DETERMINING THE SOURCE(S) OF WATER IN THE LUNAR INTERIOR. J. J. Barnes[1], R. Tartèse[1], M. Anand[1,2], I. A. Franchi[1], S. S. Russell[1,2] and D. A. Kring[3], [1]Planetary and Space Sciences, The Open University, Milton Keynes, MK7 6AA, UK (jessica.barnes@open.ac.uk), [2]Department of Earth Sciences, Natural History Museum, London, SW7 5BD, UK, [3]Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX 77058, USA.

Introduction: Recently, there have been numerous studies investigating the amount and isotopic composition of water in lunar materials [e.g., 1-8]. The combined results from these investigations have provided two major insights that have challenged the long-standing paradigm of an anhydrous Moon. The first major insight relates to the new estimates for the water content of the bulk silicate Moon (BSM) ranging from ~ 10 to ~ 400 ppm H_2O [e.g., 1-7,8]. The second major insight is related to the source of lunar water, which ranges from Oort cloud comets [2], to carbonaceous chondrite-like asteroids [e.g., 3-5,7], or perhaps even from the proto-Earth [3,5]. Whilst we have some understanding about the flux of asteroids and comets to the Moon during the purported 'late heavy bombardment' (LHB; ~ 10 % comets, 90 % asteroids, [e.g., 9]), we have very limited understanding of the flux of these objects during the first ~ 100 Ma of lunar history (i.e., during lunar differentiation or lunar magma ocean (LMO) stage).

In this study, we have estimated the mass of water delivered to the Moon in the first 100 Ma of its geological history that satisfies current estimates of water in the BSM, followed by an estimate of the relative proportions of asteroidal and cometary material delivered to the Moon that is consistent with the H-isotopic composition of water in the lunar interior [e.g., 3-5].

Delivery of water to the Moon by asteroids and comets: The following calculations assume a lunar mantle (proxy for the LMO) of 400 km depth. Enstatite chondrites have not yet been considered since they contain low abundances of water [e.g., 10], but they will be included in follow-on studies. We have considered two end-members in which ~ 10 ppm H_2O [i.e., 3.94×10^{17} kg H_2O] and up to 400 ppm H_2O [i.e., 1.58×10^{19} kg H_2O] were added to the lunar interior. These calculations use the following δD values averaged from [11-12] and for simplicity assume that the bulk δD values are equivalent to the δD value of the water they contain: CI = +80 ‰, CO = -50 ‰, CM = +30 ‰, CV = +15 ‰, CR = +630 ‰, 103P = +34 ‰ [13], and Oort cloud comets = ~ +900 ‰ [14].

Scenario 1 (Moon accreted dry). This scenario assumes the Moon accreted without any water, and therefore, received all of its water post-lunar accretion but prior to the solidification of a significantly thick crust. In this scenario the initial δD signature of the lunar interior is not related to the total amount of water added since it is assumed that there is no water in the Moon to begin with. Thus, a number of combinations for water from carbonaceous chondrites (CI, CO, CV, CM) and Jupiter-Family 103P-like comets are permitted as these result in δD values between -50 ‰ and +80 ‰. When mixed with 97 % of water from CI-type chondrites, 3 % of water from CR-type chondrites is permitted in order to yield a final δD value < +100 ‰. In contrast, up to 2 % water from Oort Cloud-like comets can be accommodated (98 % water from CI-type chondrites). Importantly, a δD value of < -50 ‰ is not achieved through any of the mixing calculations, and thus offers no explanation for the low δD values reported by [5-6]; suggesting that either there is another source of water (perhaps proto-Solar [15]) which we have not yet considered for the Moon but has been for Earth [e.g., 16], or that the Moon didn't in fact accrete dry.

Scenario 2 (Moon accreted with some water). In this case it is assumed that the Moon accreted with 1 ppm H_2O (i.e., 3.94×10^{16} kg H_2O) [17], and any additional water (9 to 399 ppm H_2O) was added to the lunar mantle during the 'LMO phase' of the Moon. In both cases it is assumed that water in the lunar interior was characterized by an initial δD value of -200 ‰ (based on the results of [5] and estimates of [4,18]). We have modeled the proportions of asteroids and comets that could have been accreted in order for the lunar interior to retain a δD value of < +100 ‰ [e.g., 3-4]. The mixing of waters from carbonaceous chondrites of CI-, CM-, CO-, and CV-types, and 103P-like comets, in differing proportions, results in a lunar interior characterized by δD value from ~ -64 to +52 ‰ for addition of 9 ppm H_2O, and δD value from ~ -49 to +79 ‰ for the addition of 399 ppm H_2O. Conversely, CR-type carbonaceous chondrites are characterized by elevated δD signatures and when mixed with water from CI-type chondrites, < 10 % water from CR-type material is allowed in order to retain a final δD value of < +100 ‰ from the addition of 9 ppm H_2O (Fig.1), and < 4 % of water from CR-type chondrites when 399 ppm H_2O is added. It is found that < 7 % water is contributed by Oort Cloud comets (the remaining 93 % from CI-type chondrites) for the addition of 9 ppm H_2O, and < 3 % cometary water may be contributed during addition of 399 ppm H_2O (Fig.1).

However, based on N isotopes and C/N ratios, the lunar interior is best matched with CO-type carbonaceous chondrites [19]. Since CO-type carbonaceous chondrites have lowest δD values of the materials we have considered, the 2-component mixing model was adapted to assume that CO-type carbonaceous chondrites contributed the majority of lunar water. For the addition of 9 ppm H_2O, < 20 % water from Oort-like comets and up to 27 % water from CR-type chondrites can be accommodated (when mixed with ~ 80 % and 73 % water from CO-type chondrites, respectively). This implies the addition of 0.04 % of lunar mass (from CO-type) which is consistent with [7,20]. However, for the addition of 399 ppm H_2O, < 16 % water from Oort-like comets and up to 22 % water from CR-type chondrites is permitted (when mixed with ~ 84 % and 78 % water from CO-type chondrites, respectively), and this increases the amount of CO-chondrite material accreted to the Moon to ~ 1.9 % of the lunar mass which is not consistent with previous estimates [e.g., 7], suggesting that CO-type chondrites did not deliver the majority of water to the lunar interior.

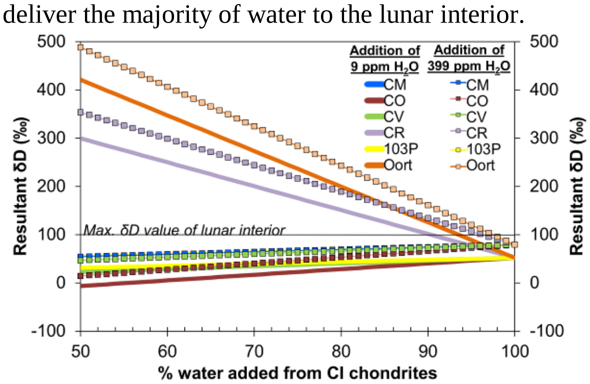

Figure 1. Plot showing the final δD value of the lunar interior following the late-addition of 9 and 399 ppm H_2O (from 2-component mixing of water of CI-type carbonaceous chondrites with water from CM, CO, CV, 103P-like comets, and Oort Cloud-like comets) against the % of the water added that was contributed by CI-type carbonaceous chondrites alone. Note that in all cases mixing of waters from CI with CM, CO, CV, and 103P results in δD values < +100 ‰.

It is important to note the recent measurement by the ROSINA mass spectrometer onboard the Rosetta spacecraft, indicates that Jupiter-Family comet 67P actually has an elevated δD value of +2400 ‰ [21] much higher than that of 103P. In such a case, < 2 % water from 67P-like comets could have been added (with any remaining water from CI-chondrites) during the addition of 9 ppm H_2O to a lunar interior characterized by a δD signature of -200 ‰.

A very depleted-H reservoir in the Moon? There is also evidence that the δD signature of the lunar interior is heterogeneous and in places may be as low as -600 ‰ [6]. Therefore, the model for *scenario 2* was modified, assuming the water in the lunar interior before late-addition, had a δD value of -600 ‰. The calculations indicate that up to 18 % water from CR-type carbonaceous chondrites can be mixed with water from CI-type chondrites, and up to 12 % water from Oort cloud comets can be mixed with water from CI-type chondrites (both for the addition of 9 ppm H_2O).

This work has important implications for the types of material bombarding the Earth-Moon system ca. 4.5 Ga ago. Based on this work, most of lunar interior water could have been derived from CI-type carbonaceous chondrites with minor contributions from CO-type and/or CM-type carbonaceous chondrite materials. Our data best fits with the scenario in which the Moon didn't accrete completely dry following the Giant-Impact event, and that, perhaps some water was accreted in the so-called 'cold-start' origin of the Moon as suggested by [7], with the remaining water added during the LMO-phase (i.e., *scenario 2*). Considering all of the uncertainties associated with these types of calculations (including the assumption that the types of materials we call chondrites today are actually representative of the asteroids that were present ~ 4.5 Ga ago) it is possible that the lunar interior received ~ 5-10 % contribution of its water from comets (with δD signatures of +900 ‰), which is consistent with estimates of [16] for Earth and implies a similar flux of asteroidal and cometary material as has been postulated for the LHB [e.g., 9]. Future work will also take into consideration the adding highly siderophile elements to the lunar interior during late-addition.

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