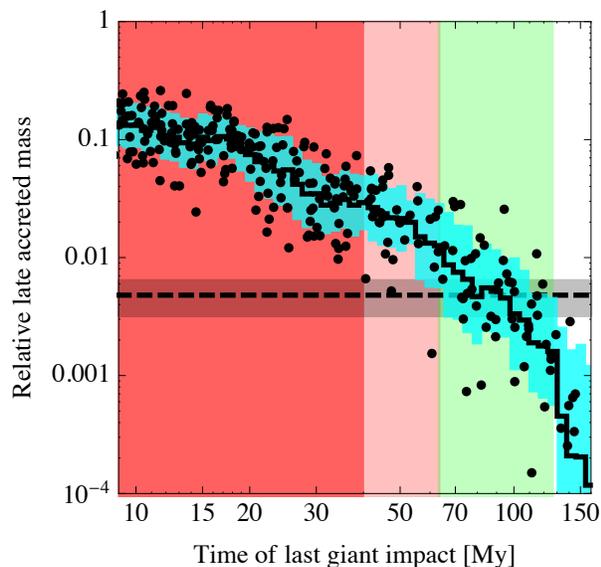


PLANET FORMATION WITHIN THE GRAND TACK MODEL. S. A. Jacobson^{1,2}, A. Morbidelli¹, D. C. Rubie², K. Walsh³, D. P. O'Brien⁴, S. Raymond⁵, S. Stewart⁶ and S. Lock⁶, ¹Observatoire de la Côte d'Azur, Laboratoire Lagrange, B.P. 4229, Nice Cedex 06304, France (seth.jacobson@oca.eu), ²Universität Bayreuth, Bayreuth, Germany, ³Southwest Research Institute, Boulder, CO, USA, ⁴Planetary Science Institute, Tucson, AZ, USA, ⁵Université Bordeaux, Floirac, France, ⁶Harvard University, Cambridge, MA, USA

Introduction: We present conclusions from a large number of N-body simulations of terrestrial planet formation. We focus in this abstract on results obtained from the recently proposed Grand Tack model, which couples the gas-driven migration of giant planets to the accretion of terrestrial planets. In this model the first inward and then outward migration of Jupiter and Saturn creates a truncated disk of embryos and planetesimals, the subsequent evolution of which eventually broadly reproduces the orbital and mass distributions of the terrestrial planets, including a small Mars. The new clock presented for measuring the age of the Moon also exists within classical simulations, in which the giant planets start and remain on their current orbits.

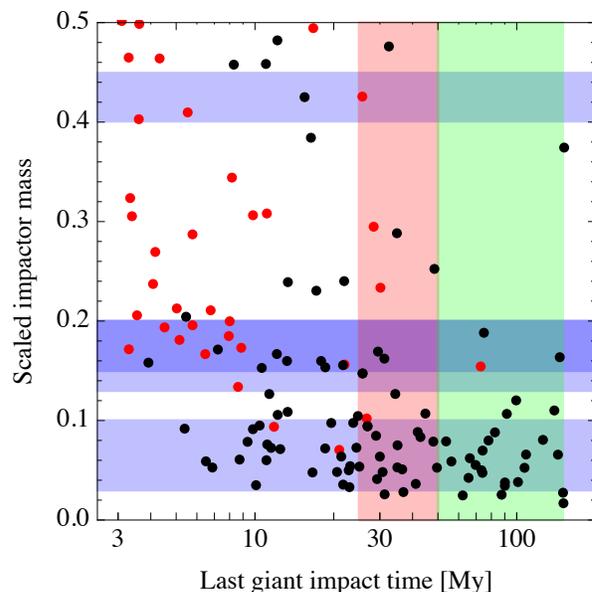
The HSE-gear Clock: We have discovered a new clock for dating the Moon-forming event. This clock uses an estimate of the late accreted mass ($0.048 \pm 0.016 M_E$) on the Earth from the highly siderophile elements (HSEs) [1,2] and a correlation between the timing of the last giant (embryo-embryo) impact and the mass accreted after that impact on Earth-like planets in simulated solar systems, as shown in the figure below. Dots represent the time of the last giant impact on Earth-like planets and the mass accreted afterwards.



The correlation shown as a running geometric mean with a cyan uncertainty region exists for both sets of data. We date the Moon-forming impact to $95 \pm$

35 My and rule out dates earlier than 40 My with 99.9% confidence and 63 My with 85% confidence. These dates are consistent with some but not all radiogenic chronometers.

Role of Dynamical friction: We find that the timing of the Moon-forming event is determined by the relative mass of the embryo population to the mass of the planetesimal population at the beginning of the giant impact phase (i.e. just after the oligarchic growth phase of planet formation). This is shown in the figure below, where the dots show the time of the last giant impact on Earth-like planets and the mass of the final impactor for two different initial mass ratios: 1/1 (red) and 8/1 (black).



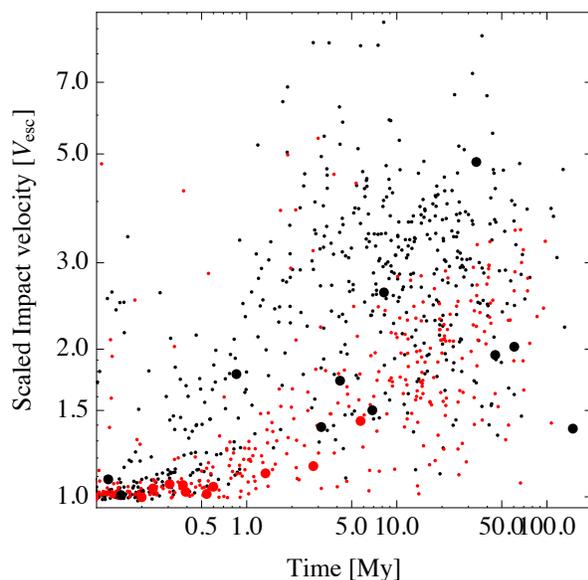
These proportions set the amount of dynamical friction—the damping of the eccentricities and inclinations of the larger bodies due to gravitational interactions with a swarm of smaller. A lower relative total planetesimal mass means less dynamical friction, and so higher eccentricities and inclinations of the embryos. Thus there is diminished mutual gravitational focusing and consequently later embryo-embryo collisions, i.e. giant impacts.

For reference, also shown in the figure above are two vertical bands, which show different model ages for the Moon-forming event from radiogenic chronometers [3,4], and four blue bands, which represent dif-

ferent hypothesized impactor masses from Moon-formation simulations [5,6,7,8].

Earth-Venus Dichotomy: While final giant impacts on Earth-like planets can resemble hypothesized Moon-forming impacts. Giant impacts in general span a very large distribution energetically. However, there are two pertinent trends. First, impacts which occur earlier typically occur at lower impact velocities (apparent in the following figure). Second, impacts which occur earlier more likely occur between similar sized bodies (apparent in the previous figure). Both of these effects are directly related to the increased dynamical friction at the start of the giant impact phase of planet formation before the planetesimal population has been significantly depleted by accretion or ejection. We did not model erosion of the planetesimal population from planetesimal-planetesimal collisions, but it could be important here.

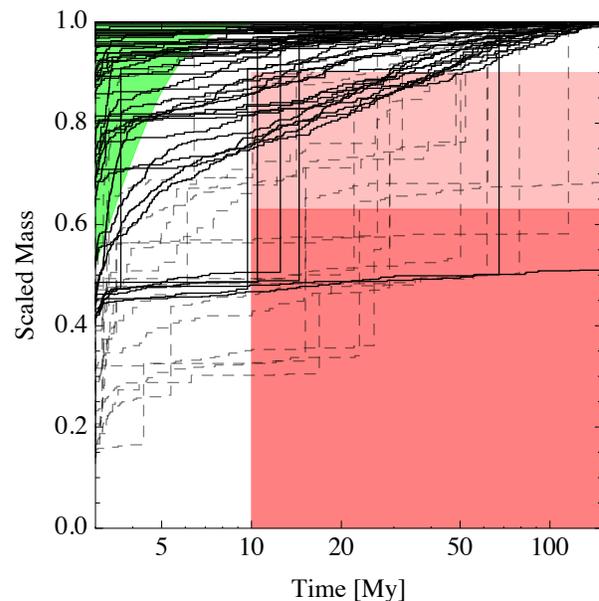
Many terrestrial planet analogs undergo both early and late giant impacts. However, often a planet undergoes impacts that are all early or mostly late. We hypothesize that this is the fundamental distinction between Earth and Venus. Atmospheric loss is difficult [9] and requires very energetic impacts that we associate with later events. Earlier impact events occur at too low velocities to remove significant portions of a planet's atmosphere. Excitingly, we find examples of this dichotomy within our simulations as shown below.



In this simulation, there are two terrestrial planets 0.9 (black) and 0.93 (red) M_E . All of their giant (large dot) and planetesimal (small dot) accretion events are shown above. The last giant impact of the Venus analog (red) occurs 6 My after the start of the simulation, while the Earth analog has a last giant impact at 150

My. The much higher velocity impacts suffered by the Earth analog result in larger atmospheric loss, although some atmosphere is likely still retained.

Mars as Stranded Embryo: Lastly, given the model ages for Martian differentiation from Hf-W evidence, we conclude that Mars must be a stranded embryo and could not have participated in the giant impact phase of oligarchic-oligarchic (i.e. embryo-embryo) collisions. The figure below shows the mass growth of Mars analogs from two different suites of simulations: 0.025 M_E (dashed) and 0.08 M_E (solid) initial mass embryos. The green region is a growth prediction from Hf-W evidence and a geochemical model from [10] and the red region are two growth regions hypothesized to be ruled out from Hf-W evidence using a more model independent interpretation [11]. Only when the oligarchs begin with masses near that of Mars do they more consistently match the Hf-W constraints.



References: [1] H. Becker et al., *GCA*, 70, 17, 4528-4550 (2006), [2] R. Walker, *CdEG*, 69, 2, 101-125 (2011), [3] S. Jacobsen, *AREP*, 33, 531-570 (2005), [4] M. Touboul, *Nature*, 450, 7173, 1206-1209 (2007), [5] R. Canup, *Science*, 338, 6110, 1052 (2012), [6] A. Reufer et al., *Icarus*, 221, 1, 296-299 (2012), [7] R. Canup, *Icarus*, 196, 2, 518-538 (2008), [8] M. Cuk & S. Stewart, *Science*, 338, 6110, 1047 (2012), [9] H. Genda & Y. Abe, *Nature*, 433, 7028, 842-844 (2005) [10] N. Dauphas & A. Pourmand, *Nature*, 473, 7348, 489-492 (2011), [11] F. Nimmo & T. Kleine, *Icarus*, 191, 2, 497-504 (2007).