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The Last Stages of Terrestrial Planet Formation: Dynamical Friction and the Late Veneer

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The final stage of terrestrial planet formation consists of the cleanup of residual planetesimals after the giant impact phase. Dynamically, a residual planetesimal population is needed to damp the high eccentricities and inclinations of the terrestrial planets to circular and coplanar orbits after the giant impacts stage. Geochemically, highly siderophile element (HSE) abundance patterns inferred for the terrestrial planets and the Moon suggest that a total of about 0.01 M⊕ of chondritic material was delivered as 'late veneer' by planetesimals to the terrestrial planets after the end of giant impacts. Here we combine these two independent lines of evidence for a leftover population of planetesimals and show that: 1) A residual population of small planetesimals containing 0.01 M⊕ is able to damp the high eccentricities and inclinations of the terrestrial planets after giant impacts to their observed values. 2) At the same time, this planetesimal population can account for the observed relative amounts of late veneer added to the Earth, Moon and Mars provided that the majority of the accreted late veneer was delivered by small planetesimals with radii ≤10 m. These small planetesimal sizes are required to ensure efficient damping of the planetesimal's velocity dispersion by mutual collisions, which in turn ensures sufficiently low relative velocities between the terrestrial planets and the planetesimals such that the planets' accretion cross sections are significantly enhanced by gravitational focusing above their geometric values. Specifically we find, in the limit that the relative velocity between the terrestrial planets and the planetesimals is significantly less than the terrestrial planets' escape velocities, that gravitational focusing yields a mass accretion ratio Earth/ Mars ~ $(\rho\oplus/\rho_{mars})(R\oplus/Rmars)^4$ ~17, which agrees well with the mass accretion ratio inferred from HSEs of 12-23. For the Earth-Moon system, we find a mass accretion ratio of ~ 200, which, as we show, is consistent with the mass accretion ratio inferred from HSE abundances of 150-700. We conclude that small residual planetesimals containing about ~ 1% of the mass of the Earth could provide the dynamical friction needed to relax the terrestrial planets' eccentricities and inclinations after giant impacts, and also may have been the dominant sources for the relative and absolute amounts of late veneer added to Earth, Moon and Mars. Our results provide an alternative scenario to that of [1] which limits HSE delivery among differentiated projectiles to diameters <2000 to 4000 km, <1000 to 3000 km, and <1000 km, respectively for the Earth, Mars and Moon. We argue that the terrestrial planets volatile elements were also delivered by the late veneer in order to account for the ~4.4Ga old terrestrial hydosphere and early felsic crust of granitoids reflected in Hadean zircons [2].

References

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