MOLYBDENUM ISOTOPIC EVIDENCE FOR AN OUTER SOLAR SYSTEM ORIGIN OF THE MOON-FORMING IMPACTOR. G. Budde, C. Burkhardt, and T. Kleine, Institut für Planetologie, University of Münster, Wilhelm-Klemm-Straße 10, 48149 Münster, Germany (gerrit.budde@uni-muenster.de).

Introduction: The Moon is thought to have formed by a giant impact between the proto-Earth and a Mars-sized planetary embryo [1]. In the canonical view, the Moon mainly consists of impactor material and is thus expected to be isotopically distinct from the Earth. However, for several elements (*e.g.*, Ti, Cr, O) Earth and Moon are isotopically very similar [2]. To account for this Earth-Moon isotopic similarity, several solutions have been proposed, including (*i*) formation of the Moon predominantly from proto-Earth material [3,4], (*ii*) post-giant impact equilibration between Earth and Moon [5], and (*iii*) derivation of proto-Earth and impactor from the same isotopically homogeneous reservoir [6]. These different solutions make very different predictions regarding the nature of the Moon-forming impactor and the dynamics of the giant impact.

Here we examine these fundamental issues using the nucleosynthetic Mo isotope dichotomy between *carbonaceous* (CC) and *non-carbonaceous* (NC) meteorites [7,8]. These represent two spatially distinct reservoirs that coexisted between <1 and ~4 Ma after Solar System formation, where the CC (outer Solar System) and NC (inner Solar System) reservoirs were most likely separated as a result of the formation of Jupiter in between them [7,9].

As the Earth predominantly formed from inner Solar System material, it is expected to have an NC-like isotopic composition. However, we have recently demonstrated that the Mo isotope signature of the bulk silicate Earth (BSE) is intermediate between those of the NC and CC reservoirs, indicating that the Earth accreted a significant amount of CC-like material late in its growth history [10]. As a siderophile element, most of the Mo in the BSE derives from the last 10–20% of accretion [11], meaning that its Mo isotope composition should be strongly influenced by the Moon-forming impactor. Here we show that the Mo isotope signature of the BSE allows constraining the provenance of the Moon-forming impactor, which in turn provides critical new insights into Earth's late-stage formation history and the origin of the Moon.

Methods: The Mo present in the BSE derives from three components: The proto-Earth's mantle (Earth's mantle just before the giant impact), the Moon-forming impactor (the last large body colliding with Earth), and the late veneer (the material added to Earth's mantle after the giant impact and the cessation of core formation). To quantify the contribution of these components, we used a Monte Carlo approach to calculate the expected Mo isotope composition of the BSE for three endmember scenarios, in which one component is assumed to have a CC composition and the other two have NC compositions (Fig. 1).

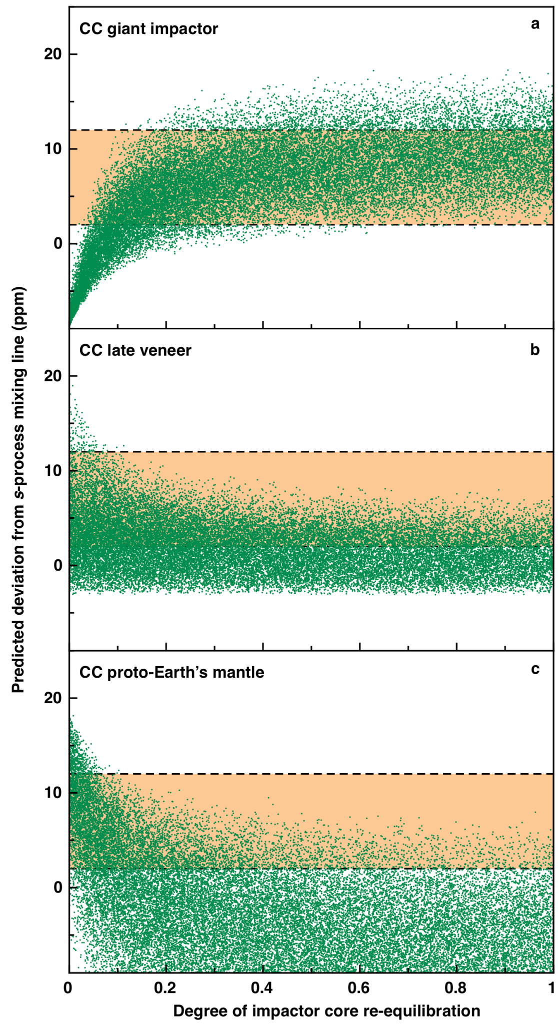

Fig. 1. Predicted deviation of the BSE from the *s*-process mixing line versus the degree of impactor core re-equilibration during the Moon-forming impact. The orange horizontal bar represents the observed composition of the BSE [10]; green dots are the results of the Monte Carlo simulation.

Results: Assuming a CC-like late veneer reproduces the BSE's Mo isotope composition in 40–50% of the cases, whereas assuming a CC-like Moon-forming impactor reproduces it in >90% of the cases, provided that more than ~20% of the impactor core equilibrated with the proto-Earth's mantle (Fig. 2). By contrast, a CC-like proto-Earth's mantle provides the best match only for an impactor core re-equilibration of less than ~10%, because then most of the Mo from the Moon-forming impactor would be directly removed into Earth's core. However, this value was likely larger than ~40% [12], meaning that it is highly unlikely that the CC-derived Mo in the BSE predates lunar formation.

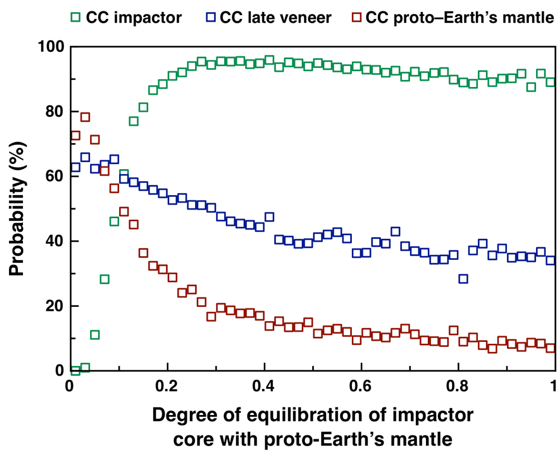

Fig. 2. Probability for matching the Mo isotope composition of the BSE for different compositions of proto-Earth's mantle, the Moon-forming impactor, and the late veneer as a function of impactor core re-equilibration during formation of the Moon.

Origin of the Moon-forming impactor: Based on our calculations alone, we cannot fully exclude that the CC-like material in the BSE was delivered by the late veneer. However, the BSE's Ru and Os isotope compositions are distinct from CC meteorites and, as such, rule out that the late veneer solely consisted of CC bodies [13,14]. Therefore, any CC contribution from the late veneer is likely smaller than the estimated late veneer mass of ~0.5% (of the Earth's mass) [15], meaning that the late veneer cannot be the sole source of CC-like material in the Earth. Instead, the BSE's Mo isotopic composition is best accounted for if the Moon-forming impactor delivered most or all of the CC-like material to Earth.

Assuming that it was Mars-sized [1], the Moon-forming impactor would have added ~10% CC-like material to Earth. This amount would be lower if the impactor were smaller or if it had a mixed NC-CC composition, which may have resulted from prior collisions between smaller NC and CC embryos. It is important to recognize that, in contrast to siderophile elements like Mo, the resulting isotopic changes of such an addition of CC-like material would be much smaller for elements that recorded Earth's full accretion history [11]. As such, a CC heritage for the last ~10% of accretion is consistent with the small ^{50}Ti and ^{54}Cr offset of the Earth (and Moon) from enstatite chondrites, which are thought to be most similar to the NC component of the Earth [11], towards CC meteorites [2].

A CC-like isotopic signature of the Moon-forming impactor implies that this impactor originated from the outer Solar System, possibly beyond the orbit of Jupiter. This conclusion is supported by dynamical models of terrestrial planet formation, which predict that due to the orbital evolution of the gas giant planets, either during an early migration [16] or a later orbital instability [17], embryos from beyond ~2.5 AU (*i.e.*, the location of the CC reservoir) were preferentially incorporated into the Earth late, often with the final large impactor [18].

Implications for the origin of the Moon: A CC-like isotopic composition for the Moon-forming impactor implies that it was isotopically distinct from the proto-Earth, which is expected to mainly represent NC-like inner Solar System material. Moreover, the Moon does not have a CC-like isotopic signature itself (its Cr and Ti isotope compositions are similar to enstatite chondrites and the Earth [2]), implying that the Moon cannot consist predominantly of impactor material. Thus, our results indicate that either the Moon formed mainly from proto-Earth's mantle material, or that there occurred post-giant impact equilibration between Earth and Moon. The former, however, seems dynamically implausible and also is difficult to reconcile with the indistinguishable ^{182}W compositions of Moon and (pre-late veneer) BSE [19]. Therefore, these observations combined support post-giant impact equilibration, such as predicted in the high-energy, high-angular-momentum giant impact model of [5].

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