TITANIUM ISOTOPE HOMOGENEITY IN THE EARTH-MOON SYSTEM: EVIDENCE FOR COMPLETE ISOTOPE MIXING BETWEEN THE IMPACTOR AND THE PROTOEARTH. J. Zhang[1,2], N. Dauphas[1,2], and A. M. Davis[1,2,3]. [1]Chicago Center for Cosmochemistry. [2]Department of the Geophysical Sciences. E-mail: junjunzhang@uchicago.edu. [3]Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637

Introduction: The prevailing model of lunar formation is that the Moon was created by a giant impact between the proto-Earth and a Mars-sized impactor [1-4]. Hydrodynamic simulations further suggested that the majority of the Moon-forming material originated from the impactor [4]. If this model is correct, one would expect some isotopic heterogeneity between the silicate Earth and the Moon, assuming the impactor was not strictly identical to the proto-Earth. Surprisingly, lunar samples are very similar in O and W isotopic compositions to the Earth [5, 6]. However, O is not a refractory element and it might not be an appropriate indicator of isotope heterogeneity between the Earth and the Moon. Tungsten is highly refractory, but ^{182}W variations are of radiogenic origin and correction of cosmic-ray effects in lunar samples is not straightforward. In contract, titanium is a highly refractory element that is not subject to any contribution from a parent radioactive nuclide. Moreover, Ti isotope heterogeneity is present in solar system materials [7, 8], so Ti would be well suited to test the isotope heterogeneity between the Earth and the Moon. Trinquier et al. [7] found normal (terrestrial) isotope composition of Ti by measuring one lunar meteorite with precisions of 0.13 and 0.32 in ε^{50}Ti using Axiom and Neptune MC-ICPMS instruments, respectively. Leya et al. [9] measured many lunar samples and found that they had terrestrial Ti isotopic composition, except one sample 71596. Nonetheless, their results were not very constraining, because of uncertainties of 0.8–3.6 in ε^{50}Ti. So it remains largely unknown whether or not isotope heterogeneity exists between the silicate Earth and the Moon.

Taking advantage of our new procedure for Ti separation and developments in MC-ICPMS analyses, we have measured the Ti isotopic compositions of many lunar samples with high precisions of 0.04–0.07 (2σ) in ε^{50}Ti and have comfirmed the isotope homogeneity between the Earth and the Moon. We discuss the implications of this finding and assess the influence of cosmogenic effects at the lunar surface.

New separation procedure: Titanium was separated via a two-stage procedure using TODGA and AG1-X8 resins, respectively. Samples were loaded onto a 2-mL TODGA cartridge, rinsed with 12 M HNO_3 to remove major matrix elements [10], and Ti was collected with Mo and minor Nb, Ta and W in 12 M HNO_3 + H_2O_2. The second separation stage was a modified version of a previously used procedure [11], using a 0.8-mL column (AG1-X8). Major matrix elements were removed with 4M HF independently from the first column and Ti was separated from Mo, Nb, Ta, and W with 9 M HCl + 0.01 M HF. The total yield for both columns exceeds 95 %.

Titanium isotopic analysis: Titanium isotopes were measured with the Thermo Neptune MC-ICPMS of the Origins Laboratory using the sample-standard bracketing technique. Samples were introduced in a 2 % HNO_3-0.005 % HF mixture via an Aridus I desolvating nebuliser. The bracketing standard was titanium solution made by dissolving Alfa Aesar Ti metal wire (99.99 %, with the source being Ti ore from Utah). The following mass-to-charge ratios were measured on Faraday collectors in multidynamic mode: $^{44}Ca^+$, $^{46}Ti^+$, $^{47}Ti^+$, $^{48}Ti^+$, $^{49}Ti^+$ and $^{50}Ti^+$ (cycle 1) and $^{49}Ti^+$, $^{51}V^+$, and $^{53}Cr^+$ (cycle 2). All measurements were made at high resolution.

Samples: The Ti isotopic compositions of 19 samples were measured in this study: 5 lunar whole rocks (one basalt 70017,27; three soil and basalt fragments 72155,37, 71055,45, and 75075,30; and one gabbro with glass 79155,36); 7 lunar ilmenite separates from samples 72155,37 (2), 70215,66 (1), 75055,40 (1), 70017,27 (1), 71055,45 (1), and 15065,7 (1); 3 terrestrial ilmenites; 3 geostandards (two BCR-2 and one BIR-1); and one Alfa Ti metal wire standard solution that was passed through the ion exchange columns.

Results and discussion: Our Ti isotope data are shown in Fig. 1 after internal normalization to a $^{49}Ti/^{47}Ti$ ratio of 0.749766 [12]. Results from previous studies are given for comparison [7, 9]. Fig. 1 shows that lunar samples have Ti isotopic compositions very similar to terrestrial samples.

The similarity in O isotopes between the Earth and the Moon led to a hypothesis that isotope equilibrium occurred via vapor exchange between a terrestrial magma ocean and a proto-lunar magma disk following the giant impact [13]. Our results of Ti isotope homogeneity indicate complete isotope mixing irrespective of elemental volatility. Unless the proto-Earth and the impactor had identical isotopic composition, there must have been direct material exchange between the impactor and the protoEarth, favoring a recent proposal that there was vigorous turbulent exchange between the magma ocean, the silicate atmosphere and the lunar disk that involved even the most refractory elements [14].

However, there are two exceptions to the overall Ti isotopic homogeneity, lunar ilmenite 15065,7 and lunar bulk sample 79155,36, which show small deficits in ^{50}Ti, with ε^{50}Ti values of -0.15 ± 0.05, and -0.17 ± 0.05

(2σ), respectively. We carefully checked the accuracy of small deficits on ε^{50}Ti in samples 15065,7 and 79155,36. (1) these solutions were passed through the second column once more and were remeasured by monitoring $^{52}Cr^{+}$ to correct the interference from $^{50}Cr^{+}$ on $^{50}Ti^{+}$ (we routinely use $^{53}Cr^{+}$ instead to do this correction). The remeasured results show ε^{50}Ti values of

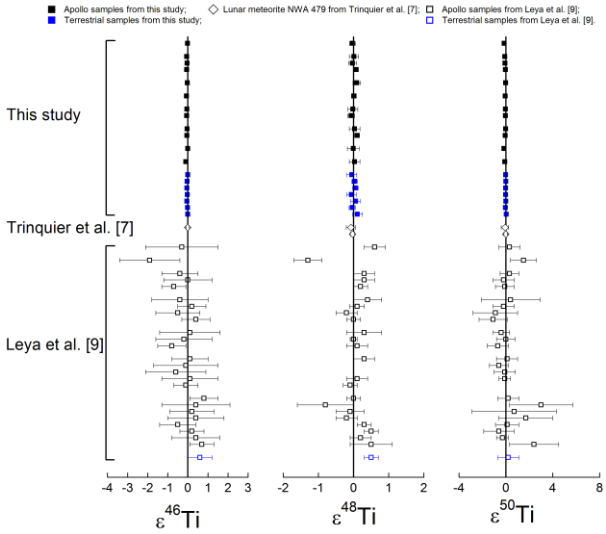

Figure 1: Titanium isotope data, ε^{46}Ti, ε^{48}Ti, and ε^{50}Ti for lunar and terrestrial samples (solid black and blue squares, respectively). All uncertainties given above are 2σ. The error bars on ε^{46}Ti, and ε^{50}Ti values are smaller than the size of the symbols. Also shown are literature data from Trinquier et al [7] (open diamonds) and Leya et al. [9] (open black and blue squares).

−0.13 ± 0.06, and −0.15 ± 0.07 for samples 15065,7 and 79155,36, respectively, in good agreement with the previous measurements. (2) $^{50}V^{+}$ is so low in our solutions (V/Ti ratio of ~ 10^{-7}) that ε^{50}Ti values show no differences before and after corrections using $^{51}V^{+}$. (3) Zr-doping and Mo-doping tests gave normal ε^{50}Ti values even with Zr/Ti and Mo/Ti concentration ratios ten times higher than those of our sample solutions. It is also unlikely that the corrections of Ti mass-dependent fractionation using internal normalization introduce any artifact isotope anomalies here, because there is no correlation between mass-dependent fractionations and non-mass-dependent isotope anomalies (Fig. 2).

One possibility is neutron capture from cosmic ray secondary neutrons on Ti isotopes in these lunar samples. Sample 79155,36 has an ^{38}Ar-Ca exposure age of 575 ± 60 Myr [15]. Using the thermal neutron capture cross-sections [16] and taking the neutron fluence of 10^{17} n/cm^2, the maximum seen in Apollo samples [17], we calculate an effect on ε^{50}Ti of −0.15, while on ε^{46}Ti and ε^{48}Ti of +0.05 and −0.06, respectively. The latter two predicted anomalies are difficult to resolve within our current uncertainties. Further work is needed to ascertain this idea.

Conclusions: High-precision Ti isotope studies on lunar samples show that the Moon has the same ε^{50}Ti as the Earth within ~0.1 ε-units, despite a range of 7 ε-units among bulk meteorites [7]. Small ε^{50}Ti deficits measured in two samples might reflect the presence of cosmogenic effects in some lunar samples. Our results provide solid evidence showing that the isotopic compositions of the Earth and the Moon were well mixed, irrespective of elemental volatility.

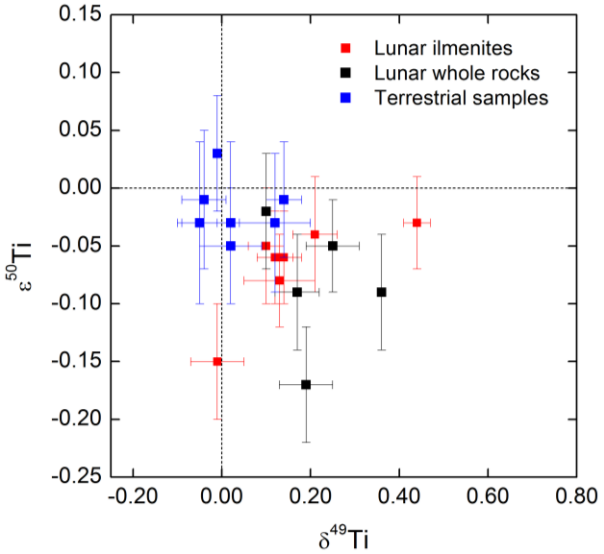

Figure 2: Titanium mass-dependent fractionations (δ^{49}Ti, in parts per 10^3) vs. Ti isotope anomalies (ε^{50}Ti, in parts per 10^4) for lunar and terrestrial samples.

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