line (Drake, 2004). Indeed, follow up work by that author on the endogeneous planetary hydration model suggests that terrestrial water could have been acquired through the adsorption of nebular water onto grains within the accretion disk, and then retained through the process of planetary accretion (Drake 2005). This idea, although feasible, currently lacks the support of quantitative studies, particularly ones that allow the calculation of the surface area to volume ratio of grain in the nebula. This ratio effectively determines the fraction of trapped water within a given grain, and currently remains completely undetermined (Drake 2005). However, it is well known that the meteorites show a gross correlation between their water content and their original heliocentric distance. Enstatite chondrites, from the innermost part of the asteroid belt (~2 AU), are the driest known meteorites in the Solar System (0.05-0.1% in mass) (Morbidelli *et al.*, 2000). This seems to suggest that planetesimals formed in the feeding zones of the terrestrial planets should have had an even lower water content. In addition, a non-negligible fraction of their water should have been lost during their accretion process. Taken together, the weight of this evidence is such that endogenous water scenarios are currently thought insufficient to explain the total hydration of the terrestrial worlds, and prevailing opinion is that the water presently on the Earth and its neighbours came, in the main, from an exogeneous source.

The exogeneous scenario can be split into two main categories: early exogeneous accretion, occurring while the terrestrial planets are still growing, and late exogeneous accretion, otherwise known as the *Late Veneer model*. The process of early exogeneous accretion is thought to have occurred during the depletion of the primordial asteroid belt. Morbidelli *et al.,* (2000) describe two such scenarios.

The first scenario examined by Morbidelli *et al.,* involves the sculpting of the primordial asteroid belt, as proposed by Petit *et al.,* (2001), in which the effect of planetary embryos spread over the entire inner Solar System is considered. In this model, asteroids and embryos from the outer asteroid belt, which contain approximately 10% water by mass, collide with the accreting worlds. Individually, asteroidal objects have a fairly low probability of collision with the terrestrial planets, and the bulk of such collisions tend to occur at a very early stage, just after the formation of Jupiter. Embryos, however, are more efficient at delivering material to the inner planets, and tend to do so over a longer timescale (tens of millions of years), toward the final stages of planetary accretion. In this scenario, then, these embryos are considered to be the primary source of volatiles, with only a small contribution being made by the smaller, asteroidal, bodies.

In the second scenario, there is no need for massive embryos. The excitation and depletion of the primordial asteroid belt is a direct result of the combined effects of gas drag (Franklin & Lecar, 2000) and the sweeping of secular resonances through the belt. In this case, the terrestrial planets accrete their volatiles from asteroidal material slowly sleeting inwards from just beyond the ice line, in addition to a significant hydrated contribution from water trapped in hydrated silicates. As mentioned earlier, such silicates can survive a long way interior to the ice line, and would constitute a significant fraction of the incoming material from the inner asteroid belt.

In these scenarios, assuming no prior hydration from *in*-situ material, it is usually anticipated that Venus, the Earth, and Mars would acquire much the same mix of volatiles, and that they would have had an almost identical D:H value in their water. However, given the proximity of Mars to the asteroid belt, it is quite possible that it would be far more likely to accrete material from the inner regions of the belt and the interior terrestrial planets, since only a little stirring would be necessary to emplace such material on Mars-encountering orbits. This simple argument could in turn easily result in the dominant contribution to Martian hydration coming from asteroidal material interior to the ice line during the later stages of its formation. This would clearly lead to the red planet having a different initial D:H value to the Earth and Venus (e.g. Médard & Grove, 2006). Furthermore, we note that a significant amount of material would have been emplaced in the outer region of the asteroid belt from further out during Jupiter's formation, sourced from the huge number of planetesimals which formed beyond Jupiter and were then scattered. Taking this into account, it is clear that the terrestrial planets would be influenced by material from a wide variety of locations within the solar nebula. Indeed, if the Martian volatile budget is the result of a significantly different mix of material to the other terrestrial worlds, it seems certain that the initial deuteration levels on these worlds should have displayed significant differences. A further illustration of the potential for different hydration histories between Mars and the Earth is revealed in Lunine *et al*. (2003). If the delivery of water from the inner Asteroid belt is achieved by a very few stochastic impacts from planetary embryos which formed in that region, it is clearly feasible that Mars would have received no such impact. In this case, the deuteration of Mars would clearly have a far more cometary origin than that the Earth.

In contrast to the idea of early exogenous hydration, models of late exogeneous hydration, such as the famous "Late Veneer" (Owen & Bar-nun, 1995), are currently less widely accepted. Such models suggest that the terrestrial planets formed effectively dry, and that their volatiles were accreted significantly later, during, and as a result of the Late Heavy Bombardment (LHB). In such models, the inner Solar System was inundated with material from the outer asteroid belt and the outer Solar System, and it is clear that the terrestrial planets would have received the bulk of their hydration from objects which formed over a wide range of heliocentric distances. In this case, it is vitally important to understand how the proportions of the various water bearing bodies falling on the terrestrial planets vary from one to the next. It is clear that the impactors crashing through the inner Solar System during the LHB would have origins both in the outer asteroid belt and the outer Solar System (Gomes *et al.*, 2005). What would Venus, the Earth, and Mars have experienced during this period? It is clear that the three planets would have experienced a similarly enhanced impact regime, but less clear that the mix of impacting bodies would have been the same.

It is interesting, from the perspective of exogeneous hydration models, to look at the way that the location of a planet in the inner Solar System affects the relative contributions to the impact flux provided by asteroidal and cometary material, the latter originating from beyond Jupiter and richer in water ice than asteroidal material. This is particularly apposite in the case where the D:H ratio within the water of an accreted body is a function of its formation location.

3) Simulating the impact flux

Our simulations, conducted in order to study the differences between the asteroidal and cometary contributions to the terrestrial planet impact flux, were carried out using the hybrid integrator within the *MERCURY* package (Chambers, 1999). Test populations of massless particles were created representing asteroidal and cometary material, and followed for a period of 10 Myr under the gravitational influence of Venus, the Earth, Mars, Jupiter, Saturn, Uranus and Neptune, in their current orbits. These massive bodies interacted fully with one another, and also exerted their influence on all the test particles used to examine the evolution of the different populations studied. Since the goal was to compare the impact fluxes on Venus, the Earth, and Mars, these were artificially inflated so that the Earth's radius was increased to a million kilometres, with the radii of the other two planets being scaled in proportion to their actual radii. In an earlier work (Horner & Jones, 2008), we used this method to great effect to examine the effect of the planet Jupiter on the terrestrial impact rate, and at that time carried out detailed tests to prove that the inflation had the expected effect, with no unforeseen drawbacks. In effect, this “super-sizing” of the terrestrial planets increases the size of the target they present to debris on planet-crossing orbits, and the rate with which impacts occur changes such that the impact rate scales directly with the cross-sectional area of the planet (the effective size of the target presented to the in-falling planetesimal). Such direct simulation, made possible through the ongoing advance in computing power available to the modern scientist, allows the impact rate on the terrestrial planets to be directly obtained, marking a significant and important improvement over earlier methods, which made use of Öpik’s equations (Öpik, 1951) to obtain estimates of the impact flux from much smaller scale simulations.

For the initial test, bombarder populations were created by randomly distributing particles in perihelion distance *q*, aphelion distance *Q*, orbital inclination *i*, longitude of the ascending node *Ω*, argument of perihelion *ω*, and mean anomaly *M* (Murray & Dermott, 1999). The asteroid population was constructed from particles having $0° < i < 10°$, *q* and *Q* set between 2 and 4 AU (with *q* calculated first and *Q* calculated afterwards, giving a smooth distribution in *q* rather than *a*). In any variable, between the boundaries, the probability *P* of a given value was constant – except in the case of the aphelion distance. For each object, the aphelion was randomly determined to be a value between the perihelion distance and the outer boundary. As perihelion was itself smoothly, but randomly, distributed between 2 and 4 AU, this resulted in P(Q) increasing as a function of Q. For the comets, the limiting values taken were $5 < q < 10$ AU, $5 < Q < 30$ AU and $0° < i < 30°$ (since we were simulating a population analogous to the Centaurs in the modern outer Solar system, in which objects at low inclinations are dominant, this range of *i* is a reasonable one). The three rotation angles (*ω*, *Ω* and *M*) were randomly set between 0° and 360°. In total, 100,000 particles were created in each of the two populations.

The particles were followed for 10 Myr, or until they were removed from the system by ejection, collision with the Sun, or collision with one of the planets. The timing and mechanism of removal from the Solar System was recorded in an output file, which allowed collisional histories to be obtained for each of the planets – see Table 1.

After examining the results of this first set of simulations, we decided to perform a second set of simulations, in this case comparing the inward flux from objects in the inner and outer parts of the outer Solar System. Here, we split the space between Jupiter and Neptune into two, and populated each region with 50,000 objects. The first group of objects, which we called the "JNS" population, were created with semi-major axes between 6 and 10 AU, eccentricities less than 0.2, and inclinations less than 10 degrees. The second group, the "SNN" objects, were created with the same spread of eccentricities and inclinations, but with semi-major axes between 10 and 30 AU. In this case, randomisation on the basis of eccentricities and semi-major axes, rather than perihelion and aphelion distances, was used, since there was no requirement for the population to be tightly constrained within a given area (as opposed to the case of the asteroid belt, where a $\{q:Q\}$ distribution allows the belt to be well constrained). The rotational orbital elements for each population were again distributed randomly between 0 and 360 degrees. In both populations, as before, the distribution of objects in each element was created to be smooth, with all values having equal probability.

Table 2 provides details of the number of impacts on Venus, Earth, and Mars from objects which began life in the JNS and SNN regions. It is immediately clear that more objects are flung inward to collisions with these planets from those objects that start near the orbits of Jupiter and Saturn. However, this is not altogether unexpected, since the majority of objects coming inward from the SNN population will first pass through the JNS population on their way to the terrestrial planets (objects on Centaur-like orbits beyond Saturn are typically transferred inwards through a series of perihelion-aphelion interchanges, as described in Horner *et al*., 2003), and will simply typically take a longer time to reach the inner Solar system. Indeed, we believe that this is the primary reason that the ratios between the number of impacts on Venus/Mars to the number on the Earth is so similar between the two runs (effectively identical, given the precision of the results quoted) – simply, the SNN population is effectively a second test of the impact ratios from the JNS region, delayed by the time that it takes the particles involved to evolve inward from one region to the other.

As a third and final test, we examined the effect of a highly stirred asteroid belt, akin to that which might have led to the late heavy bombardment due to the effects of Jupiter and Saturn in the Nice model, on the impact fluxes on the three terrestrial worlds. In this run, we looked at objects with initial perihelia between 0.5 and 2.0 AU, semi-major axes between 2.0 and 4.0 AU, eccentricities greater than 0.2 and inclinations less than 10 degrees. Once again, objects were distributed with uniform probabilities across each element. These objects were chosen to represent an already planet crossing population which had been injected from the main belt during a catastrophic destabilisation event. 100,000 such particles were created and, again, followed for 10 Myr. The impact rates experienced by the planets in this run are significantly higher than any of the others – because almost all of the initial objects were set on planet-crossing orbits at the start of their lives (Table 3). It should be noted here that, as a result of the distribution chosen for these objects, a significant number began the runs on orbits which were already planet crossing. Given that the population we wished to study was chosen to represent the aftermath of a sudden, violent stirring of the asteroid belt, this seemed a reasonable, albeit extreme, case to chose. In reality, it is more likely that such an event would lead to a less strongly stirred belt, whose members would then evolve as simulated. This extreme setup was chosen to contrast with the asteroid belt examined earlier, to highlight the differences between our current Solar System and that at the time of the Late Heavy Bombardment, and we encourage the reader to view these two runs as representing two ends of the spectrum between a quiescent and turbulent Solar System.

One way to present the results of these three simulations is to consider the ratio of impacts on each planet normalised to that on the Earth. This normalisation is applied in Table 4. It is immediately clear that cometary and asteroidal populations have a very different spread of impact fates, when one considers their effects on the terrestrial planets. For example, Mars receives far more asteroidal impactors than either the Earth or Venus, while it receives far fewer cometary objects than either of the other terrestrial planets studied. The results for the stirred asteroid belt ($N_{\text{ast-stir}}$) appear to be intermediate between those for the cometary populations and those for the originally cool disk used for $N_{\text{ast-init}}$ (the asteroid belt used in our first set of integrations). This is as expected – since many of the objects in $N_{\text{ast-stir}}$'s initial population are on highly eccentric planet crossing orbits, often with aphelia beyond Jupiter, it is only to be expected that there would be members of that population that behave more like their cometary brethren than the more stable belt described in Table 1.

Throughout our simulations, it is clear that Venus experiences a smaller proportion of asteroidal collisions than the Earth, and Mars a greater proportion, whilst the cometary impact flux is more closely tied to the size of the targets presented by the planets (although, once again, the greater ease with which objects can be dropped on to Mars than Venus leads to the Martian value being enhanced over that which would be expected were the impact rate solely governed by planet cross-sectional area). Under the assumption that cometary objects would contain more deuterium than their asteroidal counterparts, this would appear to suggest that the initial D:H ratio on Venus would have been higher than that on the Earth, which in turn will be higher than that on Mars, should the water on these planets have been sourced from populations akin to those studied.

The ratios today are such that D:H for Venus is about 150 times that of the Earth, but D:H for Mars is *higher* than that of the Earth, by about five times (Donahue *et al.,* 1982; de Bergh *et al.,* 1991; Owen *et al.,* 1988)). However, various fractionating loss processes have operated since these planets were born, some with uncertain effects (Jones, 2007), so the present D:H ratios cannot be used to infer the primordial ratios. However, we can use some simple examples to show how the kind of results we obtained above could be translated into D:H values incorporated in the terrestrial planets.

4) Discussion

The values of N_f in Table 1 imply that the number of asteroids hitting a planet *per comet* varies drastically through the inner Solar System. What does this mean? If we look at the formation of the planets, and their acquisition of volatiles, these results must be considered in terms of the three main competing theories outlined above.

First, we have the endogenous accretion model, which requires that volatiles were acquired by the planets *during their formation*. As stated earlier, this theory is currently considered insufficient to explain the level of terrestrial hydration. Nevertheless, it is important to consider the effect of our results on its implications for terrestrial deuteration. Historically, in the discussion of such models, it has been argued that endogenous hydration means that the planets would have similar volatile budgets, since some of the volatiles would be sourced from asteroids beyond the ice line, with the bulk coming from *in-situ* hydrated silicates. However, our results show that such an assumption may no longer be valid. Under the assumption that Jupiter has already formed by the time the terrestrial planets are coming together, then it is clear that there will be a flux of cometary material through the inner Solar System, which would add to the volatiles incorporated in the planets. How that fraction compares to the amount of asteroidal volatiles sleeting through the inner Solar System, or the amount of water incorporated from *in-situ* hydrated silicates remains undetermined. However, even in the case where the cometary fraction is orders of magnitude lower than the other sources, these results still show that one could reasonably expect differences between the primordial D:H values in the water of the terrestrial planets, simply because an asteroidal contribution finds it much harder to reach Venus than Mars. Were the asteroidal flux enhanced by the effects of gas drag, one might expect that the difference between Venus and Mars would be even greater, as both Mars and the Earth have their opportunity to sweep up the bulk of the asteroidal material prior to its arrival at Venus.

Such considerations could be considered to be particularly relevant when one considers the “Early Exogenous Water” models, since the ratio of material from near and beyond Jupiter incorporated in the planets could play a significant role in determining their final D:H abundances. However, since these models require the great bulk of hydrating material to be sourced from a small number of embryos in the outer Asteroid belt, it seems that the variations between cometary and asteroidal flux on the planets in question would have little or no effect on the overall levels of deuteration on these worlds.

In the *"Late Veneer"* model, in which the terrestrials are assumed to have formed (nearly) dry, or become devolatilised through their formation, receiving their volatiles later (maybe during the LHB?), our results are particularly interesting. As an example: following the Nice model (Gomes *et al.*, 2005), in which the number of asteroids and comets hitting the Earth during the LHB are roughly equivalent, then it is clear from our results that Mars would originally exhibit a much more asteroidal D:H ratio, while Venus would have a more cometary value. This suggests, then, that Venus would have a volatile make-up closer to that of the outer Solar System, when compared to

Mars, with the Earth somewhere in the middle. From our results with an excited asteroid belt, similar to that which might have been caused by a disturbance like that proposed in the Nice model, it is clear that the excitement of the belt can cause an increased asteroidal flux on the Earth and Venus, when compared to the rate at Mars. However, despite this increase, it seems that the impact flux would still lead to a significant disparity between the number of cometary and asteroidal bodies falling onto Venus when compared to those on Mars, and so we would still expect Mars's initial D:H ratio to be significantly more asteroidal in nature than that on Venus, were the water entirely sourced in this way. It should be noted here that recent simulations carried out by the Nice group (Morbidelli, private communication) find the opposite result - that with certain initial conditions Mars actually receives significantly more cometary material, and less asteroidal impacts per unit area than the Moon. The differences between their results and ours likely result from different initial conditions, but they serve to highlight the need for a more detailed understanding to be reached of the processes by which the terrestrial planets are hydrated.

A more rigorous mathematical examination of the situation highlights how such variations in impact rate can lead to a significant, albeit modest, level of variation in deuteration between the terrestrial planets. In the following, we consider the case where all the volatiles were brought to the terrestrial planets through the processes described earlier, not through collision with a planet-sized embryo.

First, let us assume that an upper bound on the cometary contribution to the Earth's volatile budget can be derived by examining the isotopic hydrogen-mass balance within carbonaceous chondrites, comets and the present-day Earth (Deloule *et al.*, 1998). Such calculation yields:

$$f_{\oplus} \leq (149 - 128)/(309 - 128) = 0.12, \qquad (1)$$

where $f_{\oplus}$ is the fraction of terrestrial water provided by cometary bodies of high D:H, 149 is the present-day mean D:H ratio of the bulk Earth, as determined by Lécuyer *et al.*, (1998), measured in parts per million, while 309 is the accepted value for highly deuterated cometary water, and 128 is a minimum possible D:H ratio for the primitive Earth, corresponding to the minimum value measured in carbonaceous chondrites. Hence, the D:H ratio of the present-day Earth's water suggests a cometary contribution not exceeding 12% (though we here caution the reader that the D:H value for cometary objects is based on a very small sample, and may change significantly as comets from different reservoirs are measured in future. Nevertheless, it gives a reasonable starting point for our calculat<ion).

We now aim to determine the D:H ratio acquired by water on Mars and Venus at the time of their formation. We consider three populations of objects in our calculations: SNN comets, JNS comets and the asteroids. For simplicity, we ignore prior mixing between the dynamically linked JNS and SNN populations, and also assume that only the SNN comets are highly enriched in deuterium, with the JNS comets and the asteroids sharing the same low D:H ratio. With these assumptions, the fraction $f_{\oplus}$ of water delivered by high-D comets to Earth can be expressed as follows:

$$f_{\oplus} = \frac{N_{\mathrm{SNN}_{\oplus}}}{N_{\mathrm{SNN}_{\oplus}} + N_{\mathrm{AST}_{\oplus}} + N_{\mathrm{JNS}_{\oplus}}} = \frac{1}{1 + \frac{N_{\mathrm{AST}_{\oplus}}}{N_{\mathrm{SNN}_{\oplus}}} + \frac{N_{\mathrm{JNS}_{\oplus}}}{N_{\mathrm{SNN}_{\oplus}}}} \leq 0.12 \tag{2}$$

As a result, using only these simple assumptions, one can derive the following relationship between the respective numbers of asteroids and comets that collided with the youthful Earth:

$$\frac{N_{\mathrm{AST}_{\oplus}}}{N_{\mathrm{SNN}_{\oplus}}} + \frac{N_{\mathrm{JNS}_{\oplus}}}{N_{\mathrm{SNN}_{\oplus}}} = \frac{1}{f_{\oplus}} - 1 \geq \frac{1}{0.12} - 1 = 7.33 \tag{3}$$

Now, let us define f_p, the fraction of water delivered by high-D comets to a given planet:

$$f_{\mathrm{P}} = \frac{N_{\mathrm{SNN}_{\mathrm{p}}}}{N_{\mathrm{SNN}_{\mathrm{p}}} + N_{\mathrm{AST}_{\mathrm{p}}} + N_{\mathrm{JNS}_{\mathrm{p}}}} = \frac{1}{1 + \frac{N_{\mathrm{AST}_{\mathrm{p}}}}{N_{\mathrm{SNN}_{\mathrm{p}}}} + \frac{N_{\mathrm{JNS}_{\mathrm{p}}}}{N_{\mathrm{SNN}_{\mathrm{p}}}}} \tag{4}$$

From Table 4, we note that the relative delivery efficiency to the terrestrial planets from SNN and JNS comets are essentially the same, while those from the asteroid belt are very different. This means that considering only SNN comets and asteroids, and neglecting the contribution from JNS comets, will therefore give an upper value of the possible D:H ratio in this simplified case. With these simplifications, Equation (4) becomes:

$$f_{\mathrm{p}} = \frac{1}{1 + \frac{\alpha_{\mathrm{p}} N_{\mathrm{AST}_{\oplus}}}{\beta_{\mathrm{p}} N_{\mathrm{SNN}_{\oplus}}}} = \frac{1}{1 + \frac{\alpha_{\mathrm{p}}}{\beta_{\mathrm{p}}}\left(\frac{1}{f_{\oplus}} - 1\right)} \leq \frac{1}{1 + 7.33\frac{\alpha_{\mathrm{p}}}{\beta_{\mathrm{p}}}} \tag{5}$$

where $\alpha_{\mathrm{p}} = \frac{N_{\mathrm{AST}_{\mathrm{p}}}}{N_{\mathrm{AST}_{\oplus}}}$ and $\beta_{\mathrm{p}} = \frac{N_{\mathrm{SNN}_{\mathrm{p}}}}{N_{\mathrm{SNN}_{\oplus}}}$. As can be seen from Table 4, the normalized impact ratios for Venus and Mars are $\alpha_{\mathrm{V}} = 0.29$, $\beta_{\mathrm{V}} = 0.82$, $\alpha_{\mathrm{M}} = 2.39$ and $\beta_{\mathrm{M}} = 0.27$. We can then determine upper limits for the fraction of impacts resulting from highly deuterated comets at Venus and Mars. These upper limits are $f_{V,max}$ = 0.278 and $f_{M,max}$ = 0.015 for Venus and Mars, respectively. In the case of a highly excited asteroid belt, similar to that used in our third simulation, α_V and α_M are 0.50 and 1.29. In this case, $f_{V,max}$ and $f_{M,max}$ become 0.183 and 0.028, respectively.

On the other hand, the initial D:H ratio of water in planet p is derived from f_p by:

$$f_p = ((D{:}H)_p - 128)/(309 - 128) \leq f_{p,max} \qquad (6)$$

$(D{:}H)_{Venus}$ and $(D{:}H)_{Mars}$ must therefore not exceed 178.7×10^{-6} and 130.7×10^{-6}, respectively. These values correspond to approximately 1.20 and 0.88 times the value taken for the present day bulk Earth, respectively. In the case of a highly excited asteroid belt, $(D{:}H)_{Venus}$ and $(D{:}H)_{Mars}$ do not exceed 160.6×10^{-6} and 133.1×10^{-6}, respectively, and these values correspond to approximately 1.08 and 0.89 times the value taken for the present day bulk Earth.

A more realistic estimate can be obtained by assuming some a priori mixing ratio between objects that formed in the JNS and SNN regions. According to Morbidelli *et al.*, (2000) and references therein, the JNS population could have contained of order 50-100 $M_\oplus$, while the SNN population contained a further 50 $M_\oplus$ of material. In our simulations, the same number of particles was used in both populations. Hence, a realistic value of the ratio $\frac{N_{JNS_p}}{N_{SNN_p}}$ would be 1-2 times that from Table 2. Inserting this into Eq. (3), we find:

$$\frac{N_{AST_\oplus}}{N_{SNN_\oplus}} \geq \frac{1}{0.12} - 1 - A \qquad (7)$$

with either A = 944/489 or A= 2×944/489. As a result, Eq. (5) becomes:

$$f_p = \frac{1}{1+\dfrac{\alpha_p N_{AST_\oplus} + \gamma_p N_{JNS_\oplus}}{\beta_p N_{SNN_\oplus}}} = \frac{1}{1+\dfrac{\alpha_p}{\beta_p}\left(\dfrac{1}{f_\oplus} - 1 - A\right) + \dfrac{\gamma_p}{\beta_p}A} \leq \frac{1}{1+\dfrac{\alpha_p}{\beta_p}(7.33 - A) + \dfrac{\gamma_p}{\beta_p}A} \qquad (8)$$

where $\gamma_p = \dfrac{N_{JNS_p}}{N_{JNS_\oplus}}$.

Taking A = 944/489, and using the normalized impact ratios for Venus and Mars from Table 4 (namely $\alpha_V = 0.29$, $\beta_V = 0.82$, $\gamma_V = 0.78$, $\alpha_M = 2.39$, $\beta_M = 0.27$, and $\gamma_M = 0.34$), it is clear that the upper limits for the fraction of highly deuterated comets accreted by Venus and Mars would be $f_{V,max} = 0.211$ and $f_{M,max} = 0.019$. In this case, $(D:H)_{Venus}$ and $(D:H)_{Mars}$ would not exceed 166.2 × 10^{-6} and 131.4 × 10^{-6}, respectively, values that correspond to approximately 1.12 and 0.88 times the mean D:H ratio of the value obtained for the bulk Earth. In the case of a highly excited asteroid belt, (i.e. taking $\alpha_V = 0.50$ and $\alpha_M = 1.29$), we obtain $f_{V,max} = 0.163$ and $f_{M,max} = 0.034$ as upper limits for the fraction of high-D comets accreted by Venus and Mars. In this case, the upper bounds on $(D:H)_{Venus}$ and $(D:H)_{Mars}$ can be placed at 157.5 × 10^{-6} and 134.2 × 10^{-6}, respectively, values that correspond to approximately 1.06 and 0.90 times the mean D:H ratio of the value obtained for the bulk Earth.

On the other hand, if we take A = 2× 944/489, with otherwise unchanged conditions, we obtain $f_{V,max} = 0.170$ and $f_{M,max} = 0.027$ in the case of the classic asteroid belt. In this case, the resulting upper limits on $(D:H)_{Venus}$ and $(D:H)_{Mars}$ lie at 158.8 × 10^{-6} and 132.9 × 10^{-6}. These values correspond to approximately 1.07 and 0.89 times the bulk Earth value, respectively. Finally, in the case of a highly excited asteroid belt, we obtain $f_{V,max} = 0.147$ and $f_{M,max} = 0.045$. In this case, the maximum possible $(D:H)_{Venus}$ and $(D:H)_{Mars}$ are 154.6 × 10^{-6} and 136.1 × 10^{-6}, respectively. These values correspond to approximately 1.04 and 0.91 times the bulk Earth value.

Plugging Eq. (1) into Eq. (2) or Eq. (3) allowed us to estimate the relative importance of the various reservoirs of impactors (asteroids and comets), assuming they were the only source of volatiles. If we now consider the case of a planet-sized embryo colliding with the Earth, while Venus and/or Mars can avoid such an impact, then we can no longer place a constraint on the fraction of highly D-enriched comets compared to asteroidal impactors. Hence, the (D:H) could be anywhere between asteroidal and cometary, especially for Mars which is more likely to have avoided impact from an embryo (Lunine *et al.*, 2003). In this case, we must resort to other means to estimate the relative importance of the various reservoirs. As mentioned above, Morbidelli *et al.* (2000) assumes a SNN population of 50 $M_\oplus$ of material. In order to give a lower limit to the enrichment in Deuterium in Mars, we will use the upper limit for the populations with low D:H ratios. Hence we assume a JNS population of 100 $M_{\oplus,}$ and 4 $M_\oplus$ of material in the asteroid belt. Hence, for Mars, we obtain:

$$(D{:}H)_{Mars} = \frac{\left(\frac{3777\times 4}{100000}\right)\times 128 + \left(\frac{324\times 100}{50000}\right)\times 128 + \left(\frac{131\times 50}{50000}\right)\times 309}{\frac{3777\times 4}{100000} + \frac{324\times 100}{50000} + \frac{131\times 50}{50000}} \times 10^{-6} = 153 \text{ x } 10^{-6}$$

Dividing by 2 the two low-(D:H) populations yields $(D{:}H)_{Mars}$ = 173 x 10^{-6}. Hence, in such a case, primordial Mars can be significantly more D-enriched than the Earth.

As can be seen through this admittedly simplified series of examples, variations in the impact fractions occurring at each terrestrial planet can easily lead to a variation of 10-20% in the initial level of deuteration on those planets. Future measurements of D:H across the Solar System could help to refine these estimates, though it seems unlikely that the resulting variation, planet-to-planet, would exceed a factor of two or so. Nevertheless, it is clear that the assumption of a constant initial D:H ratio across the terrestrial worlds does not stand up to this closer analysis, and future work examining the history of deuteration across the inner Solar System should take this into account.

On a more general level, our results are particularly interesting since they highlight the need for a more detailed study of the sources of impactors across the inner Solar System. Such work would require far more detailed model populations for the cometary and asteroidal threat, and would have to include a study of the effects of the Oort cloud comets. Our simple calculations have shown that this is an area which merits significant further study.

5) Conclusions

Through a number of detailed *n*-body simulations, we have studied the way in which the impact rates on Venus, the Earth and Mars vary as a function of the source population of impactors. As a result of different delivery mechanisms, we found that, for our simple source populations, Mars is far more likely to be impacted by asteroidal material than either the Earth or Venus, even in situations where the asteroid belt has been hugely stirred and destabilised (as has been suggested occurred to cause the Late Heavy Bombardment). For cometary impactors, even those originating on low eccentricity orbits beyond Jupiter, the situation is reversed – the impact rate on Mars becomes significantly lower than that on the other two terrestrial planets studied – a result, primarily, of Mars presenting a smaller target to the in-falling bodies than the other two planets. These two effects lead to the obvious conclusion that the terrestrial planets will have received significantly different quantities of impact-sourced material from the various reservoirs of debris in the Solar system, which has major implications for the hydration history of the worlds in question.

In our simulations, when compared with the Earth, Venus receives less material from both reservoirs (asteroidal and cometary). However, the amount of cometary material falling on the planet is significantly closer to that falling on the Earth than the relative contributions from asteroidal material. In other words, when compared to the Earth, Venus would be expected to accrete more cometary material per asteroid impactor, while Mars would expect significantly less cometary material per asteroid impactor. This therefore leads to the slightly surprising conclusion that, in terms of accreted material, Venus is more representative of the outer Solar System than Mars, with the Earth falling somewhere in-between.

Given recent work (e.g. Horner *et. al.*, 2007), it is clear that the D:H ratio within water on a given small body may be strongly related to its formation location. This, coupled with the results in this work, tends to suggest that, at least in terms of the volatile component brought by impacting bodies, Venus would have a nascent D:H value in water higher than that on the Earth, which would, in turn, be higher than that for Mars (since objects with greater formation distances would have higher D:H). At the very least, this effect should be taken into account when assumptions are made about the initial deuteration levels on these worlds.

Different models of planetary formation and hydration involve different reservoirs of hydrated bodies falling onto the terrestrial planets. Previous studies of the flux of hydrated material to the terrestrial planets (Levison *et al.*, 2001; Lunine *et al.*, 2003) have examined particular aspects of planetary formation (the evolution of Uranus and Neptune as a potential source for the Late Heavy Bombardment, and the origin of water on Mars). Although the results of those studies relied on a great number of specific assumptions which may or may not reflect the still poorly understood birth of our Solar system (the formation and relocation of Uranus and Neptune being delayed by ~600 Myr from that of the Solar system, Mars having experienced no important giant impact during the late stages of its formation (c.f. Andrews-Hanna *et al.*, (2008), who show strong evidence that such a collision did occur - though there is no reason to suspect that the impactor was not a dry embryo), they act to highlight the uncertainty in the origin of water on the terrestrial planets. Both works suggested that Mars and the Earth would have experienced significantly different hydration histories, and, when taken in concert with our results, make it clear that simple assuming that each of the terrestrial planets would have initially had the same level of deuteration, and the same hydration history, can no longer be considered valid. Indeed, both our results and those of these earlier works show that the various hydration models currently proposed for the terrestrial planets would lead to different D:H signatures, when combined with knowledge of the impact rates from the source reservoirs. It is possible that such information, with more detailed modelling, could help to provide an extra constraint on models of the formation of our planetary system. Since the results of Levison et al. (2001) and Lunine et al. (2003) suggest different results to our own, it is obvious that our knowledge of the detail of terrestrial planet formation and hydration is currently insufficient to predict the true original deuteration level on each of the planets considered. However, the one shared conclusion of our three works is that assuming the same initial values for the Venus, the Earth and Mars is dangerous and unfounded, and it is clear that, as future work further refines our knowledge of our Solar system's formation, the origin of water on the terrestrial planets is a topic which requires significant further study.

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References

Andrews-Hanna, J. C., Zuber, M. T., Banerdt, W. B. 2008. The Borealis basin and the origin of the martian crustal dichotomy. *Nature* **453**, 1212-1215.

Bockelée-Morvan, D., and 11 colleagues 1998. Deuterated Water in Comet C/1996 B2 (Hyakutake) and Its Implications for the Origin of Comets. *Icarus* **133**, 147-162.

Chambers, J. E. 1999. A hybrid symplectic integrator that permits close encounters between massive bodies. *Monthly Notices of the Royal Astronomical Society* **304**, 793-799.

de Bergh, C., Bezard, B., Owen, T., Crisp, D., Maillard, J.-P., Lutz, B. L. 1991. Deuterium on Venus - Observations from earth. *Science* **251**, 547-549.

Deloule, E., Robert, F., Doukhan, J. C. 1998. Interstellar hydroxyl in meteoritic chondrules: implications for the origin of water in the inner solar system. *Geochimica et Cosmochimica Acta* **62**, 3367-3378.

Donahue, T. M., Hoffman, J. H., Hodges, R. R., Watson, A. J. 1982. Venus was wet - A measurement of the ratio of deuterium to hydrogen. *Science* **216**, 630-633.

Donahue, T. M. 1999. New Analysis of Hydrogen and Deuterium Escape from Venus. *Icarus* **141**, 226-235.

Drake, M. J. 2005. Origin of Water in the Terrestrial Planets. *Meteoritics & Planetary Science* **40**, 519-527.

Drake, M. J. 2004. Origin of Water in the Terrestrial Planets. *Meteoritics & Planetary Science*, vol. 39, Supplement. Proceedings of the 67th Annual Meeting of the Meteoritical Society, August 2-6, 2004, Rio de Janeiro, Brazil, abstract no.5031 39, 5031.

Drouart, A., Dubrulle, B., Gautier, D., Robert, F. 1999. Structure and Transport in the Solar Nebula from Constraints on Deuterium Enrichment and Giant Planets Formation. *Icarus* **140**, 129-155.

Franklin, F., Lecar, M. 2000. On the transport of bodies within and from the asteroid belt. *Meteoritics and Planetary Science* **35**, 331-340.

Geiss, J., Reeves, H. 1981. Deuterium in the solar system. *Astronomy and Astrophysics* **93**, 189-199.

Gomes, R., Levison, H. F., Tsiganis, K., Morbidelli, A. 2005. Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature* **435**, 466-469.

Gurwell, M. A. 1995. Evolution of Deuterium on Venus. *Nature* **378**, 22.

Horner, J., Evans, N. W., Bailey, M. E., Asher, D. J. 2003. The populations of comet-like bodies in the Solar system. *Monthly Notices of the Royal Astronomical Society* **343**, 1057-1066.

Horner, J., Mousis, O., Hersant, F. 2007. Constraints on the Formation Regions of Comets from their D:H Ratios. *Earth Moon and Planets* **100**, 43-56.

Horner, J., Mousis, O., Alibert, Y., Lunine, J. I., Blanc, M. 2008. Constraints from deuterium on the formation of icy bodies in the Jovian system and beyond. *Planetary and Space Science* **56**, 1585-1595.

Horner, J., Jones, B. W., 2008. Jupiter – Friend or Foe? I: The Asteroids. *International Journal of Astrobiology*, *in press, to appear in issue 7.3/7.4.*

Jones, B.W. (2007). *Discovering the Solar System*. John Wiley and Sons, Chichester, UK, Section 10.4.

Krasnopolsky, V. A., Mumma, M. J., Randall Gladstone, G. 1998. Detection of Atomic Deuterium in the Upper Atmosphere of Mars. *Science* **280**, 1576.

Lécuyer, C., Simon, L., Guy, F. 2000. Comparison of carbon, nitrogen and water budgets on Venus and the Earth. *Earth and Planetary Science Letters* **181**, 33-40.

Lécuyer, C., Gillet, P., Robert, F. 1998. The hydrogen isotope composition of seawater and the global water cycle. *Chemical Geology*, 145, 249-261.

Levison, H. F., Dones, L., Chapman, C. R., Stern, S. A., Duncan, M. J., Zahnle, K. 2001. Could the Lunar "Late Heavy Bombardment" Have Been Triggered by the Formation of Uranus and Neptune? *Icarus*, **151**, 286-306.

Lunine, J. I., Chambers, J., Morbidelli, A., Leshin, L. A. 2003. The origin of water on Mars. *Icarus*, **165**, 1-8.

Médard, E., Grove, T. L. 2006. Early hydrous melting and degassing of the Martian interior. *Journal of Geophysical Research (Planets)* **111**, 11003.

Morbidelli, A., Chambers, J., Lunine, J. I., Petit, J. M., Robert, F., Valsecchi, G. B., Cyr, K. E. 2000. Source regions and time scales for the delivery of water to Earth. *Meteoritics and Planetary Science* **35**, 1309-1320.

Mousis, O., Gautier, D., Bockelée-Morvan, D., Robert, F., Dubrulle, B., Drouart, A. 2000. Constraints on the Formation of Comets from D/H Ratios Measured in H2O and HCN. *Icarus* **148**, 513-525.

Mousis, O. 2004. An estimate of the D/H ratio in Jupiter and Saturn's regular icy satellites - Implications for the Titan Huygens mission. *Astronomy and Astrophysics* **414**, 1165-1168.

Murray, C. D., Dermott, S. F. 1999. Solar System dynamics. CUP, Sections 2.4 and 2.8.

Öpik, E. J. 1951. Collision probabilities with the planets and the distribution of interplanetary matter. *Proc. R. Ir. Acad.* **54A**, 165.

Owen, T., Maillard, J. P., de Bergh, C., Lutz, B. L. 1988. Deuterium on Mars - The abundance of HDO and the value of D/H. *Science* **240**, 1767-1770.

Owen, T., Bar-Nun, A. 1995. Comets, impacts and atmospheres. *Icarus* **116**, 215-226.

Petit, J.-M., Morbidelli, A., Chambers, J. 2001. The Primordial Excitation and Clearing of the Asteroid Belt. *Icarus* **153**, 338-347.

Robert, F., Merlivat, L., Javoy, M. 1979. Deuterium concentration in the early solar system - Hydrogen and oxygen isotope study. *Nature* **282**, 785-789.

Robert, F., Epstein, S. 1982. The concentration and isotopic composition of hydrogen, carbon and nitrogen in carbonaceous meteorites. *Geochimica et Cosmochimica Acta* **46**, 81-95.

Solomon, S. C., and 16 colleagues 2005. New Perspectives on Ancient Mars. *Science* **307**, 1214-1220.

Turner, B. E. 2001. Deuterated Molecules in Translucent and Dark Clouds. *Astrophysical Journal Supplement Series* **136**, 579-629.

Table 1. The results of the first simulation. N_{AST} gives the number of asteroid collisions upon the planet in question, N_{com} gives the number of cometary impacts, while N_f gives N_{AST}/ N_{COM} for the given planet.

Planet	Venus	Earth	Mars
N_{AST}	466	1583	3777
N_{COM}	1357	1577	436
N_f	0.34	1.00	8.66

Table 2. The results of the second simulation. N_{JNS} gives the number of collisions upon the planet in question resulting from objects initially in orbits between the planets Jupiter and Saturn, while N_{SNN} gives the number of impacts from objects which started between Saturn and Neptune. The values given in parenthesis give the ratio of impacts on that planet, from that source, compared to that on the Earth.

Planet	Venus	Earth	Mars
N_{JNS}	734 (0.78)	944 (1.00)	324 (0.34)
N_{SNN}	403 (0.82)	489 (1.00)	131 (0.27)

Table 3. The results of the third simulation. N_{AST} gives the number of collisions upon the planet in question.

Planet	Venus	Earth	Mars
N_{AST}	10867	21660	27873

Table 4. Normalised impact ratios for each of the populations used. Here, $N_{\text{ast-init}}$ gives the results of the initial asteroid run (detailed in Table 1), $N_{\text{com-init}}$ gives the equivalent results for the first cometary run (also Table 1). N_{JNS} and N_{SNN} show the results obtained from the runs detailed in Table 2, while $N_{\text{ast-stir}}$ gives the results obtained from Table 3.

	Venus	Earth	Mars
$N_{\text{ast-init}}$	0.29	1.00	2.39
$N_{\text{com-init}}$	0.86	1.00	0.28
N_{JNS}	0.78	1.00	0.34
N_{SNN}	0.82	1.00	0.27
$N_{\text{ast-stir}}$	0.50	1.00	1.29