The Lunar Cataclysm: Reality or "Mythconception"?

Marc D. Norman*

1811-5209/08/0005-0023$2.50 DOI: 10.2113/gselements.5.1.23

The impact history of the Moon has significant implications that go far beyond simply excavating the surface of a dry and lifeless world. The age distribution of lunar impact breccias inspired the idea of a catastrophic influx of asteroids and comets about 4 billion years ago and motivated new models of planetary dynamics. A late bombardment may have regulated environmental conditions on the early Earth and Mars and influenced the course of biologic evolution. The cataclysm hypothesis is controversial, however, and far from proven. Lunar explorers face the difficult task of establishing absolute ages of ancient impact basins and the sources for the impactors.

Keywords: impact, breccia, cataclysm, geochronology, Imbrium, Moon, Late Heavy Bombardment

INTRODUCTION

The origin of planets is an energetic process. Planetary embryos grow rapidly, leading to impressive collisions between bodies the size of the Moon and Mars within a few million years after collapse of the solar nebula. These collisions release sufficient energy to cause large-scale melting and magmatic differentiation of terrestrial planets, setting the stage for their subsequent evolution. To a surprising degree, however, early geological environments continued to be shaped by celestial events long after the Hadean magma oceans had cooled and crystallized. Major unexpected insights stimulated by study of lunar samples include the fundamental importance of megascale impacts in the formation and early evolution of planetary systems, and the realization that intense bombardment persisted for hundreds of millions of years after the nebula had dissipated.

Impact craters on the airless Moon range in size from a few microns up to a few thousand kilometers. Most of the Moon's surface geology is related either directly or indirectly to the 50 or so largest impact basins identified from orbital photogeologic and geophysical mapping (Table 1). These basins have diameters ranging upward from about 300 km to 1160 km for Imbrium and 2500 km for the South Pole–Aitken basin (Table 1; see compilations by Wood 2004 and Spudis 1993 and figure 3 in Delano 2009 this issue). The collisions of asteroid-size bodies 10–100 km in diameter that formed these basins represent brief but intense tectonic events capable of profound structural modification of the lunar crust.

Large impact events create significant volumes of breccia deposits, and these were natural targets for mission planners during the Apollo expeditions. Two general classes of lunar impact breccias have been recognized: *fragmental breccias*, composed predominantly of clastic rock debris in a finely comminuted, grain-supported matrix of mineral and lithic fragments, and *melt breccias*, with a crystalline to glassy matrix that formed by cooling of a silicate melt. Based on field studies of terrestrial impact craters and photogeologic observations of late, well-preserved lunar basins such as Orientale, melt breccias are thought to occur predominantly within and close to the rim of the basin, whereas fragmental breccias can be deposited outwards up to several times the radius of the basin (Fig. 1).

Petrologists and geochemists have used impact breccias returned from the Moon by the Apollo and Luna missions, and collected as meteorites, to probe the structure of the lunar crust and the record of impact accretion prior to development of an extensive rock record on Earth. Of particular interest here are the formation ages of lunar impact basins and what they might reveal about early solar system dynamics. Impact breccias can be dated using various radioactive decay schemes, such as ^{40}Ar–^{39}Ar, ^{87}Rb–^{87}Sr, and ^{147}Sm–^{143}Nd. Melt breccias are especially useful for this because they stand the best chance of having their radioactive clocks completely reset by the impact event, although the presence of unequilibrated relict clasts (Fig. 2) has been a persistent challenge to obtaining reliable ages (Jessberger et al. 1974).

Early geochronological studies of impact melt breccias collected by Apollo astronauts from landing sites on the nearside equatorial regions of the Moon revealed a pronounced clustering of crystallization ages between 3.75 and 3.95 billion years (Jessberger et al. 1974; Turner and Cadogan 1975). This narrow range of impact breccia ages corresponds to an episode of intense crustal metamorphism defined by U–Pb isotopic compositions of lunar anorthosites, a coincidence that led Tera et al. (1974) to infer "an event or series of events in a narrow time interval which can be identified with a cataclysmic impacting rate of the Moon at ~3.9 Ga." This discovery generated competing hypotheses for the early impact flux to the Moon and, by implication, to the early Earth as well.

In one scenario, the impact flux increased dramatically at ~3.9 Ga, creating perhaps 15 or more of the lunar basins (>300 km diameter) during a "Late Heavy Bombardment" (LHB). Depending on the relationship between impactor size and basin diameter, this might imply a mass flux to the Moon on the order of 10^{22} g within 100 million years

---

* Research School of Earth Sciences, Australian National University, Canberra ACT 0200, Australia
Lunar and Planetary Institute, Houston, TX 77058, USA
E-mail: Marc.Norman@anu.edu.au

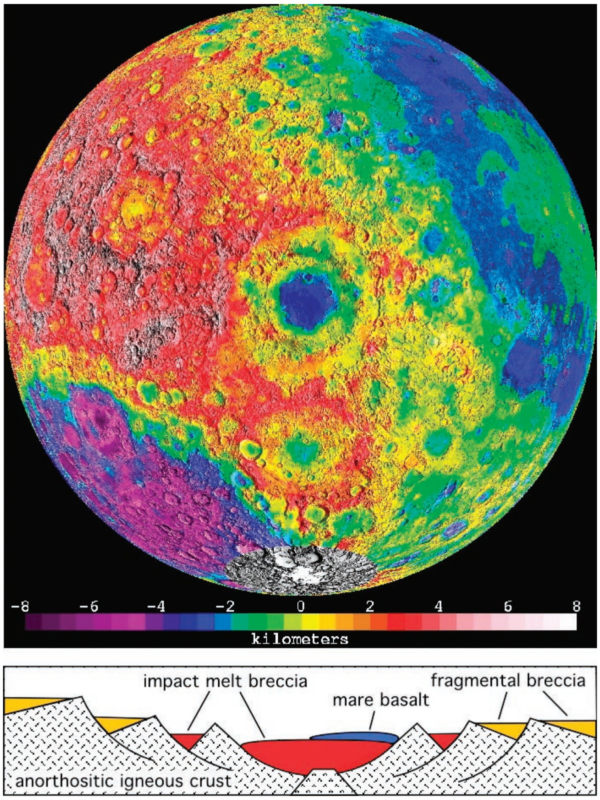

Figure 1 Top: Lunar topography centered on the Orientale basin (19°S, 95°W) based on altimetry data collected by the Clementine orbital mission. The outermost conspicuous ring of Orientale is >900 km in diameter. Below Orientale is the Mendel-Rydberg basin. To the upper left is Hertzsprung. The South Pole–Aitken basin is the purple patch on the limb to lower left. Imbrium is the dark blue, circular feature on the upper right limb. Image courtesy of Paul Spudis (LPI, Houston). Bottom: Schematic cross-section of a multiring basin illustrating the distribution of impact breccias. Not to scale.

(Ryder 2002), equivalent to about 0.3% of the current mass of the asteroid belt and an accretion rate 25,000 times higher than the annual impact flux to the Moon over the past 3.6 billion years. Alternatively, the impact flux may have declined more steadily, with relatively minor temporal fluctuations, since formation of the Moon's crust. In this scenario, the apparent clustering of impact breccia ages may be caused by destruction or burial of older deposits by ejecta from more recent events such as those that formed Imbrium and Serenitatis, or by a sampling bias due to the small area actually included within the Apollo and Luna mission footprint (Hartmann 2003; Chapman et al. 2007).

The truth is probably not as simple as either end-member scenario would suggest, but clarifying the impact history of the Moon does have significant implications. The idea of a Late Heavy Bombardment has generated new models of planetary dynamics in the early solar system, invoking either the late formation or outward migration of Uranus and Neptune (Levison et al. 2001; Gomes et al. 2005), or an unstable planet formerly between Mars and the asteroid belt (Chambers 2007). Absolute ages inferred for surface deposits on Mars and Mercury are based directly on lunar cratering curves (Hartmann and Neukum 2001; Neukum et al. 2001), so our understanding of rates and timescales of geological processes on other planets depends critically on correct interpretation of the lunar record. On Earth, the oldest preserved continental crust and earliest (albeit contentious) signs of life are strikingly similar in age to the lunar impact melt breccias. Whether this is coincidence or has more fundamental significance, better constraints on impact rates during the first 500 million years or so of solar system history would provide useful information about environmental conditions on the early Earth and Mars.

Recognizing the significance of the lunar impact record for solar system evolution, the Space Studies Board of the U.S. National Academy of Science ranked the bombardment history of the inner solar system, uniquely revealed on the Moon, as the top scientific priority for the next wave of lunar exploration (see box).

HIGHEST-PRIORITY SCIENCE GOALS FOR LUNAR EXPLORATION (SPACE STUDIES BOARD 2007)

1a. Test the cataclysm hypothesis by determining the spacing in time of the creation of the lunar basins

The history of impacts in the early Earth–Moon system, in particular around 3.9 Ga, the time that life was emerging on Earth, is a critical chapter in terrestrial planet evolution. Understanding this period is important for several reasons: to test our models of the impact rate, planetary accretion, impact frustration of life, and magma-ocean formation and evolution, and to extend and verify the chronology. In order to answer the question of whether there was a cataclysm at 3.9 Ga, samples from the oldest impact basins and high-resolution imaging from orbit are required.

1b. Anchor the early Earth–Moon impact flux curve by determining the age of the oldest lunar basin (South Pole–Aitken basin)

Although the enormous South Pole–Aitken basin is stratigraphically the oldest basin on the Moon, its absolute age is completely unconstrained. All models of the first few hundred million years of solar system history depend on whether the large basins are part of a decreasing flux of material swept up by growing planet embryos or a later separate pulse of planetesimal-sized bodies. Details of the lunar stratigraphy can be better defined by integrated high-resolution imagery and topography, but it is essential to provide an absolute date for the oldest basin, the South Pole–Aitken basin, with the type of precision that can only be obtained in Earth-based laboratories with returned samples.

1c. Establish a precise absolute chronology

A well-calibrated lunar chronology not only can be used to date unsampled lunar regions, but it can also be applied to date planetary surfaces of other planets in the inner solar system through modeling. An absolute lunar chronology is derived from combining lunar crater counts with radiometric sample ages and is thus the most precise—and in some cases the only—technique to date planetary surfaces for which samples have not been or cannot be obtained. In order to determine the precise shape of the lunar chronology curve, samples should be returned from several key benchmark craters, young lava flows, and old impact basins, which also need to be imaged at high spatial resolution.

AGES OF LUNAR IMPACT BRECCIAS

The concept of a spike in the flux of large impactors traversing the inner solar system at ~3.9 Ga was developed in some detail by Grenville Turner (Turner and Cadogan 1975; Turner 1979) and later championed by Graham Ryder (Ryder 1990; Stöffler and Ryder 2001; Ryder 2002), who proposed that 15 of the major nearside lunar basins (D >300 km) formed within an interval of ~100–200 million years (see also Jessberger et al. 1974; Wilhelms 1987; Spudis 1993). Despite early evidence for multiple large impacts closely spaced in time (Jessberger et al. 1974), analytical and geological uncertainties hampered the resolution of discrete events and obscured the relationships between individual melt breccias and specific basins or craters (Haskin et al. 1998).

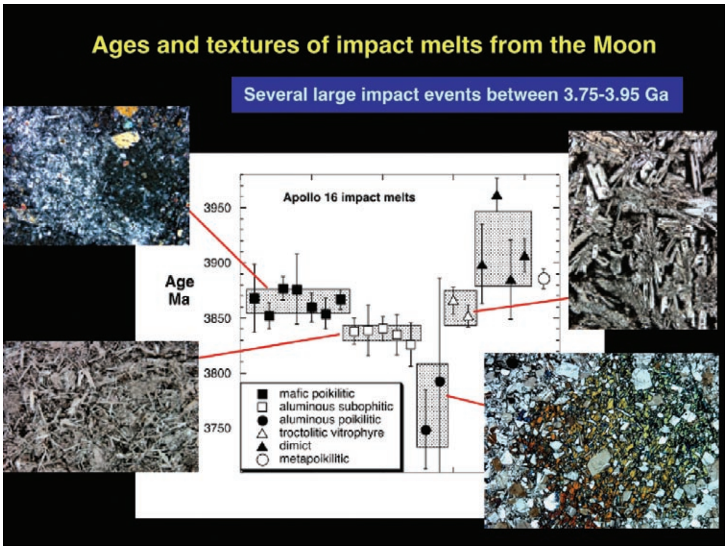

FIGURE 2 Proposed groupings of Apollo 16 impact melt breccias based on textures and ages. The groups probably represent different impact events between 3.75 and 3.95 Ga. Photomicrographs of the rock textures are shown in transmitted light using an optical microscope. Field of view for the photomicrographs is 1 × 2 mm for each sample except 2 × 4 mm for the aluminous poikilitic melt breccia. AFTER NORMAN ET AL. (2006)

The context for interpreting impact breccia geochronology improved with the adoption of a well-defined lunar stratigraphy that finally established relative ages of the large lunar basins (Wilhelms 1987). Dalrymple and Ryder (1993, 1996) pinned the absolute ages of Imbrium and Serenitatis, two of the stratigraphically younger basins, at 3.86 Ga and 3.89 Ga, respectively, from the ^{40}Ar–^{39}Ar ages of Apollo 15 and Apollo 17 impact melt breccias measured using next-generation mass spectrometers and laser microsampling to avoid unequilibrated relict clasts. These melt-breccia suites were selected specifically to represent the best candidates for primary ejecta from these two great basins, although some debate continues about the geological relationships between these basins and lunar rock suites collected at other landing sites (Stöffler and Ryder 2001). Considering that three other basins (Hertzsprung, Sikorsky-Rittenhouse, Bailly) are placed stratigraphically between Serenitatis and Imbrium (TABLE 1) and that the Schrödinger and Orientale basins are both not much younger than Imbrium based on crater density populations (Wilhelms 1987), it seems clear that several large (>10 km diameter) impactors must have hit the Moon within a relatively narrow interval of time, around 3.7–3.9 billion years ago, some 500–700 million years after initial magmatic differentiation of the lunar crust and mantle.

Recent geochronological studies of lunar impact breccias provide additional evidence of a Late Heavy Bombardment. For example, ages and textural groupings of melt breccias from the Apollo 16 site resolve at least four or five discrete impact events ranging in age from 3.75 to 3.95 Ga (FIG. 2). Lunar meteorites, which probably sample regions far removed from the Apollo landing sites, also lack impact ages older than 4 Ga (Cohen et al. 2000, 2005), as do glass particles from the near-surface regolith based on ^{40}Ar–^{39}Ar ages (Culler et al. 2000; Levine et al. 2005). Differences in ages and initial ^{87}Sr/^{86}Sr ratios of crystalline impact melt breccias from the Apollo 14 and 16 sites (Papanastassiou and Wasserburg 1971, 1972) are consistent with multiple impact events. A straightforward interpretation of the distribution of lunar melt-breccia ages is that numerous impacts sufficiently large to generate abundant crystalline impact melt breccias occurred within the interval 3.75 to 3.95 Ga, and that such events were much less common after that time. The central nearside region of the Moon in the vicinity of the Apollo landing sites seems to have been comprehensively resurfaced by these events.

A LATE SPIKE?

The key question is how the flux of impactors changed from 4.5 to 3.8 Ga. Resolving a singular spike in the cratering rate from a more continuous although perhaps bumpy prior history may sound like a straightforward problem, but the available record is sparse and often lacks critical context. The paucity of impact-melt-breccia crystallization ages older than 4.0 Ga has been cited as strong evidence supporting a late cataclysm (Ryder 2002), but our poor understanding of regolith dynamics on the Moon diminishes the significance of this observation (Chapman et al. 2007). Compounding this problem, the provenance of many depositional units on the surface of the Moon and their genetic relationships to major basins are not well known.

In 2004 my colleagues and I identified one of the Apollo 16 anorthositic rocks (67955) as a melt breccia likely to have a significantly older age based on its texture and bulk composition. Although the argon and Rb–Sr systems were disturbed, a ^{147}Sm–^{143}Nd mineral isochron produced an age of 4.20 ± 0.07 Ga (Norman et al. 2007). We interpreted this to be the age of a melt-forming impact event, the first such event older than 4 Ga to be documented in a lunar sample. This discovery shows that we can lift the veil of the lunar cataclysm and start to probe the older impact history of the Moon, but how much emphasis we should place on the age of a single sample is difficult to assess. Turner (1979) presented statistical arguments that a genuine gap in lunar impact ages between 4.2 and 3.9 Ga would favor an increased cratering rate at 3.9 Ga. On the other hand, Hartmann's (2003) megaregolith model for the lunar crust also predicts this type of age distribution, with a few older samples from large impact events preserved in the near-surface regolith. The current distribution of impact-melt-breccia ages does appear consistent with a 300-million-year gap, possibly favoring a Late Heavy Bombardment, but the sampling is obviously thin and the extent of late basin–ejecta deposits on the nearside region of the Moon needs further clarification.

LUNAR BASINS

The absolute ages of most lunar basins are unknown. Despite the best efforts of mission planners, only Apollo 17 successfully sampled a geologically well-constrained impact-melt deposit that can be linked with confidence to a major basin (Serenitatis). The inferred age of Imbrium relies more critically on interpretation of samples collected at the Apollo 14 and 15 sites, whose geological context is less well established. A few small fragments of anorthositic breccia sampled at the rim of the Crisium basin by Luna 20 also yielded ages of 3.85–3.89 Ga (Swindle et al. 1991), but the provenance of these fragments and their relationship to the Crisium basin are unknown.

Interpretations relating lunar surface deposits to specific basins are the critical link for assessing the reality (or otherwise) of the lunar cataclysm. An excellent example is the Descartes Formation, a regional unit on the central nearside that was sampled at North Ray crater (1 km diameter) by the Apollo 16 mission in 1972. Mission planners tentatively identified the Descartes Formation as Imbrium ejecta based on orbital photography (Muehlberger et al. 1980), but a consensus developed among lunar scientists that an origin as Nectaris ejecta was more likely (James 1981). As Nectaris is one of the stratigraphically older nearside basins (Table 1), the ~3.9 Ga ^{40}Ar–^{39}Ar ages that were determined for Descartes breccia clasts were considered as strong support for the lunar cataclysm hypothesis (James 1981).

Recent high-precision ^{40}Ar–^{39}Ar dating of additional clasts from the Descartes breccias, however, has established an age that is identical with those of the Apollo 15 rocks thought to represent Imbrium ejecta, and resolvably younger than Serenitatis (Norman and Duncan 2008). As Nectaris is stratigraphically older than Serenitatis, this precludes an origin for these breccias as Nectaris ejecta and points instead toward emplacement by the Imbrium basin-forming impact. The trace-element signatures of these breccias are consistent with a source in the KREEP-rich northwestern-nearside quadrant of the Moon, also supporting an origin as Imbrium rather than Nectaris ejecta (Norman and Duncan 2008). This effectively pulls the pin on the absolute age of Nectaris and removes one of the key arguments supporting a lunar cataclysm.

The absolute ages of older basins such as South Pole–Aitken (SPA) and the 28 other pre-Nectaris basins are completely unknown. Establishing the ages of these basins will be a difficult but necessary test for evaluating the Late Heavy Bombardment hypothesis. To illustrate the possible implications of this uncertainty, Figure 3 shows three model curves representing the pre-Imbrium impact flux to the lunar crust. The curves were obtained by converting crater-density populations on ejecta deposits of the lunar basins (data from Wilhelms 1987) to model ages pinned by the South Pole–Aitken, Nectaris, and Imbrium basins. South Pole–Aitken is the oldest basin on the Moon, and Imbrium is one of the youngest. Nectaris is an intermediate-age basin with well-preserved geological relationships relative to other central-nearside basins such as Imbrium, Serenitatis, and Crisium.

The ages assumed for these model curves are given in the caption of Figure 3. These particular ages for Nectaris and SPA were guided by our recent age determination for breccia 67955, the assumption that larger basins are more likely to be sampled because they produce the largest volumes of impact melt, Wilhelms' (1987) preference for a 4.2 Ga age for SPA, and recent suggestions by Korotev et al. (2002) and Warren (2003) that Nectaris may be as old as 4.1 Ga. The analysis assumes a constant flux of smaller impactors that formed craters with diameters >20 km.

All of the curves show a series of steps that imply temporal changes in the arrival of basin-forming projectiles relative to the background population of smaller craters. A surprising result of this exercise is that all three sets of age assumptions produce curves that apparently imply an episode of **early** heavy bombardment in which cumulative basin diameter (a proxy for impactor flux) increases rapidly in the interval between SPA and the Keeler-Heaviside basin (Fig. 3). Evidence for a **late** (post-Nectaris) cataclysm relies critically on the assumed age of Nectaris relative to SPA and Imbrium. The case for a Late Heavy Bombardment would be strongest if SPA is quite young (~4 Ga). In this case, all of the lunar basins would have formed in an interval of about 250 million years and the heavy bombardment between SPA and the Keeler-Heaviside basin could be part of an extended late cataclysm that would have been most intense early in the sequence of lunar basin formation (Fig. 3).

If SPA and Nectaris are both at the older end of the age range (e.g. 4.4 and 4.1 Ga, respectively), the younger half of the cratering curve appears as a sequence of steps with

Table 1 List of proposed lunar basins with diameters (in km) greater than 300 km, in stratigraphic sequence from youngest (Orientale) to oldest (South Pole–Aitken)

Basin	Diameter	Age
Orientale	930	3.75 Ga?
Schrödinger	320	|
Imbrium	1160	3.85 Ga
Bailly	300	|
Sikorsky-Rittenhouse	310	|
Hertzsprung	570	|
Serenitatis	740	3.89 Ga
Crisium	1060	|
Humorum	820	|
Humboldtianum	700	|
Mendeleev	330	|
Korolev	440	|
Moscoviense	445	|
Mendel-Rydberg	630	|
Nectaris	860	3.9–4.2 Ga?
Grimaldi	430	|
Apollo	505	|
Freundlich-Sharonov	600	|
Birkhoff	330	|
Planck	325	|
Schiller-Zucchius	325	|
Amundsen-Ganswindt	355	|
Lorentz	360	|
Smythii	840	|
Coulomb-Sarton	530	|
Keeler-Heaviside	780	|
Poincare	340	|
Ingenii	650	|
Lomonosov-Fleming	620	|
Nubium	690	|
Mutus-Vlacq	700	|
Tranquillitatis	800	|
Australe	880	|
Fecunditatis	990	|
Al-Khwarizmi-King	590	|
Pingre-Hausen	300	|
Werner-Airy	500	|
Balmer-Kapteyn	550	|
Flamsteed-Billy	570	|
Marginis	580	|
Insularum	600	|
Grissom-White	600	|
Tsiolkovsky-Stark	700	|
South Pole–Aitken	2500	4.0–4.4 Ga?

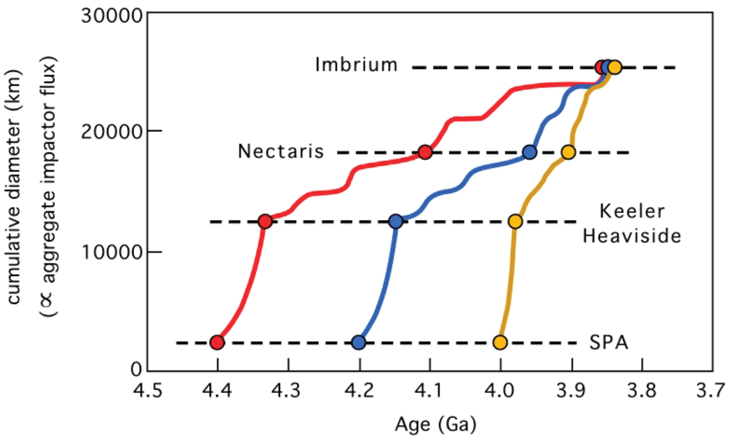

Figure 3 Model age versus cumulative basin-diameter curves for three sets of assumed age constraints. Basin diameter is assumed to scale with impactor size, so cumulative diameter is a proxy for aggregate impactor flux. SPA = 4.4 Ga, Nectaris = 4.1 Ga (red curve); SPA = 4.2 Ga, Nectaris = 3.95 Ga (blue curve); and SPA = 4.0 Ga, Nectaris = 3.9 Ga (yellow curve). Imbrium was fixed at 3.85 Ga for all three curves. Population densities of craters with diameters >20 km occurring on the basin ejecta deposits (Wilhelms 1987) are used to estimate time increments between the basins. SPA = South Pole–Aitken. Modified after Norman and Lineweaver (2008)

a relatively constant and gentle slope. This scenario provides little support for a uniquely late cataclysm between 3.95 and 3.75 Ga, in which case the predominant clustering of lunar impact-melt ages must reflect a nearside, equatorial, geographical selection effect or a bias in preservation such as the burial of older deposits by younger ejecta. A modest post-Nectaris increase in cratering flux seems to be implied if the age of Nectaris is <4 Ga, and the increase would be even more apparent if ages of 4.4 Ga and 3.95 Ga were assigned to SPA and Nectaris, respectively. The specific results are obviously model-dependent, but the exercise illustrates the critical necessity of accurately defining absolute ages of lunar basins for constraining the Late Heavy Bombardment hypothesis.

IMPLICATIONS FOR SOLAR SYSTEM DYNAMICS

Where these basin-forming impactors came from, why they invaded the inner solar system at this particular time long after planetary accretion had ceased, and their influence on the geological evolution of the terrestrial planets are hot topics. Maintaining a long-lived reservoir of planetesimals that could produce a Late Heavy Bombardment is a tricky problem (Bottke et al. 2007). A currently popular dynamical explanation invokes a gradual increase in the orbital distances of the outer planets, which destabilized a reservoir of icy planetesimals (see review by Michel and Morbidelli 2007). This model predicts an initial wave of comets followed by objects derived from the asteroid belt, although the fraction of asteroids relative to comets traversing the inner solar system is poorly constrained (Gomes et al. 2005). The size distribution of lunar craters (Strom et al. 2005) and the siderophile-element signatures of lunar impact breccias (Norman et al. 2002; Kring and Cohen 2002; Puchtel et al. 2008) suggest a source for the impactors within the asteroid belt, but we lack sufficiently complete temporal sampling of lunar basins to test the prediction in detail. This model is attractive because it explains several aspects of solar system architecture, but the essential question of whether or not a unique event is required to explain the late basin-forming collisions remains unresolved.

An alternative scenario is that an early phase of intense cratering occurred during the interval represented by the South Pole–Aitken and Keeler-Heaviside basins (Fig. 3), possibly not long after the lunar crust solidified, followed by numerous megascale collisions, either in clusters or at quasi-regular intervals, until they ceased abruptly about 3.7 billion years ago. In this scenario, the late basins would be seen as the terminal stages of an impact continuum that was unique to the earliest stages of planetary evolution. Changes in the flux and size distribution of impactors might relate to a transition from cometary to asteroidal source populations, collisional evolution in the source population(s), or contributions from surviving planetesimals left over from terrestrial planet formation (Gomes et al. 2005; Bottke et al. 2005; Bottke 2008, pers. comm.). More definitive information about the absolute ages of lunar basins and the provenance of the incoming projectiles, coupled with insights derived from numerical modeling, will be necessary to answer these questions.

SAMPLING TARGETS FOR FUTURE MISSIONS

The upcoming decade promises to be an exciting time for lunar exploration, with several nations planning orbital and landed missions to the Moon. This provides an unprecedented opportunity to expand our understanding of our nearest planetary neighbor and to solve some of the vexing problems that have been around since the Apollo missions, including the Late Heavy Bombardment hypothesis.

Reliably dating one or more of the older, pre-Nectarian lunar basins will require careful assessment of site geology and sampling of specific targets with a well-defined geological context. Random samples of regolith probably will not be sufficient to reliably associate a sample with a specific basin, as shown by our experience in the complex highland terrane sampled by the Apollo missions. The planned series of international lunar missions over the next decade should provide an excellent information base on which to identify potentially useful landing sites, provided that the flight instruments are capable of sufficient spatial resolution and that they measure the relevant properties of the lunar surface. Long-term observations of a specific area associated with the proposed NASA outpost should help resolve detailed aspects of local geology through samples returned to Earth.

The South Pole–Aitken basin is an attractive exploration target for several reasons, but especially because it is the largest and oldest recognized basin on the Moon and a reliable age would pin the entire lunar stratigraphy. The SPA megastructure is complex, however, with the pre-Nectarian basins Australe, Ingenii, Poincare, Planck, and Apollo all occurring either within or proximal to the SPA basin interior. The Schrödinger basin also occurs within the SPA complex, potentially adding an Imbrian-age overprint to the area. Quantitative ages for any of these basins would vastly improve our understanding of the impact history of the lunar crust and the early Earth, but mission planners will need to provide sufficiently detailed site geology and sampling targets to enable researchers to link the ages obtained from returned samples to specific basins with a high degree of confidence.

ACKNOWLEDGMENTS

Reviews by Bill Bottke, Paul Spudis, and Don Bogard and editorial guidance from Pierrette Tremblay and guest editor John Delano are greatly appreciated.

REFERENCES

Bottke WF Jr, Durba DD, Nesvorný D, Jedicke R, Morbidelli A, Vokrouhlický D, Levison H (2005) The fossilized size distribution of the main asteroid belt. Icarus 175: 111-140

Bottke WF, Levison HF, Nesvorný D, Dones L (2007) Can planetesimals left over from terrestrial planet formation produce the lunar Late Heavy Bombardment? Icarus 190: 203-223

Chambers JE (2007) On the stability of a planet between Mars and the asteroid belt: Implications for the Planet V hypothesis. Icarus 189: 386-400

Chapman CR, Cohen BA, Grinspoon DH (2007) What are the real constraints on the existence and magnitude of the late heavy bombardment? Icarus 189: 233-245

Cohen BA, Swindle TD, Kring DA (2000) Support for the lunar cataclysm hypothesis from lunar meteorite impact melt ages. Science 290: 1754-1756

Cohen BA, Swindle TD, Kring DA (2005) Geochemistry and ^{40}Ar-^{39}Ar geochronology of impact-melt clasts in feldspathic lunar meteorites: Implications for lunar bombardment history. Meteoritics & Planetary Science 40: 755-777

Culler TS, Becker TA, Muller RA, Renne PR (2000) Lunar impact history from ^{40}Ar/^{39}Ar dating of glass spherules. Science 287: 1785-1788

Dalrymple GB, Ryder G (1993) ^{40}Ar/^{39}Ar age spectra of Apollo 15 impact melt rocks by laser step-heating and their bearing on the history of lunar basin formation. Journal of Geophysical Research 98(E7): 13085-13096

Dalrymple GB, Ryder G (1996) Argon-40/argon-39 age spectra of Apollo 17 highlands breccia samples by laser step heating and the age of the Serenitatis basin. Journal of Geophysical Research 101(E11): 26069-26084

Delano JW (2009) Scientific exploration of the Moon. Elements 5: 11-16

Gomes R, Levison HF, Tsiganis K, Morbidelli A (2005) Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. Nature 435: 466-469

Hartmann WK (2003) Megaregolith evolution and cratering cataclysm models—Lunar cataclysm as a misconception (28 years later). Meteoritics & Planetary Science 38: 579-593

Hartmann WK, Neukum G (2001) Cratering chronology and the evolution of Mars. Space Science Reviews 96: 165-194

Haskin LA, Korotev RL, Rockow KM, Jolliff BL (1998) The case for an Imbrium origin of the Apollo thorium-rich impact-melt breccias. Meteoritics & Planetary Science 33: 959-975

James OB (1981) Petrologic and age relations of the Apollo 16 rocks: implications for subsurface geology and the age of the Nectaris basin. In: Proceedings of the Lunar and Planetary Science Conference 12, pp 209-233

Jessberger EK, Hueneke JC, Podosek FA, Wasserburg G. (1974) High resolution argon analysis of neutron-irradiated Apollo 16 rocks and separated minerals. In: Proceedings of the Lunar Science Conference 5, pp 1419-1449

Levine J, Becker TA, Muller RA, Renne PR (2005) ^{40}Ar/^{39}Ar dating of Apollo 12 impact spherules. Geophysical Research Letters 32: L15201, doi: 10.1029/2005GL022874

Levison HF, Dones L, Chapman CR, Stern SA, Duncan MJ, Zahnle K (2001) Could the lunar "Late Heavy Bombardment" have been triggered by the formation of Uranus and Neptune? Icarus 151: 286-306

Korotev RL, Gillis JJ, Haskin LA, Jolliff BL (2002) On the age of the Nectaris basin. In: Lawrence DJ, Duke MB (eds) The Moon Beyond 2002: Next Steps in Lunar Science and Exploration. The Lunar and Planetary Institute, Houston, abstract #3029

Kring DA, Cohen BA (2002) Cataclysmic bombardment throughout the inner solar system 3.9–4.0 Ga. Journal of Geophysical Research 107(E2): 5009, doi: 10.1029/2001JE001529

Michel P, Morbidelli A (2007) Review of the population of impactors and the impact cratering rate in the inner solar system. Meteoritics & Planetary Science 42: 1861-1869

Muehlberger WR, Hörz F, Sevier JR, Ulrich GE (1980) Mission objectives for geological exploration of the Apollo 16 landing site. In: Papike JJ, Merrill RB (eds) Proceedings of the Conference on the Lunar Highlands Crust. Pergamon Press, New York, pp 1-49

Neukum G, Ivanov BA, Hartmann WK (2001) Cratering record in the inner Solar System in relation to the lunar reference system. Space Science Reviews 96: 55-86

Norman MD, Duncan RA (2008) Age and origin of Apollo 16 feldspathic fragmental breccias. Geochimica et Cosmochimica Acta 72: A689

Norman MD, Lineweaver CH (2008) New perspectives on the lunar cataclysm from pre-4 Ga impact melt breccia and cratering density populations. In: Short W, Cairns I (eds) Proceedings of the 7th Australian Space Science Conference. National Space Society of Australia, Sydney, ISBN 978-0-9775740-1-8, pp 73-83

Norman MD, Bennett VC, Ryder G (2002) Targeting the impactors: siderophile element signatures of lunar impact melts from Serenitatis. Earth and Planetary Science Letters 202: 217-228

Norman MD, Duncan RA, Huard JJ (2006) Identifying impact events within the lunar cataclysm from ^{40}Ar–^{39}Ar ages and compositions of Apollo 16 impact melt rocks. Geochimica et Cosmochimica Acta 70: 6032-6049

Norman MD, Shih CY, Nyquist LE, Bogard DD, Taylor LA (2007) Early impacts on the Moon: crystallization ages of Apollo 16 melt breccias. Lunar and Planetary Science Conference XXXVIII, The Lunar and Planetary Institute, Houston, abstract #1991

Papanastassiou DA, Wasserburg GJ (1971) Rb–Sr ages of igneous rocks from the Apollo 14 mission and the age of the Fra Mauro formation. Earth and Planetary Science Letters 12: 36-48

Papanastassiou DA, Wasserburg GJ (1972) The Rb-Sr age of a crystalline rock from Apollo 16. Earth and Planetary Science Letters 16: 289-298

Puchtel IS, Walker RJ, James OB, Kring DA (2008) Osmium isotope and highly siderophile element systematics of lunar impact melt breccias: Implications for the late accretion history of the Moon and Earth. Geochimica et Cosmochimica Acta 72: 3022-3042

Ryder G (1990) Lunar samples, lunar accretion, and the early bombardment history of the Moon. Eos 71: 313 and 322-323

Ryder G (2002) Mass flux in the ancient Earth-Moon system and benign implications for the origin of life on Earth. Journal of Geophysical Research 107(E4): 5022, doi 10.1029/2001JE001583

Space Studies Board (2007) The Scientific Context for Exploration of the Moon: Final Report. The National Academy Press, Washington, DC, ISBN 978-0-309-10919-2, 120 pp

Spudis PD (1993) The Geology of Multi-Ring Impact Basins. Cambridge University Press, Melbourne, 263 pp

Stöffler D, Ryder G (2001) Stratigraphy and isotope ages of lunar geological units: chronological standard for the inner Solar System. Space Science Reviews 96: 9-54

Strom RG, Malhotra R, Ito T, Yoshida F, Kring DA (2005) The origin of planetary impactors in the inner solar system. Science 309: 1847-1850

Swindle TD, Spudis PD, Taylor GJ, Korotev RL, Nichols RH, Olinger CT (1991) Searching for Crisium basin ejecta: chemistry and ages of Luna 20 impact melts. In: Proceedings of the Lunar and Planetary Science Conference 21, pp 167-181

Tera F, Papanastassiou DA, Wasserburg GJ (1974) Isotopic evidence for a terminal lunar cataclysm. Earth and Planetary Science Letters 22: 1-21

Turner G (1979) A Monte Carlo fragmentation model for the production of meteorites: implications for gas retention ages. Proceedings of the Lunar and Planetary Science Conference 10: 1917-1941

Turner G, Cadogan PH (1975) The history of lunar bombardment inferred from ^{40}Ar-^{39}Ar dating of highlands rocks. Proceedings of the Lunar Science Conference 6: 1509-1538

Warren PH (2003) Lunar Prospector data imply an age of 4.1 Ga for the Nectaris basin and other problems with the lunar 'cataclysm' hypothesis". Workshop on Large Meteorite Impacts, The Lunar and Planetary Institute, Houston, abstract #4129

Wilhelms DE (1987) The Geologic History of the Moon. U.S. Geological Survey Professional Paper 1348, 302 pp

Wood CA (2004) Impact Basin Database compiled August 14, 2004, www.lpod.org/cwm/DataStuff/Lunar%20Basins.htm