DYNAMICAL EVOLUTION AND BOMBARDMENT OF THE EARLY SOLAR SYSTEM: A FEW HIGHLIGHTS FROM THE LAST 50 YEARS. W. F. Bottke[1] [1]Southwest Research Institute and NASA's SSERVI-ISET Team, Boulder, CO (bottke@boulder.swri.edu).

Introduction. Over the last several decades, there has been a transformation in our theoretical understanding of early Solar System evolution. Historically, it was thought that the planets and small bodies formed near their current locations. Starting in the 1980's with pioneering work by Ward, Lin, and Papaloizou, (for planet–gas disk interactions) in the late 1970s and Fernandez and Ip (for planet–planetesimal disk interactions) in the early 1980s, however, it has now become clear that the structure of the Solar System most likely changed as the planets grew and migrated [e.g., 1, 2].

Evidence for giant planet migration can be found in the orbital structures of the Kuiper belt, Trojans, irregular satellites, etc. [3]. At least one period of migration was driven by interactions between the giant planets and a massive outer cometesimal disk [4]. As the giant planets moved to their current orbits, previously stable reservoirs of impactors became destabilized, leading to enhanced bombardment rates on the Earth, Moon and Solar System worlds [5].

The timing of giant planet migration, however, is unclear. Late migration models, in which a delay between planet formation and migration produced a discrete "late heavy bombardment" (LHB) episode ~500 Myr after the Earth-Moon system formed, now appear to violate key constraints [e.g., 6]. New work instead argues for early migration, with major consequences for terrestrial planet and Moon formation [e.g., 7]. With that said, some constraints are still easier to explain with an impact "uptick" ~4 Ga [5].

Here we briefly discuss these advances, their implications, and questions driven by models/constraints.

Planet Migration in Grand Tack Model. It has been argued that inner Solar System bodies, giant planet cores, and the primordial Kuiper belt formed by the accumulation of initially small objects. While much progress has been made with this model, making a planetary system that reproduces the system we see is still difficult. Planetary orbits are often too excited, Mars analogs are too big, and asteroid belts are too patchy. This has led to intriguing proposed solutions.

One model designed to address the issue of Mars and asteroid belt formation is the so-called "Grand Tack" [8]. Hansen (2009) [9] showed that all of the terrestrial planets could form with masses and orbits like those observed today if the Venus-Earth region between 0.7 and 1 AU initially contained small bodies, while the regions where Mercury and Mars orbit today were empty. While Hansen's paper was provocative, his initial conditions were ad hoc. Walsh et al. (2011) [8] noted that in the hydrodynamic simulations of Masset & Snellgrove (2001) [10], which followed the orbital migration of Jupiter and Saturn in a gas disk, Jupiter could have migrated inward all the way to ~1.5 AU from the Sun. At that point Jupiter and Saturn could have become trapped in their mutual 2:3 resonance and would have begun to move outward.

The Grand Tack model studied the gravitational scattering of asteroids by Jupiter and Saturn during their inward, then outward migration. This model not only reproduces the mass and mixture of spectral types in the asteroid belt, but also truncates the planetesimal disk from which the terrestrial planets form, as in Hansen's work. This allowed them to form a low-mass Mars. In this scenario, Mars was one of many embryos forming near 1 AU at the time of Jupiter and Saturn's migration, but was later scattered out to 1.5 AU by its siblings. It also predicts that many C-type asteroids were once residents of the giant planet zone.

Planet Migration in the Nice Model. The most natural explanation for the dynamical structure of the Kuiper Belt is that the giant planets radially migrated by exchanging orbital energy and momentum with an early cometesimal disk once located beyond Neptune [e.g., 3]. Many works have found that this migration led to a "dynamical instability" in the outer Solar System, when scattering encounters among giant planets excited their orbital eccentricities/inclinations [e.g., 4].

A quantitative version of this scenario is the "Nice model" [3, 4]. It describes how Uranus/Neptune were scattered into a large cometesimal disk, flinging its members throughout the Solar System. This model can explain the orbits of the giant planets. The scattered inhabitants of the original planetesimal disk, which look like D- and P-type asteroids, were captured in dynamically stable pockets in the asteroid belt, Jupiter Trojans, Neptune Trojans, irregular satellites, and Kuiper belt regions [3]. These scattered comets are also a potential early bombardment or LHB source.

As the giant planets moved to new orbits during the instability, asteroids were also moved onto planet-crossing orbits from the primordial main belt. They too are a plausible early bombardment or LHB source.

Timing of the Nice Model. Originally, it was proposed that the giant planet migration/instability occurred ~4 Ga and triggered the lunar LHB [5]. However, new studies of the collisional evolution of the outer disk contradict this idea, because they indicate that the disk must have dispersed within the first 100 Myr of Solar System history [e.g., 6], too early to account for the youngest lunar basins. This new constraint implies that giant planet migration occurred simultaneously with the final stages of terrestrial planet formation. Early migration/instability also avoids a serious prob-

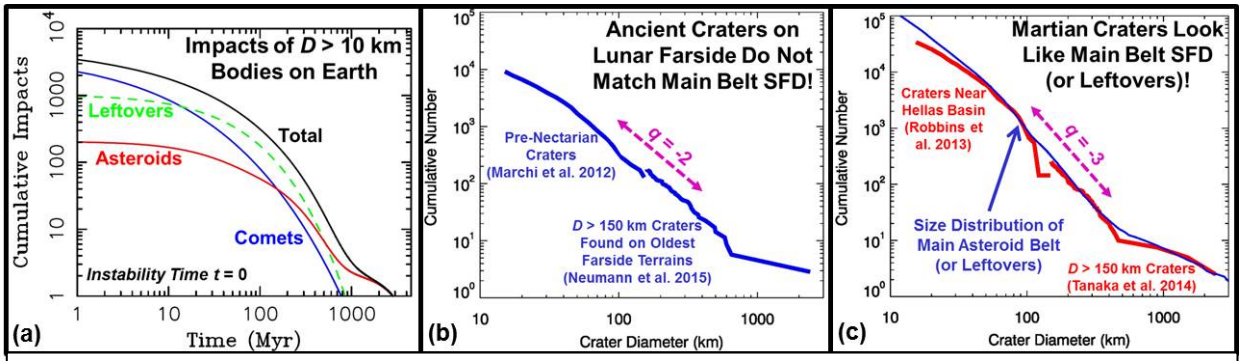

Fig. 1. (a) Earth impacts from instability at t = 0. (b-c) Basins/craters on lunar farside and Mars scaled to entire world.

lem: the over-excitation of terrestrial planet orbits typically associated with late migration [e.g., 11].

The Nice Model and Planet Formation. An early instability and subsequent giant planet migration can strongly influence terrestrial planet formation [7]. The excitation of planetesimals near the Mars zone by giant planet migration can potentially yield a low-mass Mars as well as terrestrial planets with sizes/orbits similar to those observed. It may even produce a dynamically excited asteroid belt [12]. When combined with models showing that C-type asteroids from the giant planet region are captured into the primordial main belt by early gas drag processes [13, 14], an early Nice model might eliminate the need for a Grand Tack model. Bombardment models with an early Nice model are also intriguing (**Fig 1a**).

With that said, much work is needed to confirm this scenario. No one yet knows the range of initial conditions capable of reproducing the terrestrial planets, asteroid belt, giant planets, and Kuiper belt, nor how much delay takes place between the dispersal of the Solar nebula and the onset of planetary migration. New models runs in this area are a priority.

Early Bombardment. The sources and timing of early bombardment have been debated for decades, largely because constraints are limited. A turning point may be near, however, with spacecraft data yielding insights into the bombardment histories of both the Moon and Mars. Testing both worlds in tandem may allow us, for the first time, to rule out specific bombardment options.

Lunar farside. Using GRAIL data, Evans et al. (2018) identified all D > 90 km craters on the Moon, even those buried by maria [15]. They found that the lunar farside was much older than the nearside. By combining GRAIL's farside basins with ancient craters, one can produce a cumulative slope q ~ -2 (**Fig. 1b**). This size distribution is consistent with D > 2 km comet impactors [e.g., 16]. Conceivably, these ancient lunar basins/craters could come from comet bombardment produced by early planet migration.

Lunar nearside. Procellarum, a huge magmatic feature that erased older terrains, dominates the nearside [17]. Its age may be defined by the urKREEP reservoir [~4.3 Ga; 15]. Its basin/crater size frequency distribution (SFD) may match that expected from asteroid or leftover planetesimal impacts.

Martian southern hemisphere. Mars's preserved surface history starts with the formation of the ~10,000 km Borealis basin [e.g., 18]. Borealis is likely older than ancient Martian zircons [ages 4.43-4.48 Ga; 19]. After Borealis, Mars's southern hemisphere bombardment was limited to one SPA-sized basin (Hellas) and two roughly Imbrium-sized basins (Argyre/Isidis) [18]. Its basin/crater size frequency distribution matches that expected from asteroid or leftover planetesimal impacts (**Fig. 1c**).

These constraints suggest some combination of early comet and later asteroid/leftover planetesimal bombardment on Moon/Mars, but details are unresolved.

It has been argued that leftover planetesimals from the Grand Tack may make the observed lunar/Martian basins [20]. For this to work, numerous SPA-sized and smaller basins need to be "erased" on the Moon and Mars prior to ~4.35 Ga. At present, this model cannot explain the different crater SFDs seen in **Fig. 1b,c**.

Late Bombardment. An early Nice model favors a "declining bombardment" scenario on the Moon/Mars (i.e., many early impacts, fewer late ones), but such models cannot yet explain certain constraints (e.g., 2 of 3 largest lunar basins likely formed ≤ 3.9 Ga; Many H chondrite and HED meteorites have ^{40}Ar-^{39}Ar shock degassing ages of ~3.5-4.0 Ga, while few are ~4.1-4.4 Ga; 5). These constraints may still be easier to explain if an impact "uptick" took place ~4 Ga [5]. This raises the question: does another source for the LHB exist?

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