Dating the first ~100 Ma of the solar system: From the formation of CAIs to the origin of the Moon

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Introduction

Key events in the early evolution of the solar system are the condensation of the first solids (CAIs), the formation of chondrules, and the accretion and differentiation of planetary bodies. Dating these events is key to understanding the early evolution of the solar nebula and the planet formation process. We discuss recent advances in the application of ^{182}Hf-^{182}W chronometry to obtain such time constraints.

Age of CAIs and Chondrules

In most meteorites, high-Ca pyroxene, the major host of radiogenic ^{182}W/^{184}W, is a minor component. Hf-W dating of meteorites, therefore, re-quires low-blank methods and sensitive mass spectrometric techniques for precise and accurate W isotope ratio measurements on small quantities of W. We recently refined our techniques to meet these requirements and can now precisely determine highly radiogenic ^{182}W/^{184}W for as little as ~2-3 ng W. This allows resolution of time differences of less than ~1 Ma. We applied these new techniques to determine an absolute age for CAIs of 4568.6±0.7 Ma, which is ~1.5 Ma older than their Pb-Pb age [1]. The latter thus does not seem to date CAI formation. The Hf-W age for the formation of H chondrite chondrules is 1.7±0.7 Ma, consistent with ~2 Ma Al-Mg ages for L and LL chondrules [2, 3]. In contrast, chondrules from carbonaceous chondrites formed more than ~0.5 Ma later, as constrained by differences between their Pb-Pb ages [4, 5] and the Hf-W age for CAIs.

Age of the Moon

Precisely dating the Moon requires determining the purely radiogenic ^{182}W/^{184}W of lunar samples. This is challenging because the ^{182}W/^{184}W of lunar whole-rocks largely reflect the production of cosmogenic ^{182}W. However, lunar metals contain no such cosmogenic ^{182}W and precise ^{182}W/^{184}W measurements for such metals reveal that the Moon formed and differentiated >60 Ma after CAI formation. Combined with other chronological evidence this indicates that the giant Moon-forming impact probably occurred ~100 Ma after condensation of the first solids [6]. This event most likely marks termination of the major stage of terrestrial planet formation.

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Hafnium-Tungsten chronometry of lunar differentiation

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Application of Hf-W chronometry to date lunar differentiation critically depends on determining whether ^{182}W variations among lunar samples reflect ^{182}Hf-decay within the lunar mantle. Lunar whole-rock samples are not suitable for this task due to the presence of cosmogenic ^{182}W [1, 2]. In contrast, high-purity metal separates from lunar samples do not contain any Ta-derived cosmogenic ^{182}W. They have constant ε^{182}W (ε^{182}W=0.01% deviation from terrestrial ^{182}W/^{184}W), indicating differentiation of the lunar mantle *later* than ~60 Ma after CAI formation [3]. However, mineral separates from low-Ti mare basalt 15555 were shown to have constant but elevated ε^{182}W in spite of different Ta/W [4]. Likewise, ferroan anorthosite 60025, in spite of its young exposure age, has an ^{182}W excess [5]. If these ^{182}W excesses reflect ^{182}Hf-decay in the lunar mantle, then the Moon must have formed and differentiated *earlier* than ~60 Ma after CAI formation, inconsistent with the result from lunar metals. To address this issue we obtained new W isotope data for low-Ti mare basalt 15555 and ferroan anorthosites 60025 and 62255.

A non-magnetic fraction of sample 15555 has ε^{182}W=0.9±0.3 and Ta/W~4.6. For a given Ta/W, the previously reported ε^{182}W for mineral separates from 15555 [4] seem to be shifted to higher values compared to our new data. However, the expected cosmogenic ^{182}W as a function of Ta/W, calculated using the Sm isotopic composition of 15555 [6], is consistent with ε^{182}W and Ta/W obtained here. Therefore, after proper correction for cosmogenic ^{182}W, the ε^{182}W of 15555 is identical to the other mare basalts.

Pure plagioclase separates from ferroan anorthosites 60025 and 62255 have ε^{182}W=0.0±0.3 and -0.6±0.8, indistinguishable from ε^{182}W values for the mare basalts and KREEP. We conclude that all lunar samples have indistinguishable ε^{182}W values, confirming that differentiation of the lunar mantle occurred later than ~60 Ma after CAI formation, consistent with the results for lunar metals [3].

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