CONSTRAINING THE LATE HEAVY BOMBARDMENT OF THE MOON USING Ru ISOTOPES IN LUNAR IMPACTITES.

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Introduction: The heavily cratered surfaces of Mercury, the Moon, and Mars indicate that a late heavy bombardment (LHB) occurred after the formation of their rigid crusts [1]. A variant of the LHB, sometimes called the terminal lunar cataclysm, has been used to account for a possible spike in impact reset ages on the Moon (and other bodies, including the howardite-eucrite-diogenite, or HED, parent body) around 3.9 Ga [2, 3]. A proposed source of the increased impact flux is a relatively late orbital instability of the giant planets, which may have scattered compositionally diverse objects in the asteroid belt (and elsewhere) into terrestrial planet-crossing orbits [3, 4]. Alternatively, the LHB may simply be due to a monotonic decline of impacts from planetesimals leftover from the main phase of accretion [5]. Ultimately, the timing and collateral effects of any dynamical instabilities that may have occurred, along with the nature and origin of the impactors, are not well constrained. These dynamical processes have implications for the composition of the building blocks of the terrestrial planets, including those which may have accreted during latest stages of accretion.

The impactors involved in some of these processes can be directly investigated using lunar impactites, which formed via the modification of lunar target rocks by large impacts. As siderophile elements are strongly depleted in the Moon's crust due to core formation, but have comparatively high concentrations in most projectile materials, impactites are often enriched in siderophile elements inherited from the impactor. The highly siderophile element Ru is particularly useful in this regard because parent body-specific nucleosynthetic Ru isotope anomalies are observed at the bulk meteorite scale [e.g., 6]. Ruthenium isotopes can also differentiate between the non-carbonaceous (NC) and carbonaceous (CC) nebular reservoirs [e.g., 7], which likely represent the inner and outer regions of the protoplanetary disk, respectively. Combined, this makes it possible to use Ru isotopes to link lunar impactors to distinct types of meteorites and even to specific areas of the disk from where these impactors originated.

Here we present the first Ru isotope data from lunar impactites, including an Apollo 16 sample and a lunar meteorite. As proof of concept, we analyzed two eucrite impact melts, which are also presented. These data are used to determine the provenance of lunar impactors and, ultimately, to constrain the nature of the LHB.

Approach: As the Ru in the bulk silicate Earth (BSE) was delivered almost entirely by late accretion, the Ru isotopic composition of the BSE is representative of late-accreted material (here, called the late veneer). Further, nearly all meteorite groups have anomalous Ru isotopic compositions relative to the BSE [6]. Thus, the late veneer had a rather unique isotopic composition.

The existing models for the LHB can be tested using Ru isotopes, as some proposed scenarios, e.g., the lunar cataclysm and accretion tail of leftover planetesimals, are expected to involve isotopically distinguishable impactors. In the case of a dynamically-driven lunar cataclysm, an isotopically diverse asteroid belt would supply isotopically distinct impactors that are not expected to be similar to the BSE/late veneer. In an accretion tail scenario, impactors would be from the same nebular feeding zone as the major building blocks of the Earth and Moon and would scatter around the isotopic composition of the BSE/late veneer (Fig. 1).

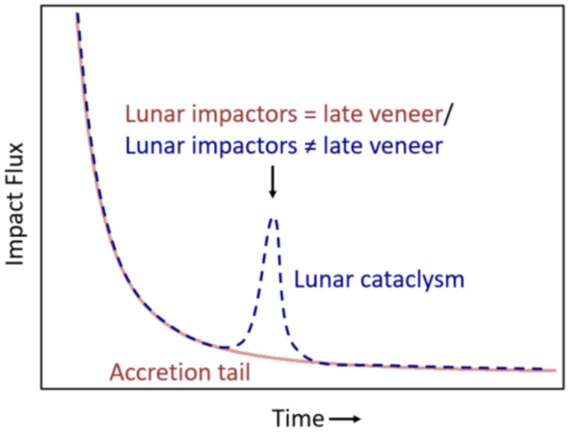

Fig. 1. Expected impactor Ru isotopic compositions for two endmember impact fluxes to the Moon. Most dated Apollo impact melts correspond to the time of the putative lunar cataclysm. If the lunar impactor signatures are distinct from the BSE (late veneer) composition, it would support the lunar cataclysm; if the impactors scatter around the BSE, it would not.

Experimental Methods: Impactites having relatively abundant metal were targeted for this study. These samples are Apollo 16 impact melt samples 60315, 62235, 64475, 67935, and 68815, as well as lunar feldspathic breccia meteorites NWA 5000 and NWA 11228. In addition, the two eucrite impact melts NWA 1644 and NWA 12340 were investigated. Powdered splits or metal separates from the impactites were digested in 2:1 conc. HNO_3:HCl using an *Anton Paar* high pressure asher at 320 °C. Ruthenium was separated from the matrix and purified using a three-stage cation and anion exchange chromatographic procedure [8].

Isotopic compositions of Ru were determined using a *Thermo Scientific Neptune Plus* MC-ICP-MS at Münster. The isotopic compositions are reported in ε notation (parts-per-10^4 deviations from terrestrial standards). The data are normalized to ^{99}Ru/^{101}Ru. The external reproducibility (2SD) of the repeated analysis of terrestrial standards is ± 16 ppm for ε^{100}Ru.

Results: Ruthenium isotope data for four impactites are shown in Figure 2. Data for additional samples will be presented at the conference. Typically, between 50-150 ng of Ru are extracted from such samples, which is sufficient for three or fewer individual analyses, so the 2SD external reproducibility is applied as the uncertainty for each. Our results for two eucrite impact melts (NWA 1644 and NWA 12340) and two lunar impactites (60315 and NWA 11228) indicate that the impactor components in them all belong to the NC suite. The impactor signature in NWA 12340 is similar to ordinary chondrites, and the impactor signatures in NWA 1644, NWA 11228, and 60315 are indistinguishable from the Ru isotopic composition of terrestrial solution standards and the BSE.

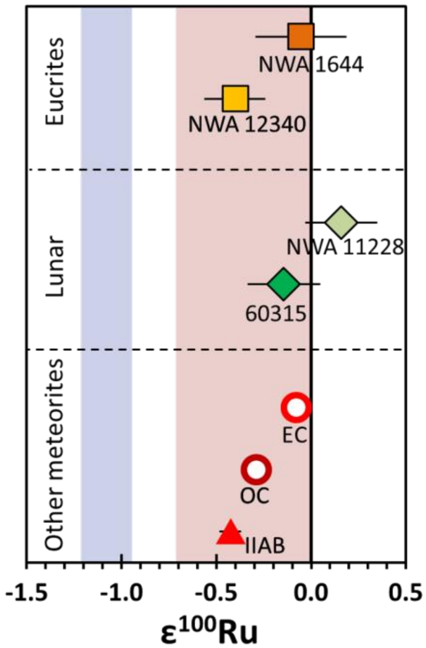

Fig. 2. Ru isotopic compositions of HED and lunar impactites, shown with some NC groups [6, 9]. The ranges of Ru isotopic compositions in iron meteorites from the CC (blue) and NC (red) suites are shown.

Discussion: The NC compositions of the impactites measured here suggest that the impactors sampled thus far originated only in the inner solar system. Moreover, NWA 1644, NWA 11228, and 60315 have isotopic compositions that overlap the BSE Ru isotopic composition within uncertainty. Therefore, the lunar (and one HED) impactors were likely from a similar region to the late-accreted material added to the Earth following the Moon-forming impact. This indicates that, since the time of late accretion, the impactors to the Earth and Moon may not have changed in composition. If this result is reproduced for the majority of other lunar impact melts, then the lunar cataclysm triggered by a dynamical instability would not be supported. In this case, the impactor signatures in 60315, NWA 11228, and NWA 1644 may be representative of planetesimals that were left over from the main accretion phase of the terrestrial planets. If confirmed by additional data from more lunar impactites, this would provide strong evidence in favor of the accretion tail scenario of the LHB.

In terms of the eucrite impact melts, their NC nature is not necessarily expected, given that HEDs, particularly howardites, are known to include carbonaceous chondrite clasts [10]. Because the clasts are similar to carbonaceous chondrite groups that belong to the CC suite, this material likely originated in the outer solar system. This, combined with the evidence of NC impactors to the HED parent body, implies that impactors were sourced from both the inner and outer solar system, which may simply reflect the compositional variety of asteroids within the asteroid belt.

Conclusions: This work demonstrates that Ru isotopes in lunar impactites are a powerful tool to determine the origin and dynamics of the LHB. The data obtained thus far suggest that the LHB reflects the accretion tail of terrestrial planet formation, and not a lunar cataclysm. This work is ongoing and additional data will be presented at the meeting. Further analyses of several impactites from the Moon and the HED parent body will determine how variable the impactors to the Earth-Moon system and throughout the inner solar system may have been, and, thus, by what mechanism and from where they were delivered. Either way, current data suggest that it will be possible to support either a lunar cataclysm scenario or an accretion tail scenario, contributing to a long-standing debate in lunar science.

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