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Late veneer and late accretion to the terrestrial planets

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ABSTRACT

It is generally accepted that silicate-metal ('rocky') planet formation relies on coagulation from a mixture of sub-Mars sized planetary embryos and (smaller) planetesimals that dynamically emerge from the evolving circum-solar disc in the first few million years of our Solar System. Once the planets have, for the most part, assembled after a giant impact phase, they continue to be bombarded by a multitude of planetesimals left over from accretion. Here we place limits on the mass and evolution of these planetesimals based on constraints from the highly siderophile element (HSE) budget of the Moon. Outcomes from a combination of N-body and Monte Carlo simulations of planet formation lead us to four key conclusions about the nature of this early epoch. First, matching the terrestrial to lunar HSE ratio requires either that the late veneer on Earth consisted of a single lunar-size impactor striking the Earth before 4.45 Ga, or that it originated from the impact that created the Moon. An added complication is that analysis of lunar samples indicates the Moon does not preserve convincing evidence for a late veneer like Earth. Second, the expected chondritic veneer component on Mars is 0.06 weight percent. Third, the flux of terrestrial impactors must have been low ($\lesssim 10^{-6}$ $M_\oplus$ Myr^{-1}) to avoid wholesale melting of Earth's crust after 4.4 Ga, and to simultaneously match the number of observed lunar basins. This conclusion leads to an Hadean eon which is more clement than assumed previously. Last, after the terrestrial planets had fully formed, the mass in remnant planetesimals was $\sim 10^{-3}$ $M_\oplus$, lower by at least an order of magnitude than most previous models suggest. Our dynamically and geochemically self-consistent scenario requires that future N-body simulations of rocky planet formation either directly incorporate collisional grinding or rely on pebble accretion.

1. Introduction

The formation of the terrestrial planets is a long-standing problem that is gradually being resolved. In traditional dynamical models the terrestrial planets grow from a coagulation of planetesimals into protoplanets and subsequently evolve into a giant impact phase, during which the protoplanets collide with each other to lead to the terrestrial planets. Several variations of this scenario exist, of which the *Grand Tack* model is currently popular (Walsh et al., 2011). The Grand Tack relies on early gas-driven migration of Jupiter and Saturn to gravitationally sculpt the inner solid circum-solar disc down to ∼1 AU after which terrestrial planet formation proceeds from solids in an annulus ranging from roughly 0.7 AU to 1 AU. Grand Tack has booked some successes, such as its ability to reproduce the mass-orbit distribution of the terrestrial planets, the compositional gradient, and total mass of the asteroid belt (Walsh et al., 2011). Subsequent evolution of the solar system after terrestrial planet formation, all the way to the present, however, has mostly been studied in separate epochs with disconnected simulations.

Brasser et al. (2016) scrutinised the Grand Tack model in more detail and built a database of simulations that is used here. Since published simulations had rarely been run for much longer than 200 Myr into the evolution of the solar system, we sought to test the model predictions specific to the long-term evolution of the terrestrial system. In this work we calculate the evolution of the terrestrial planets for up to 300 Myr. We aim to obtain the amount of mass accreted by the terrestrial planets after the Moon-

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forming event and whether this accreted mass is compatible with the highly-siderophile element (HSE) budgets of the inner planets, the early lunar and terrestrial cratering records and the nature of the purported late veneer. We also consider the surface conditions on the Hadean Earth from geochemical data and conclude with the implications of our simulations for future models of terrestrial planet formation.

2. Constraints from the Moon on the remnant planetesimal mass

The unexpectedly high abundance of HSEs in Earth's upper mantle is a mystery because it is expected that these elements would be effectively sequestered into the core. One popular explanation suggests that Earth accreted a further 0.5–0.8 weight percent (wt%) of its mass after core separation and after the Giant Impact (GI) that formed the Moon (Walker, 2009). The dearth of lunar mantle HSEs indicate that the Moon accreted approximately 0.02–0.035 wt% (Day and Walker, 2015; Kruijer et al., 2015). The ratio of accreted mass between Earth and the Moon is then 1950 ± 650, which is curious because the ratio of the gravitational cross sections of the Earth and Moon is far less ($\sim$20).

There is substantial debate in the literature about a possible late veneer on Mars. Osmium isotopes in martian meteorites indicate that Mars accreted chondritic material after core formation (Brandon et al., 2012), although it is unclear how much material was added to the martian mantle. Walker (2009) suggested that Mars experienced a mass augmentation of $\sim$0.7 wt%, comparable to Earth's. A recent analysis of metal-silicate partitioning for the platinum group elements in martian meteorites, however, combined with theoretical partitioning models used to construct inverse models of Mars' mantle composition, instead show that the concentration of HSEs in the martian mantle can be solely established by metal-silicate equilibration early in the planet's history (Righter et al., 2015). This obviates the need for substantial accretion on Mars during the late veneer epoch. Effective removal of the requirement for much accretion on Mars is important because now the Moon need no longer be regarded as anomalous in the relatively low amount of material it accreted after its formation; only Earth's unusually high HSE abundance demands explanation. This allows us to predict the amount of accretion experienced by Mars when calibrated to the Moon.

The high ratio of the terrestrial and lunar HSE budgets led (Bottke et al., 2010) to conclude that the size-frequency distribution of the remaining planetesimals from planet formation had to have been shallow even at large sizes, and the majority of the mass delivered to the Earth should have come from a few large objects comparable to Ceres. The low number of objects leads to a stochastic impact regime for large objects that statistically favours collisions with Earth (Sleep et al., 1989). Hence, the amount of mass accreted on the Moon must be representative of the mass in remnant planetesimals from terrestrial planet formation that are volumetrically smaller than those colliding with Earth.

The probability that the mass of each impactor exceeds m is $P(m) = (m/m_{\rm min})^{-\gamma}$, with $m > m_{\rm min}$. When $\gamma \leq 1$ the total delivered mass is dominated by a single projectile, and the approximate mass delivered to the Earth versus the Moon is $m_{\rm e}/m_{\rm l} = (\sigma_{\rm e}/\sigma_{\rm l})^{1/\gamma}$ (Sleep et al., 1989), where $\sigma_{\rm e,l}$ are the gravitational cross sections of the Earth and Moon, respectively. This ratio can become high when $\gamma \ll 1$. Since $\sigma_{\rm e}/\sigma_{\rm l} \sim 20$, the probability of the Earth being struck by the largest 13 objects is $(19/20)^{13} > 0.5$. The largest verifiable projectile to have struck the Moon created the South Pole-Aitken basin; its diameter was $\sim$170 km (Potter et al., 2012). The collision probability of planetesimals with the Earth is 12% (see below), so there are a total of 100 objects with $D > 170$ km, and thus the expected diameter of the largest projectile (99th percentile) is approximately 1700 km, assuming a main asteroid belt size-frequency distribution ($\gamma \sim 0.7$).

Recently Raymond et al. (2013) showed that a population of planetesimals with a total mass $\sim$0.05 $M_\oplus$ could reproduce the HSE signature in Earth's mantle after the GI over the next few hundred million years. Here we argue that the duration of the time interval that allowed for the mixing of HSEs into the mantle must have been considerably shorter, depending on the exact timing of the Moon-forming event, and should have mostly finished near 4.42 Ga, roughly $\sim$150 Myr after the formation of the proto-Sun at 4.57 Ga. Our arguments for this duration are as follows.

Radiogenic dating of lunar Apollo samples and meteorites indicate that lunar crust formation was well under way by 4.42 Ga (Nemchin et al., 2009), which is the age of the oldest lunar zircon thus far documented. Recent analysis of zircons in martian meteorite NWA 7533 indicates that the earliest crust on Mars formed before 4.43 Ga (Humayun et al., 2013). Taken together these ages suggest that both the Moon and Mars had begun to form a crust some time before 4.42 Ga. In this work, we refer to *late accretion* as those impacts that occurred after continual preservation of the planetary crust. An impact large enough to have destroyed most of the crust and contaminate planetary mantles with HSEs is dubbed a *late veneer*. We shall designate the time interval between the Moon-forming giant impact (GI) near 4.5 Ga and crust formation at 4.42 Ga as the *late veneer epoch* and the time interval after 4.42 Ga as the *late accretion epoch*. Late accretion impacts are inefficient at mixing any HSEs into the mantle and thus the majority of late veneer impacts, which delivered the HSEs, must have occurred before crust formation. The end of the late veneer epoch corresponds closely to the last major differentiation event on the Earth at 4.45 Ga (Allègre et al., 2008), during which the bulk silicate reservoirs were separated when the crust was still molten.

The above arguments can be used to constrain the mass of leftover planetesimals in the inner solar system subsequent to the Moon-forming event, delimiting the rate at which this material is cleared by the terrestrial planets. In principle the total mass of planetesimals decreases with time as $m_{\rm left} = m_{\rm init} f(t)$, where $f(t)$ is the decay function. The amount of mass accreted on the Moon between the time of the GI, assumed to have occurred at 4.5 Ga, and crust formation is

$$m_{\rm init} P_{\rm l}[f(140) - f(60)] = 0.025\,{\rm wt\%} \sim 3 \times 10^{-6}\ M_\oplus, \qquad (1)$$

where is $m_{\rm init}$ is the initial mass in planetesimals and $P_{\rm l}$ is the probability of impact of a planetesimal with the Moon. The accretion is measured from 4.5 Ga to 4.42 Ga, the approximate duration of the late veneer epoch in our model. Equation (1) holds regardless of the size-frequency distribution of the remnant planetesimals.

In a collisionless system, the mass in leftover planetesimals follows a stretched exponential decay $m_{\rm left} = m_{\rm init} \exp[-(t/\tau)^\beta]$. Brasser et al. (2016) find a stretching parameter $\beta \sim 0.44$, and e-folding time $\tau \sim 12$ Myr. Assuming that this rate of decay holds until the birth of the solar system, substituting 0.5% for the impact probability with the Moon (see below) the mass of remnant planetesimals at the time of the GI is then $m_{\rm left} = 10^{-3}\ M_\oplus$.

This mass is at least an order of magnitude lower than the 0.05 $M_\oplus$ that Brasser et al. (2016) obtained with the canonical Grand Tack model, or most other terrestrial planet formation simulations. For example, the classical simulations of Matsumura et al. (2016) also have a remnant planetesimal mass of 0.05 $M_\oplus$ after 200 Myr. If the estimate of the remaining mass in planetesimals from Brasser et al. (2016) is correct, then after 150 Myr of evolution it is typically 5% of the initial mass. At the time of the Moon-forming impact at 4.5 Ga the planetesimal mass typically is $m_{\rm left} \sim 0.1\ M_\oplus$. Then the Moon is expected to be struck by