DIFFERENCES BETWEEN THE IMPACT REGIMES OF THE TERRESTRIAL PLANETS: IMPLICATIONS FOR ISOTOPIC ABUNDANCES. J. Horner[1], O. Mousis and B. W. Jones[1], [1]Physics and Astronomy, The Open University, Walton Hall, Milton Keynes, UK, MK10 9HQ (j.a.horner@open.ac.uk), [2]Observatoire de Besançon, CNRS-UMR 6091, 41 bis, avenue de l'Observatoire, BP 1615 Besançon, France.

Introduction: The study of the ratio between deuterium and hydrogen in water can tell us many things about the conditions in the early Solar System. Recent modeling work (e.g. [1,2]) suggests that the D:H ratio in the water within icy bodies will vary as a function of their formation distance from the Sun. The closer to the Sun a body formed, the lower the D:H ratio within its water would be. Through the outer Solar System, the value changes quite dramatically, as one moves through the regions in which asteroidal and cometary bodies would have formed.

Another field in which knowledge of the D:H ratio in water is important is the study of the atmospheres of the terrestrial planets, Venus, the Earth and Mars. Here, examination of the current D:H ratio is used to study a variety of planetary properties, from the hydration history of Venus [3], to the behaviour of different aquifers on Mars [4]. However, all these works require a prior knowledge of the original D:H ratio on these planets - a value which is currently unknown.

Many authors assume, in the lack of any other data, that the native D:H ratios within the water on Venus and Mars were the same as the terrestrial value. This assumption informs the decisions made within the studies of these bodies, together with affecting the conclusions obtained. It is not clear, however, that the original D:H ratios on these bodies would have equaled the terrestrial value. In fact, given the chaotic nature of planetary accretion, together with the effects of late giant impacts and the late heavy bombardment, it seems likely that the planets would obtain their vola-tiles from a variety of different reservoirs, and may therefore have water with a wide variety of D:H values.

Three main theories exist for the hydration of the terrestrial planets. The most prevalent, at the current time, is that the terrestrial planets incorporated their volatiles as they accreted, from material slowly sleeting inwards from just outside the snowline [5], together with a significant contribution of water trapped in hydrated silicates, which can survive well within the snowline. In this scenario, it would be expected that the three planets discussed would incorporate effectively the same mix of native volatiles, and that they would have an almost uniform D:H incorporation within their water. However, some work has shown that such accretion is less efficient for Mars, which may have required a significant asteroidal contribution during the later stages of its formation, which would lead to the red planet having a slightly different initial D:H value to the Earth or Venus [6].

The second scenario, that of the "Late Veneer" [7], is less widely accepted, but suggests that the planets formed effectively dry, and that their volatiles were accreted later, during, and as a result of, the Late Heavy Bombardment (LHB). In this model, 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 radii, and hence, in the models described above, with widely ranging D:H values. In this case, it is vitally important to understand how the balance of D:H bearing bodies falling on the terrestrial planets varies 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 [8].

What would the other two atmosphere-bearing terrestrial planets have experienced during this period? It is clear that both would have experienced a similarly enhanced impact regime, but less clear that the mix of impacting bodies would have been the same.

The final model, "early Exogenous Water" [9], suggests that the terrestrial planets were hydrated by material falling inwards from the outer regions of the asteroid belt. This material would have been emplaced in that region during Jupiter's formation, sourced from the huge number of planetesimals which formed beyond the planet and were scattered. In this case, as with the situation with the LHB, it is clear that the terrestrial planets would be influenced by material from a wide variety of locations within the Solar nebula, and thus that the D:H values on these worlds could be different. It is clearly interesting, then, 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.

Simulating the impact flux: In order to study the differences between the asteroidal and cometary contributions to the terrestrial planet impact flux, integrations were carried out using the hybrid integrator within the *MERCURY* package [10]. Test populations were created representing asteroidal and cometary material, and were followed for a period of 10 Myr under the gravitational influence of Venus, the Earth, Mars, Jupiter, Saturn, Uranus and Neptune, in their current configuration. Since the goal was to follow the impact flux on Venus, the Earth, and Mars, these were artificially inflated by lowering their densities, in such a way that the Earth's radius was increased to 1 million kilometers, with the radii of the other two planets being scaled in proportion to their radii.

The bombarder populations were created by randomly distributing particles in q, Q, i, ω, M, and Ω. The asteroid population was constructed from particles having $0° < i < 10°$, q and Q set between 2 and 4 AU (with the perihelion distance calculated first, and the aphelion distance calculated afterwards, giving a smooth distribution in q rather than semi-major axis a). For the comets, the limiting values taken were $5 < q < 10$ AU, $5 < Q < 30$ AU and $0° < i < 30°$. The three rotation angles (ω, M and Ω) were randomly set between 0° and 360°. In total, 50000 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 massive bodies. The timing and means 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.

Planet	**Venus**	**Earth**	**Mars**
N_{ast}	**216**	**826**	**1914**
N_{com}	**686**	**759**	**199**
N_f	**0.315**	**1.09**	**9.62**
N_f/N_{fe}	**0.290**	**1.00**	**8.84**

Table 1: Table showing the results of the collision 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 the ratio of these two values for the given planet. The final row shows the value of N_f, normalised so that that for the Earth equals 1.00

Discussion: In simple terms, the results shown 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? Well, if we look at the formation of the planets, and their acquisition of volatiles, these results must be considered in terms of the two main competing theories, as discussed above.

Firstly, we have the theory that volatiles were acquired by the planets *during their formation*. It has been argued that this means that the planets would have similar volatile budgets - since some of the volatiles would be sourced from the asteroid belt, with the bulk coming from *in-situ* silicates. However, our results show that this simple assumption may no longer be valid. Under the assumption that Jupiter has already formed by the time the terrestrials 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 local 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 would expect a difference in the primordial D:H values in the water of the terrestrial planets, simply as a result of the fact the 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 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 debates are particularly relevant when one considers the “early Exogenous Water” model, since the relative balance if *cis*- and *trans*-Jovian material incorporated in the planets could play a significant role in determining their final D:H abundances.

In the paradigm of the "Late Veneer", in which the terrestrials are assumed to have formed 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 [8], 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, 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 playing “piggy in the middle”.

References:

[1] Mousis et al. (2007) MNRAS, 1175. [2] Horner et al. (2007) EM&P, 100, 43. [3] Donahue (1999), Icarus, 141, 226. [4] Bertaux & Montmessin (2001), JGR, 106, 32879. [5] Morbidelli et al. (2000), M&PSn 35, 1309. [6] Médard & Grove (2006), LPI Contributions, 1335, 68-69 [7] Ozernoy & Ipatov (2001), BAAS, 33, 1352. [8] Gomes et al. (2005), Nature, 435, 466. [9] Morbidelli et al. (2000), Meteor. Planet. Sci., 35, 1309-1320. [10] Chambers (1999), MNRAS, 304, 793