IRON ISOTOPE EVIDENCE FOR FORMATION OF THE MOON THROUGH PARTIAL VAPORISATION. F. Poitrasson[1,2] , A.N. Halliday[2], D.C. Lee[2,3], S. Levasseur[2] and N. Teutsch[2,4], [1]Laboratoire de Géochimie, CNRS, 38, rue des 36 Ponts, 31400 Toulouse, France (Franck.Poitrasson@cict.fr) [2]Department of Earth Sciences, ETH-Zentrum, Sonneggstrasse 5, 8092 Zürich, Switzerland. [3]Institute of Earth sciences, Academia Sinica, Academia Road section 2, Nankang, Tapei 115, Republic of China. [4]EAWAG, Überlandstrasse 133, 8600 Dübendrof, Switzerland.

Introduction: The currently favoured scenario of the origin of the Moon through a Giant Impact, in which a body approaching the size of Mars hit the proto-Earth and yielded ejecta leading to the Moon remains hypothetical. The alternative theories, especially the capture or co-accretion hypotheses cannot be totally excluded in the view of the present data available [1,2]. The Giant Impact theory predicts extremely high temperatures, sufficient to vaporise part of the mantle and cores of the proto-earth and impacting planet Theia [3,4]. We have thus measured the Fe isotope composition of the Earth, Moon and meteorites thought to come from Mars and asteroid 4 Vesta to see if this highly energetic process left an imprint on the planetary iron isotope signatures.

Methods: A minimum of one gram of rock was powdered and homogenised for each sample to ensure whole-rock representativity. An aliquot was dissolved and iron was purified using anionic exchange chromatography [5]. The Fe isotope composition was determined by MC-ICP-MS (Nu Plasma) using the sample-standard bracketing technique using the international IRMM-14 Fe isotopic standard [6]. Special care was taken to ensure that matrix effects were not present. Repeated analyses of an in house hematite standard over one year indicate that the $^{57}Fe/^{54}Fe$ ratio can be measured with a reproducibility of 0.09‰ (2SD) provided that each sample is analysed several times across different analytical sessions. Although less precisely measured, $^{57}Fe/^{56}Fe$ ratios are in good agreement with $^{57}Fe/^{54}Fe$ values. Analyses of the hematite standard using high resolution MC-ICP-MS (Nu 1700 and Finnigan Neptune) are indistinguishable within uncertainty to our repeated measurements made at low resolution.

Results: Meteorites of the SNC group, though to come from Mars, and eucrites, assumed to sample asteroid 4 Vesta, give $\delta^{57}Fe/^{54}Fe$ values indistinguishable to the international IRMM-14 Fe isotopic standard. In contrast, ten lunar samples, spanning a large range of composition from anorthosite, norite, olivine basalt, KREEP basalt and high titanium basalt give a mean that is 0.2‰ heavier than meteorites from Mars and Vesta. Only two picritic lunar glasses are isotopically similar to the standard. Mantle-derived terrestrial samples yield a mean $\delta^{57}Fe/^{54}Fe$ indistinguishable from a previously reported value based on 46 terrestrial igneous rocks [7]. This figure is intermediate between the Moon and Mars. Student's t-tests show that the terrestrial mean is significantly different from the averages of Mars, Vesta and the Moon at a confidence level of more than 99%.

Why planetary differences? Previous reported data for chondrites, their inclusions, as well as terrestrial samples define a greater spread [8]. However, these data likely represent small-scale heterogeneity as well as the imprint of aqueous fluids. The planetary means reported here are based on repeated analyses of large igneous samples derived from planetary mantles. Furthermore, the planetary differences observed cannot be ascribed to variable mineralogical contents or magmatic processes given that the samples analysed span a wide petrological range, especially noticeable for Mars, Earth and Moon. Similarly, there are no correlations between planetary $\delta^{57}Fe/^{54}Fe$ means and mantle oxygen fugacities, Fe content, volatile content, relative core sizes or heliocentric position.

Origin of the Moon: The different Fe isotope compositions of the Earth and the Moon exclude an origin by fission from the terrestrial mantle or by co-accretion with the Earth. On the other hand, if the Moon was captured by the Earth, the different iron isotope composition might be explained if the Moon formed in a different part of the solar system. However, this is inconsistent with O and Cr isotope data [9,10], and with the observation that Mars and Vesta, located 0.84 AU apart, with different O isotope composition, have the same Fe isotope signature. On the other hand, vaporisation of bodies in space can generate kinetic isotope fractionation, leaving residues with a relatively heavier isotope signature. Hence, the heavy Fe of the Earth, and more especially the Moon can be explained if light iron was partially lost during vaporisation. Only the Giant Impact theory can account for the energy required to partially melt and vaporise major portion of the Earth and the impacting planet Theia. In this scenario, the picritic lunar glasses with $\delta^{57}Fe/^{54}Fe$ values indistinguishable from Mars and Vesta, may represent the deepest part of the Moon's mantle [11] that accreted from essentially rocky material. This would provide evidence that the early lunar magma ocean did not involve the deepest part of the Moon.

Amount and timing of iron loss: Taking Mars as a reference, Rayleigh kinetic isotope calculations suggest that the material from which the Moon formed lost up to 1% of its iron, whereas the Earth lost up to 0.5%. Such small losses would remain undetectable in planetary bulk chemical composition estimates. However, these figures may represent minimum values if Rayleigh kinetic isotope fractionation during evaporation was limited by iron diffusion in the molten globules; if evaporation occurred under gas confining pressure; or if gas condensation in space occurred close to equilibrium [12]. Assuming a minimum temperature of 2000K to generate noticeable vaporisation of rocks [13], we compute that it will take between a few months to a few years for molten globules to loose 1% of their iron. This estimate is very sensitive to temperature, however. Nevertheless, the small amount of Fe loss and this timing are close to the figures obtained in numerical simulations [14,15].

Comparison with O and K isotopes: The lack of resolvable bulk planetary $\delta^{18}O$ difference between the Moon, the Earth, Mars and Vesta may result from larger variations due to magmatic fractionation and alteration for O compared to Fe isotopes. This may thus blur such a fine 0.2‰ effect. Humayun and Clayton [12] calculated that up to 2% of K evaporation would lead to unnoticed kinetic isotope effect given their analytical uncertainties. Although K is more volatile than Fe, it is feasible that the difference of loss between these elements is less than a factor of two. Accordingly, it has been shown experimentally that the iron evaporation flux is more than one order of magnitude larger if it evaporates from metal iron compared to iron oxide [16]. Hence, the contrasted isotopic information given by Fe and K isotopes could be explained if we consider that a significant proportion of the vaporised Fe comes from planetary cores, whereas K will only occur as oxide in planetary mantles and may have evaporated less readily. This conclusion is consistent with certain numerical simulations showing that the Giant Impact will especially heat planetary interiors and involve ejection of a fraction of metallic cores in space.

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