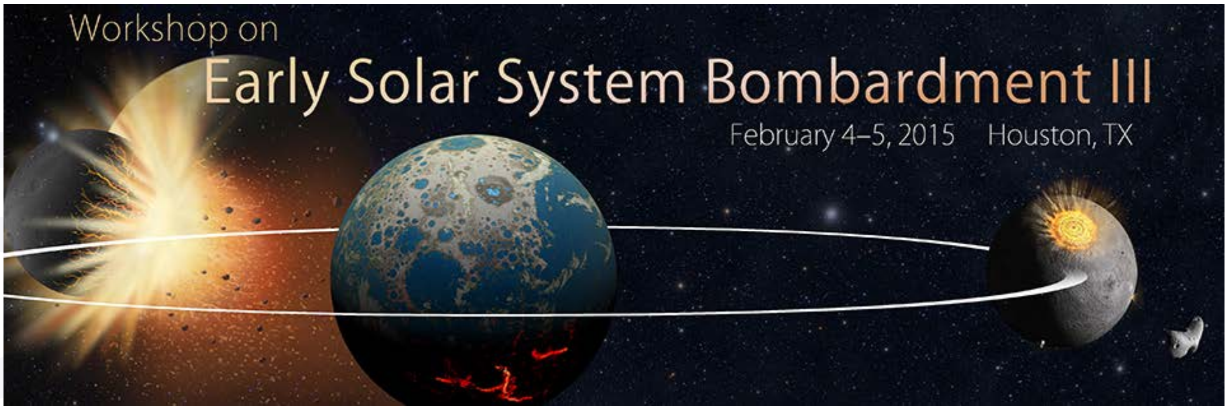
Workshop on Early Solar System Bombardment III

February 4–5, 2015
Houston, Texas



The third edition of an influential series of workshops was held at the Lunar and Planetary Institute in Houston, Texas, earlier this year. The scope of the meeting was to investigate a range of collisional events from the late stages of planetary accretion to the end of the basin-forming epoch on the Moon. That scope included the giant impact hypothesis for the formation of the Earth-Moon system, the lunar (or inner solar system) impact cataclysm hypothesis, and implications that these hypotheses may have for collisions elsewhere (e.g., on Mars) and the accretional and orbital evolution of the outer giant planets. In the spirit of great workshops, it provided a forum for discussion of current ideas and glimpses of new ideas that will significantly enhance our exploration of those solar system processes. The meeting included a few invited talks that were designed to identify broad issues, but it was dominated by contributed oral and poster presentations.

Canup opened the meeting with a discussion of the development of the giant impact model. The “canonical” model involved an oblique, low-velocity collision between the proto-Earth and a body twice the diameter of the Moon (~0.1 to 0.15 $M_{\oplus}$), producing an Fe-poor, ~1.5 to 2 lunar-mass disk, that is dominated by debris from the impactor, with a system angular momentum similar to that in the current Earth-Moon system. That model has been challenged, however, by measurements of similar O-isotope compositions on both the Earth and Moon. Because Mars and Earth have different O-isotope compositions, it is often assumed there was a gradient in O-isotope compositions for objects that formed between the Earth and Mars, which would imply the impactor, and thus Moon, had a different O-isotope composition than the proto-Earth. The O-isotope observation was compounded by a presentation by Touboul, Walker, and Puchtel. They refined techniques to measure W isotopes, knocking down the uncertainties so that a real difference has now been detected between the Earth and Moon. The offset, however, is best explained by assuming that the W-isotopic compositions of the two bodies were identical immediately following formation of the Moon, and that they then diverged as a result of disproportional late accretion to the Earth and Moon.

Dynamical solutions for the O-isotope conundrum exist in the literature, but Canup concluded those appear to have low overall probabilities (on the order of 1% or less). Jacobsen et al. then examined the accretion (or feeding zones) of the proto-Earth, Mars, and the likely impactor assuming (a) an O-isotope gradient in the solar system between the Earth and Mars and (b) the Grand Tack scenario for solar system formation (i.e., in which Jupiter and Saturn migrate inward and sculpt the inner disk). Their model suggests the impactor must have formed in the vicinity of the proto-Earth. Alternatively, it was also noted during discussion that it may be time to reexamine the assumption of an O-isotope gradient in the inner solar system. Additional dynamical and geochemical contributions to the discussion were provided by Pahlevan and Morbidelli, Quarles and Lissauer, Charnoz and Michaut, and Righter.

Workshop participants then explored the concept of collisional erosion during accretion. Bojibar et al. presented a model in which an Earth with a bulk enstatite chondrite composition is stripped of its proto-crust by impacts, followed by fractional recondensation of the ejecta; e.g., for total erosion of 15 to 45% of the Earth's mass, 100% of the Ca and Al recondenses, while only 10% of Mg and 5% of Si recondense to produce Earth's composition. Potter and Kring also examined collisional erosion during the accretion of the Earth as a possible mechanism for explaining nonchondritic geochemical signatures in the Earth. They found it can work, but only under some low-probability circumstances.

A large fraction of the meeting examined the chronology of early solar system impacts. Several papers discussing the Ar-Ar radiometric system were presented by Swindle and Kring; Norman; Zellner and Delano; Boehnke et al.; and Hartmann. Those papers were followed by others discussing the U-Pb system in zircon and other accessory phases: Crow, McKeegan, and Moser; Wielicki and Harrison; and Moser. It became clear that there are disagreements in the Ar-Ar community about how to best measure the K-Ar system and interpret the data. It also became clear that zircon U-Pb data complement the Ar-Ar data, providing an opportunity to look at (generally) older impact and magmatic events. Likewise, U-Pb analyses of lunar phosphate minerals provide complementary chronologic data. Thus, evolving tools (Ar-Ar) and new tools (U-Pb analyses of zircon and phosphate) are providing a growing dataset to test the cadence of impacts during the basin-forming epoch.

To better interpret the ages, it was generally agreed that the geologic context of existing Apollo samples needs to be clarified and that future sample sites need to be carefully selected to determine the ages of specific basins, issues that were explored by Cohen, Petro, and Lawrence, as well as Hurwitz and Kring.

A key to understanding the processes that led to bombardment is the source(s) of early solar system impactors. Walker et al. reported siderophile element and Os-isotope evidence of chondritic and iron asteroid impactors in Apollo 15 and 16 samples (i.e., in the vicinity of Nectarian and Early Imbrian basins). In contrast, Bottke et al. suggested debris left over from the Moon-forming giant impact produced the Moon's pre-Nectarian craters and, more broadly, Jackson et al. suggested that giant impacts during planetary accretion generated debris that dominated the impactor flux. In a twist of that theme, Minton et al. suggested that the proposed Borealis impact event on Mars generated the debris in the late heavy bombardment. The caveat raised during workshop discussion involved the nature of the debris ejected by giant impacts. Most large or giant impact simulations suggest the ejected debris would be melt and vapor (the protolunar disk is, for example, initially melt and vapor), but the models above require ejected debris to be solid and/or to have condensed from the melt and vapor with a fragmentation size distribution.

A presentation of potentially overlooked lunar basins was provided by Frey. That discussion of the basin-forming epoch was then amplified by a discussion of impact events on the Hadean and Archean Earth, led by Marchi et al., Lowe and Byerly, and Koeberl et al. A potential measure of even younger impact events, as deduced from Copernican craters on the Moon, was presented by Mazrouei, Ghent, and Bottke. That inner solar system record was complemented by descriptions of collisional processes that may have affected Vesta (Stickle et al.), comets (de Niem and Kührt), and the outer solar system (Movshovitz et al. and Schmedemann et al.).

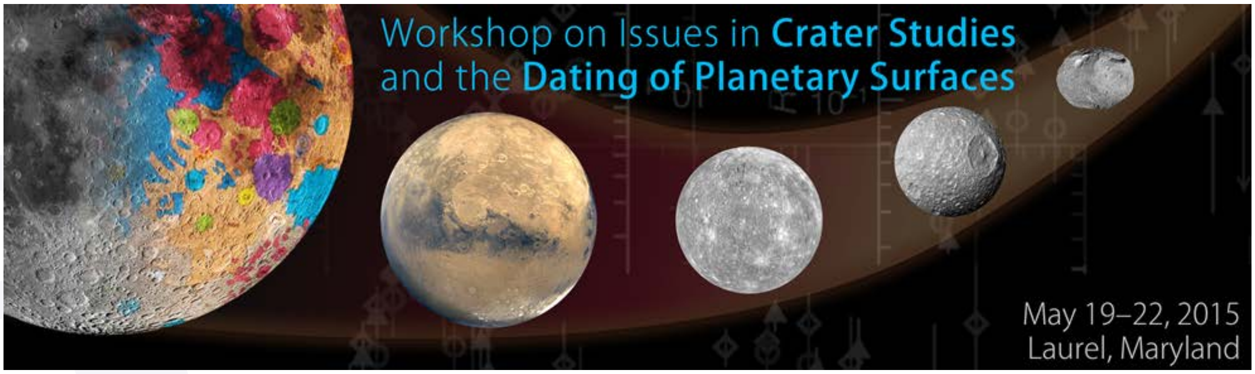
The consequences of early solar system bombardment was investigated first by Kiefer et al., who examined the density of lunar lithologies and implications a prolonged period of bombardment would have on gravity. Two papers (Kring et al. and McGovern et al.) argued that the South Pole-Aitken basin-forming impact triggered a magmatic epoch. That model was prompted, in part, by a collection of U-Pb ages derived from lunar zircon.

To capture the full scope of the workshop's science, we invite you to view the online LPI archive where all the extended abstracts are available: *http://www.hou.usra.edu/meetings/bombardment2015/pdf/program.pdf*.

— Text provided by David Kring and Robin Canup

Workshop on Issues in Crater Studies and the Dating of Planetary Surfaces

May 19–22, 2015
Laurel, Maryland



Impacts are the main exogenic process that shape the surfaces of solid bodies in the solar system. Craters are studied by observationalists, dynamicists, and experimentalists, but often in isolation from each other. Craters inform a wide variety of investigations, including modeling surface ages, understanding surface modification processes, and investigating dynamics of small bodies and the solar system as a whole, and as such they (or results from crater studies) are used by many planetary scientists.

Large advances were made in the early decades of work on and with craters, and a general consensus was developed about the impact history of the solar system and the population of bodies that created that