

EXPLORING PLANET MIGRATION AND EARLY SOLAR SYSTEM BOMBARDMENT. W. F. Bottke, D. Nesvorný, S. Marchi, H. Levison, R. Canup. Southwest Research Institute and NASA's SSERVI-Institute for the Science of Exploration Targets (ISET) Team, Boulder, CO, USA (bottke@boulder.swri.edu)

Introduction: One of the recent revolutions in our thinking about how our Solar System formed, driven in large part by the orbital properties of Pluto and Kuiper Belt objects, is the concept that the orbits of the outer planets migrated substantially after their formation. The dynamical causes and timing of this globally-important process are a topic of active work and debate, with broad implications for planet accretion models, early solar system dynamical stability, volatile delivery to the terrestrial planet region, and the early impact rate throughout the solar system.

A quantified and well-developed description of this behavior is provided by the "Nice model" [1-2]. The Nice model is an umbrella term for a broad class of dynamical models in which the giant planets experienced a dynamical instability that led to a violent reorganization of the outer planets. Specifically, Uranus/Neptune entered into a large disk of small icy planetesimals (i.e., comets) residing between ~20 and 30 AU and flung its members throughout the Solar System, while the migration of Jupiter/Saturn drove portions of the primordial asteroid belt onto planet-crossing orbits. Even more intriguingly, current models indicate our Solar System once had 5 giant planets: Jupiter, Saturn, and three Neptune-like ice giants. One ice giant was lost via an encounter with Jupiter, but not before producing Jupiter's Trojans/irregular satellites and implanting comets into the asteroid belt [e.g., 3].

The Nice model is potentially powerful because it not only explains the current orbits of the giant planets but also the dynamical state of small body populations across the solar system. Questions remain, however, about how/when (and for some, if) it happened.

One potential way to test the Nice model is to better understand the heavily cratered surfaces on the Moon and Mars. They were both battered by an intense bombardment during their first billion years or more but the timing, sources, and dynamical implications of these impacts are controversial. We argue getting the ages of the most ancient surfaces and basins on Moon/Mars should be a key goal of planetary science in 2050. These worlds are also key targets for human exploration, and as such their future study will likely involve joint involvement from both NASA's science and exploration programs (and help from SSERVI-ISET).

Testing Early Bombardment. Here we define the "Late Heavy Bombardment" (LHB) as those impact events that occurred after stabilization of planetary lithospheres such that they could be preserved as cra-

ters and basins. So far, lunar melt rocks and meteorite shock ages point toward a discrete episode of elevated impact flux between ~3.5 to ~4.0-4.2 Ga, relative quiescence between ~4.0-4.2 to ~4.4 Ga, and elevated impacts > 4.4 Ga [4, 5].

Dynamical models have so far concentrated on examining populations residual from primary accretion and destabilized by giant planet migration. Either one can potentially account for the available observations, although all have pros and cons. We believe the best solution thus far to match constraints is a hybrid model with discrete early, post-accretion and later, planetary instability-driven populations of impactors.

A key problem, though, is that we do not know whether the Nice model instability occurred after a delay that was tens of Myr after CAIs or as long as many hundreds of Ma. Only the latter case would be capable of producing a late uptick in impacts across the solar system.

The Oldest Surfaces on the Moon and Mars. A fundamental problem in testing any model of early bombardment is determining the crater or basin retention ages of the oldest lunar and martian surfaces. For example, the Moon's oldest surface could be as young as 4.35 Ga, which may date a global magmatic event [6], or as old as ~4.4-4.5 Ga, the putative age of the Moon itself (**Fig. 1**) [7]. For Mars, it is possible the oldest surfaces correspond to the age of Borealis basin, which defines Mars' global topography (**Fig. 2**) [8]. The available evidence suggests this basin formed > 4.5 Ga, but a younger formation age and more recent resurfacing cannot be ruled out. It is also possible that large basins would not be retained for some interval after Borealis formation, though this time period may be as short as a few tens of Myr.

Obtaining the Ages of Ancient Basins. Lunar data from the Apollo/Luna programs and lunar meteorites provide compelling evidence that the LHB extended back in time to at least 4.2 Ga and possibly before [9]. The problem is that nearside region of the Moon seems to have been comprehensively resurfaced by ejecta from Imbrium basin, and this has biased our view of the Moon based on the Apollo samples. The lack of absolute ages, especially for the older lunar basins, and solid constraints on the mass vs. time flux of impactors across the inner solar system, is a significant impediment to resolving the nature of the LHB.

We suggest that obtaining solid ages from several lunar and martian basins would go a long way to help-

ing us resolve the timing and nature of the LHB. The two oldest basins on the Moon and Mars, respectively, are South-Pole Aitken and Borealis (Fig. 1-2), but each have an unknown age. Obtaining the ages of basins like Nectaris (Moon) and Hellas (Mars) would also bring clarity to early bombardment history. Each represent a key basin that is located at the beginning of a geologic epoch (i.e., the beginning of the Nectarian-era and Noachian-era, respectively). Their ages would help us determine whether a “lull” in the basin-formation epoch really existed between 4.1-4.4 Ga.

Archean Era Bombardment. The earliest history of Earth is poorly understood because few rocks older than 3.9 Ga exist. Even in the Archean, which lasted between 2.5-3.7 Ga, there are very few existing outcrops of non-metamorphosed rocks. Thus, even though this was a formative time for life on Earth, we lack key information on the terrestrial impact rate.

An oft-neglected constraint comes from terrestrial impact spherule beds. When a large impactor strikes the Earth, it produces a vapor-rich ejecta plume containing numerous sand-sized melt droplets, most of which rise above the atmosphere. Eventually the droplets cool and fall back, forming a global layer that can be several mm to many cm thick for Chicxulub-sized or larger impact events. These layers tell us about large ancient impact events, even if the crater has been lost.

Multiple spherule beds have been found in Archean and early Proterozoic terrains, with the oldest spherule deposits at 3.47 Ga [e.g., 5]. Models show that their age distribution likely corresponds to 70-80 craters with $D > 150$ km forming on Earth between 1.7-3.7 Ga [5]. Collectively, they suggest the LHB had a long-lived tail that lasted to ~ 2 Ga for Chicxulub-sized impact events on Earth, with the LHB endgame taking place during the Great Oxidation Event, Snowball Earth events, etc. The problem is how to test whether impacts mattered when the flux is uncertain.

One method to get the Archean impact flux is to determine the ages of several $D > 50$ -100 km lunar impact craters formed between 1.7-3.7 Ga. Given that the likely impact ratio between the Earth and Moon is ~ 20 , we can use their ages to predict the Archean-era terrestrial flux for larger impacts with some precision. The critical issue will be to identify and date craters with a range of superposed crater spatial densities in order to fill in the gaps of our crater chronology. The precise number needed will require an analysis of LRO data combined with geologic mapping work.

Similarly, the evidence suggests Mars also had a long bombardment tail that ended in the Hesperian-era. The formation time of these large craters is highly uncertain, partly because of erosion but also because their ages are benchmarked to Apollo-derived crater chronologies whose accuracy may be is questionable [9].

Interestingly, these impacts occurred when Mars was experienced substantial water activity, which could suggest a link.

Method for Getting Ages. We suspect the most cost effective method to determining the ages of these surfaces is *in situ* dating using some combination of flyers/rovers that can reach intact outcrops of impact melt on Moon/Mars. Mobility for a single mission may be valued, given that multiple missions are costly.

Our 2050 Goals. We would like the ages for:

- **The oldest lunar and martian surfaces to determine basin retention ages.**
- **The oldest basins South Pole Aitken (Moon) and Borealis (Mars).**
- **Basins at changes in geologic epochs: Nectaris (Moon) and Hellas (Mars)**
- **Middle aged craters on Mars/Moon to fully compute crater chronologies for each world.**



Fig. 1. A map of all $D > 150$ km diameter lunar craters on the lunar nearside (red) and farside (yellow). The largest yellow circle is South Pole Aitken basin.

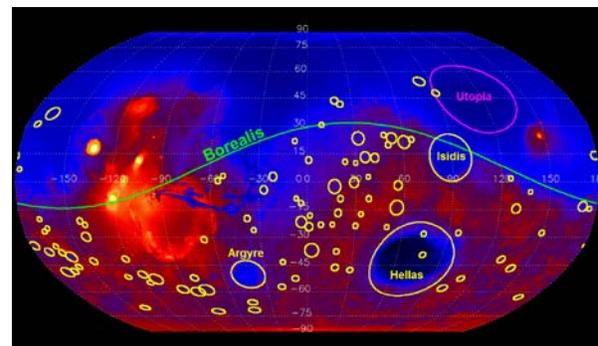


Fig. 2. A map of all $D > 150$ km diameter Martian craters. The green circle is Borealis basin.

References: [1] Tsiganis, et al. 2005. *Nature* **435**, 459. [2] Gomes et al. 2005. *Nature* **435**, 466. [3] Nesvorný & Morbidelli 2012. *Astron. J.* **144**. [4] Marchi et al. 2013. *Nature Geo.* **6**, 303. [5] Bottke et al. 2012, *Nature* **485**, 78. [5] Borg et al. 2015. *MAPS* **50**, 715. [7] Touboul et al. 2009. *Icarus* **199**, 245. [8] Andrews-Hanna et al. 2008. *Nature* **453**, 1212. [9] Bottke & Norman 2017. *AREPS*, in press.