

**THE VANADIUM ISOTOPE COMPOSITION OF THE MOON: ISOTOPIC TEST OF THE GIANT IMPACT HYPOTHESIS?** S. G. Nielsen<sup>1</sup>, M. Auro<sup>1</sup> and T. Kleine<sup>2</sup> <sup>1</sup>NIRVANA laboratories, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA, snielsen@whoi.edu, <sup>2</sup>Institut für Planetologie, University of Münster, 48149 Münster, Germany

**Introduction:** It has been hypothesized that the Moon formed at the end of Earth's major accretion in a giant impact with a Mars-sized object [1]. One of the key predictions of these models was that the Moon predominantly should be composed of material from the impactor. Hence, if the isotopic compositions of a given element were different in the proto-Earth and the impactor, then it follows that the Earth and the Moon should be characterized by disparate isotope compositions. However, increasingly precise analyses of mass independent isotope anomalies in the elements O, Ti and Cr have revealed very limited or undetectable differences between the Earth and Moon [2-5]. These analyses could either be explained by an inherent isotopic similarity between proto-Earth and the impactor [6], by assuming specific geometries for the giant impact itself [7, 8], or by post-giant impact equilibration between the Earth and the Moon [9]. Hence, there is still considerable uncertainty regarding the the exact formation conditions of the Moon.

The isotope composition of vanadium (V) is another potential tracer for identifying impactor material in the Moon. Vanadium has two isotopes with masses 50 and 51 that have a  $^{51}\text{V}/^{50}\text{V}$  ratio of  $\sim 410$ . Recent work has shown that the Earth is heavier than all chondrites investigated to date [10], with most of the isotopic variation in chondrites likely caused by a heterogeneous distribution of presolar grains. Even enstatite chondrites, which are often found to be similar to bulk Earth for other isotope systems [6], are likely lighter than the bulk silicate Earth [10]. There is no combination of ordinary, carbonaceous or enstatite chondrites that can combine to produce the V isotope composition of bulk silicate Earth (BSE, Fig. 1).

Although the reasons for the heavy isotope composition of BSE are still unclear [10], it appears most likely that the impactor had an overall chondritic composition. Therefore, there is a strong possibility that the proto-Earth and the impactor were characterized by different V isotope compositions. As such, the mass balance predicted by the original giant impact simulations [1] would suggest that the Moon be characterized by a V isotope composition that is intermediate between average chondrites and BSE.

Recent analyses of V isotopes in lunar samples have found significant variation that was likely due to the interaction with galactic cosmic rays (GCR) at the lunar surface [11]. Therefore, it was not possible to

determine if the Moon and Earth display significantly different V isotope compositions.

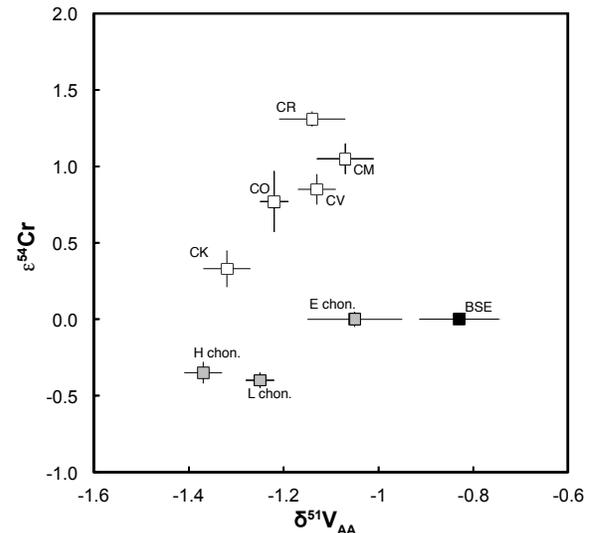


Figure 1: Plot of V isotope and  $\epsilon^{54}\text{Cr}$  variation in different chondrites and the bulk silicate Earth (BSE).

We will present V isotope data for a range of lunar samples some of which were previously shown to be devoid of GCR-induced effects [12-14]. The samples include high-Ti and low-Ti mare basalts as well as KREEP lithologies, which makes them an ideal sample set for determining the pre-exposure V isotope composition of the Moon and whether igneous processes may have caused any V stable isotope fractionation within the Moon.

**Methods:** Samples of both lunar meteorites and Apollo mission rocks were dissolved as either 100mg chips (meteorites),  $<40\mu\text{m}$  fines, or whole rock powders (Apollo samples) using double distilled concentrated mineral acids such as HF,  $\text{HNO}_3$ , HCl. The vanadium was separated from the sample matrix using a four-step cation/anion exchange chromatography procedure [10, 15]. Mass spectrometry to measure V isotope ratios was performed using a Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS), housed at the Plasma Mass Spectrometry Facility of the Woods Hole Oceanographic Institution (WHOI). Isotope compositions were calculated using standard-sample bracketing with the Alfa Aesar standard that is defined as  $\delta^{51}\text{V} = 0\text{‰}$ . Each unknown sample was interspersed with a pure V refer-

ence solution from BDH Chemicals that has now been measured in four different labs with the identical result of  $\delta^{51}\text{V} = -1.2\%$  [15-18]. The mass spectrometer was operated in a medium resolution mode, which ensured that all significant isobaric interferences in the mass spectrum (48–53 atomic mass units) were resolved from the isotopes of interest:  $^{48}\text{Ti}$ ,  $^{49}\text{Ti}$ ,  $^{50}\text{V}$ ,  $^{51}\text{V}$ ,  $^{52}\text{Cr}$  and  $^{53}\text{Cr}$  [19]. We collected  $^{51}\text{V}$  using a Faraday cup equipped with a  $10^{10}\ \Omega$  resistor, whereas Faraday cups with conventional  $10^{11}\ \Omega$  resistors were used for all other masses collected. Samples and standards were measured at a concentration of 800 ng/ml V, which produced an ion beam of  $\sim 2\ \text{nA}$  on  $^{51}\text{V}$  and  $\sim 0.005\ \text{nA}$  on  $^{50}\text{V}$ . The method consumed about 300 ng V per analysis and has an external precision of  $<0.15\%$  (2sd), which was assessed based on repeat measurements of USGS reference materials AGV-2 and BCR-2 that have also been analyzed in previous studies [18, 20, 21]. All samples were measured at least in triplicate.

**Results and discussion:** Measurements of lunar samples with significant GCR effects (as evident from anomalous Hf isotopic compositions [12-14]) are isotopically light, in agreement with other recent V isotope analyses of lunar samples [11]. However, preliminary analyses of samples with no resolved GCR effects on Hf isotopes are relatively invariant and slightly lighter than the bulk silicate Earth. The potential difference in vanadium isotopes between Earth and the Moon will be tested by conducting additional measurements of further samples devoid of GCR effects. Results of these analyses will be presented.

The potential difference between Earth and the Moon could have several possible explanations. One possibility is that lunar core formation preferentially sequestered the heavy vanadium isotope thus leaving the lunar mantle lighter than the silicate Earth. This interpretation, however, is not supported by metal-silicate equilibration experiments where no V isotope fractionation was detected [22].

Alternatively, it is possible that different lunar rocks record vanadium isotope variations that we will likely detect once we analyze a wider range of lunar lithologies. For example, partitioning of vanadium into ilmenite could, by analogy to large vanadium isotope fractionation found in magnetite on Earth [23], potentially have induced vanadium isotope fractionation. We will present data for high-Ti and low-Ti mare basalts, and KREEP-rich rocks that should reveal different vanadium isotope compositions if crystallization of ilmenite induced significant vanadium isotope fractionation on the Moon.

Lastly, a potential vanadium isotopic difference between the Earth and Moon could also be accounted for

by the giant impact if the impactor, as hypothesized above, was isotopically lighter than proto-Earth. Since the original giant impact models predict that the Moon primarily is composed of the impactor [1], a vanadium isotope composition of the Moon that is intermediate between Earth and chondrites would be consistent with the original giant impact simulations.

We will present a complete data set for lunar rocks that likely will enable us to distinguish between these three interpretations of the vanadium isotope composition of the Moon.

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