

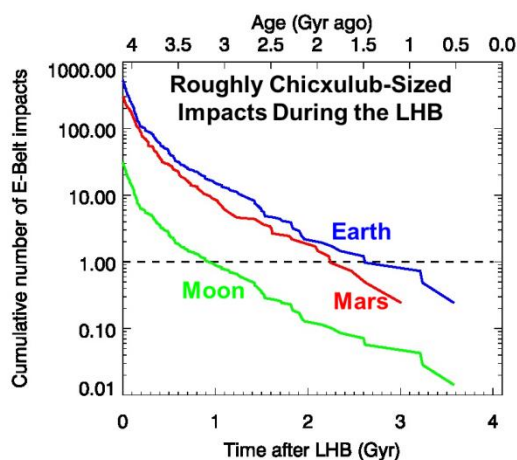
**EARLY SOLAR SYSTEM BOMBARDMENT AND EARTH'S HABITABILITY** W.F. Bottke. Southwest Research Institute and NASA's SSERVI-Institute for the Science of Exploration Targets (ISET), Boulder, CO, USA (bottke@boulder.swri.edu)

**Introduction.** The early bombardment of the inner solar system likely played a critical role in the evolution of Earth's biosphere. To glean insights into astrobiology issues, however, one first needs to know what happened when. To date, this has been problematic — the most commonly-used and cited bombardment models (i.e., impacts from a “terminal cataclysm” ~3.9 Gyr ago; impacts from a monotonically-decreasing impactor population derived from planet formation processes) do not match constraints [e.g., 1].

We suspect this murkiness of this issue has caused many in the astrobiology community to simply assume that sizeable impacts are mainly restricted to the Hadean era, and that the Archean and Proterozoic era were relatively tranquil times. This is dead wrong!

Fortunately, NASA's Lunar Science Institute and SSERVI programs have allowed many scientists to explore these issues in depth (including the author of this abstract, who has directed teams of researchers in both programs). All this work has led to a new and improved bombardment model of early solar system times that is consistent with constraints stretching from Mercury to the asteroid belt [2].

This model can explain numerous constraints, including (i) the formation ages of the younger lunar basins ( $D > 300$  km craters), (ii) the relatively young ages of many large lunar craters (2.8-3.7 Ga) formed after the basin-forming era, (iii) the quantity and timing of terrestrial impact spherule beds, formed by Chicxulub-sized impacts between 1.7-3.7 Ga, and (iv) the  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  shock degassing ages found in asteroid meteorites between 3.5-4.1 Ga [2-3].



**Fig. 1.** Asteroids hitting Earth, Moon, Mars during late heavy bombardment. Note the long impact tail for Earth that only ends ~1.6 Ga.

**The Great Archean Bombardment.** This model's predictions for Earth are surprising and interesting (Fig. 1). As an example, consider that our model predicts that ~15 basin-forming projectiles hit Earth over the Archean era between 2.5-3.7 Ga. A few of these projectiles should have rivaled the sizes of those that formed the gigantic 930 km Orientale and 1160 km Imbrium basins on the Moon. In addition, ~70 Chicxulub-sized impact events took place between 1.8-3.7 Ga. This allows us to argue that the 220-300 km Vredefort and Sudbury craters formed 1.8-2.1 Ga are the tail end of this bombardment. Finally, numerous smaller impactor were also hitting the Earth at this time, with supporting evidence provided by the extensive impact record on the Moon between 2.5-3.7 Ga.

**Astrobiology Connections to Bombardment.** The connections between impacts and events in astrobiology, however, may be this model's most intriguing trait. We find that many key events in Earth's early history are coincident with impacts in some fashion. Examples include:

- The so-called “late heavy bombardment” (LHB) that made the youngest lunar basins likely started ~4.1-4.2 Gyr ago, the same time that most Hadean-era zircons formed [4].
- The endgame of the LHB did not take place not at 3.8 Ga, but rather 1.8-2.8 Gyr ago, the same interval when major variations were taking place in the Earth's oxygen abundance (e.g., “whiffs” of oxygen, the Great Oxidation Event ~2.3-2.4 Ga, major swings in oxygen after the GOE ~2-2.3 Ga). [5]
- When the LHB finally ends, with relatively few large impacts taking place ~0.8-1.8 Ga, this interval coincides with hundreds of Myr of constant  $\delta^{13}\text{C}$  and possibly a stable euxinic ocean (e.g., the so-called “boring billion” era) [e.g., 6].

**Conclusions.** While these coincidences are intriguing, causation cannot be argued without additional evidence or associated modeling work. The goal of this talk is to solicit feedback from astrobiologists on these issues, with the hope that it will lead to new ideas and collaborative work for our diverse communities.

**References:** [1] Morbidelli, A. *et al.* (2012). *EPSL* **355-356**, 144. [2] Bottke, W.F., *et al.* (2012) *Nature* **485**, 78. [3] Marchi, S., *et al.* (2013) *Nature Geo.* **6**, 303. [4] Marchi, S. *et al.* (2014) *Nature* **511**, 578. [5] Lyons, T. W. *et al.* (2014) *Nature* **2014**, **506**, 307. [6] Lyons, T. W. *et al.* (2009) *Ann. Rev. Earth Planet. Sci.* **37**: 507