

THE LUNAR CATAclySM AND HOW LRO CAN HELP TEST IT. B. A. Cohen, NASA Marshall Space Flight Center, Huntsville AL 35812 (Barbara.A.Cohen@nasa.gov)

Introduction: One of the important outstanding goals of lunar science is understanding the bombardment history of the Moon and calibrating the impact flux curve for extrapolation to the Earth and other terrestrial planets. The "terminal lunar cataclysm," a brief but intense period of bombardment about 3.9 billion years ago, is of particular scientific interest. Radiometric dating of lunar impact-melt rocks forms the backbone of the lunar cataclysm hypothesis. A histogram of precise age determinations of impact-melt rocks shows the characteristics of the classic formulation of the lunar cataclysm hypothesis: a sharp peak at 3.9 Ga, a steep decline after 3.9 Ga perhaps only 20–200 Myr long, and few rocks of impact origin prior to ~4.0 Ga [1–3]. The paucity of impact-melt rocks older than 3.9 Ga has been variously interpreted as evidence that there was a low flux of impactors prior to ~3.9 Ga, creating few impact melt rocks [2], that the early impactor flux was so high that the lunar crust was reset and/or destroyed (the "stone wall" effect) [4], or that the dated samples may all be related to a single basin-forming event, Imbrium [5]. If the early lunar flux were much lower, then the apparent spike in impact rate would be a true "cataclysm." If the flux were much higher, than the increased flux could be viewed as simply a bump or inflection on a generally declining post-accretionary impact rate.

Mass constraints on the amount of material needed to create the large lunar basins appears to support a low pre-Nectarian flux [6], and the population of planetesimals remaining from planetary accretion would have been insufficient to produce as many basins as late as Imbrium, Serenitatis, and Nectaris [7]. Instead, insights gleaned from our improved understanding of giant planet formation and migration in planetesimal disks suggest that the Jovian planets experienced a late, sudden instability as they crossed some mutual resonance. This triggered a rapid depletion of the trans-Neptunian planetesimal disk and caused an acceleration of the migration of Jupiter and Saturn, which in turn destabilized the majority of the asteroids in the main belt. The "Nice model" built on this idea not only explains the main characteristics of the impact spike in terms of delay, intensity and duration, but also the current orbital architecture of the giant planets, the existence and the orbital distribution of many populations of small bodies (trojans, KBOs, satellites) [8–10]. This class of dynamical models, that invokes secular sweeping of the asteroid main belt via resonances, has been bolstered by work

on the size-frequency distribution of lunar craters mirrors that of the main belt [11]. The responsible impactor population, and the dynamics of its delivery, plays an important role in determining whether the impact flux history of the Moon should map onto the other terrestrial planets.

The lunar cataclysm hypothesis continues to be tested. Indeed, the top three science goals articulated in The Scientific Context for the Exploration of the Moon (SCEM) [12] relate to placing better constraints on the lunar impact flux. Because of the fine detail gleaned in terrestrial labs from existing samples, the level of precision needed to address some of the outstanding questions related to the cataclysm depends on sample return. However LRO could assist in meeting these goals in important ways:

(SCEM 1a) Test the cataclysm hypothesis by determining the spacing in time of the lunar basins. There is little recognizable pre-Nectarian terrain on the Moon for crater counting, stratigraphy, or association with rock ages. However, the timing of the large Imbrian-era basins can be constrained by using LRO high-resolution images to provide targeted crater counts of undisturbed ejecta surfaces from Orientale, Imbrium, Serenitatis, and Nectaris, as well as Imbrian-era farside basins. Identification and mapping of extant melt sheets in nearside basins such as Nectaris and in farside basins would be important in guiding future missions to sample such lithologies.

Another possibility for putting age constraints on ancient surfaces may be improved crater counting on the oldest basalt flows. In turn, stratigraphic relationships between such ancient basalt flows and basin ejecta may help bound basin formation ages. Some of these flows have been identified on the eastern limb by crater counting [13, 14]. Others may be identified based on their mineralogical or elemental affiliation with ancient basalt samples in our collection, such as the high-Al basalts and lunar meteorite Kalahari 009 [15–17]. In particular, farside flows may hold important clues. Model ages of mare deposits on the lunar farside using crater frequency distributions in 10 m/px images obtained by Kaguya's Terrain Camera identified an ancient basalt flow in Mare Nishina, at ~3.85 Ga.[18].

(SCEM 1b) Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin, the South Pole-Aitken (SPA) basin. The SPA basin, with a diameter of 2000 km, is the stratigraphically oldest lunar basin and probably created more impact melt than all other lunar craters combined.

Endogenous impact melt probably still resides on the basin floor and could be directly sampled by a robotic mission. Before that time, however, higher-resolution images to provide targeted crater counts on ejecta of basins within SPA would help bound the SPA formation age and provide constraints on the impact history provided by a scoop sample. Remote sensing of possible sample collection sites is also crucial to help determine the regional geologic context of future returned samples.

(SCEM 1c) Establish a precise absolute chronology. It is important to understand the inflections and changes in of the lunar flux throughout time so that we can judge whether a period, such as the Cataclysm, is truly anomalous. Are age-correlated changes in the apparent lunar crater size-frequency distribution due to of erasure of small craters or due to evolution of the production function? How do changes in the lunar crater size-frequency distributions reflect the impactor populations responsible for creating them? Higher-resolution images providing targeted crater counts on selected ejecta facies, such as Copernicus and Tycho, will be able to be correlated with radiometric ages. The very young end of the lunar flux curve can be examined by comparing new remote sensing data sets with Apollo-era data sets to detect formation of new craters.

References: [1] F. Tera et al. (1974) *Earth Planet Sci Lett* **22**, 1. [2] G. Ryder (1990) *Eos* **71**, 313. [3] B.A. Cohen et al. (2005) *Met Planet Sci* **40**, 755. [4] W.K. Hartmann (2003) *Met Planet Sci* **38**, 579. [5] L.A. Haskin et al. (1998), *Met Planet Sci* **33**, 959. [6] G. Ryder (2002) *J Geophys Res* **107**, DOI 10.1029/2001JE001583. [7] W.F. Bottke et al. (2007) *Icarus* **190**, 203. [8] R. Gomes et al. (2005) *Nature* **435**, 466. [9] A. Morbidelli et al. (2005) *Nature* **435**, 462. [10] K. Tsiganis et al. (2005) *Nature* **435**, 459. [11] R.G. Strom et al. (2005) *Science* **309**, 1847. [12] National Research Council (2007) *The Scientific Context for the Exploration of the Moon*, 120 pp, National Academies Press, Washington, DC. [13] H. Hiesinger et al. (2003) *J Geophys Res* **108**, 5065. [14] H. Hiesinger et al. (2000) *J Geophys Res* **105**, 29239. [15] C.R. Neal and G.Y. Kramer (2006) *Am Min* **91**, 1521. [16] G.Y. Kramer et al. (2008) *J Geophys Res* **113**, 01002. [17] A.K. Sokol et al. (2008) *Geochim Cosmochim Acta* **72**, 4845. [18] J. Haruyama et al. (2009) *Science* **323**, 905.