Late veneer and late accretion to the terrestrial planets

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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[1]. Once the planets have, for the most part, assembled after a giant impact phase[2], they continue to be bombarded by a multitude of planetesimals left over from accretion[3]. 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[4]. Second, the expected chondritic veneer component on Mars is 0.06 weight percent after 4.5 Ga; the majority of its chondritic late accretion must have arrived earlier. 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[5], 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[1] 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.

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