A GLINT OF LIGHT ON BROKEN GLASS: SOLAR SYSTEM BOMBARDMENT FROM APOLLO SAMPLES. B. A. Cohen, NASA Goddard Space Flight Center (barbara.a.cohen@nasa.gov).

Introduction: Our knowledge of absolute surface ages on other bodies, including Mars, Mercury, asteroids, and outer planet satellites, relies primarily on the cratering record of the Moon. The round craters of the Moon are easily recognized through even small telescopes and were described by many early astronomers. Yet recognition of impact cratering as a ubiquitous process shaping planetary surfaces, and its utility in understanding both stratigraphic and absolute ages, is a relatively recent development, one that was greatly advanced by the sample return of the Apollo missions.

Through the 1960's, the origin of the Moon's craters was contentious. For most of that time, volcanism was the preferred explanation for lunar features; for example Sir William Herschel, discoverer of the planet Uranus, reported a lunar volcano in eruption, observing the bright appearance of the crater Aristarchus [1]. In the early 1800's, the discovery of asteroids and the recognition that fallen meteorites were from space, strengthened the belief that cosmic rocks could bombard the Moon just as they did Earth. Baldwin's compelling work *The Face of the Moon* [2] firmly established the impact origin of lunar craters, and readers Shoemaker and Kuiper went on to found research establishments to work on lunar (and planetary) craters. As [3] recently summarized, by early 1969, nearly all evidence was that most lunar craters were of impact origin, though there were skeptics. The shape of craters and their blast origin was established, as was recognition of rays and secondary craters as impact ejecta. The relative ages of the maria, large craters, and highlands were known, and the great crater density compared with the Earth implied the antiquity of the lunar surface, but the age and cadence of crater formation was largely unknown.

Calibrating the crater record of the moon, and establishing its utility in understanding the history of the surfaces of other planets, was made possible by the return of lunar samples by the Apollo missions and the great many workers who determined their radiometric ages. The topic of lunar impact history has been the subject of numerous reviews (*e.g.,* 4-10).

The lunar chronology is best constrained in by the well-preserved surfaces of mare basalt flows and younger benchmark craters such Autolycus and Aristillus [11, 12]. Radiometric dating of local basalt samples returned from mare surfaces by the Apollo 11, 12, 15, and 17 missions showed that these lunar surfaces were very old and that the cratering flux was much less than expected [13]. Using a constant flux model, the crater-derived model ages of the ejecta blankets of smaller craters such as Cone, North Ray, Tycho, and Copernicus craters agree well with radiometric and exposure ages of the Apollo 12, 14, 16, and 17 landing sites, respectively [14, 15], but in some places can differ by a factor of 2-3, causing uncertainties in absolute age by up to 1 Gyr [14, 16]. Crater-density relationships imply that significantly older and younger basalts exist, expanding the active period of the Moon [14, 17, 18].

The older end of the flux curve is bounded by the large, nearside lunar basins. Apollo missions specifically targeted the Imbrium, Serenitatis, and Nectaris basins in order to return samples that recorded the formation age of these important features. Apollo 14 sampled primary Imbrium ejecta, whose best available age appears to be 3.92 ± 0.01 Ga based on zircon and apatite from KREEP-rich breccias and melt rocks collected there [19-22]. Apollo 17 brought back melt rocks interpreted to have formed in the Serenitatis impact, and whose aged were 20-40 million years older than Imbrium ejecta [23, 24]. The Cayley and Descartes units at the Apollo 16 site were thought to be Imbrium and Nectaris ejecta, respectively [6]. The Descartes breccias contain clasts ranging in age from coeval with the KREEP-rich, crystalline melt rocks of Imbrium ejecta, to aluminous compositions dating to 4.1-4.2 Ga [25-29].

The ages of these basins supported the idea that multiple basins formed within a narrow interval of time - a "terminal lunar cataclysm" between about 3.8 and 4.1 Ga ago, where the rate and size of impacts increased to create the nearside basins in a short period of time, well after Solar System formation. The possibility of a cataclysmic bombardment [30] has been a central concept in planetary sciences since the 1960s, following detailed geological observations of the Moon and the discovery of petrological and geochemical evidence for intense shock metamorphism at ~3.9 Ga in many Apollo samples [6, 31, 32]. The heavily cratered terrains of the Moon and other bodies such as Mercury, Mars, and Callisto also provide clear physical evidence for an elevated flux of impactors across the Solar System that continued for several hundred million years after the initial accretion and differentiation of the terrestrial planets [7, 33].

However, the relationships between samples collected by the Apollo missions and the Imbrium, Serenitatis, and Nectaris basins have been called into question by new research using samples and orbital data. There is general agreement that Imbrium appears to be 3.92 ± 0.01 Ga, based on Apollo 12 and 14 KREEP-rich melt rocks [20-22]. At Apollo 17, where the mission objective was to sample and date the Serenitatis basin, new work has reinterpreted the Sculptured Hills deposits as having an Imbrium origin [34-36]. The aluminous Descartes breccias from Apollo 16 were originally interpreted as Nectaris ejecta, but new trace-element and age data show they are coeval with KREEP-rich melt rocks interpreted elsewhere as Imbrium ejecta [27]. These updated interpretations reopen the pre-Imbrian impact history to debate, which will only be solved by absolute chronology of additional samples that have been definitively reset in lunar basins (e.g., SPA, Crisium, Nectaris, Orientale, Schrodinger).

Examples of well-documented impact-reset samples predating the putative period of late heavy bombardment are rare but extant among the Apollo and Luna collections and lunar meteorites. The general paucity of old impact ages has been known ever since the first lunar samples were brought back to the Earth and analyzed. It was also a prime reason for the introduction of the concept of the terminal lunar cataclysm (*e.g.,* 31, 37), although an alternative interpretation is that evidence of earlier impacts is masked in the available samples by the relatively late Imbrium basin-forming event [38, 39]. In addition to the possible late overprinting, which complicates the identification of earlier impacts in lunar samples, there are difficulties in unambiguous interpretation of older ages as reflecting time of impacts as opposed to other processes. Variable and often not well constrained crystallization ages of the rocks and/or incomplete resetting of different chronometers may also contribute to the scarcity of reported ages of impacts distinctly older than the proposed timing of the late heavy bombardment.

The dynamical models conceived to explain such a phenomenon encompass the gas-dust dynamics of forming disks and giant planet migration. These models are now invoked to understand not only our Solar System, but also systems of exoplanets around other stars. Such a phenomenon would also have affected the Earth at a point when other evidence shows that continents, oceans, and perhaps even life already existed. Absolute ages are the primary driver for the largest flagship mission in the 2013 Decadal Survey, Mars Sample Return, and for the highest-priority lunar mission, sample return from the South Pole-Aitken Basin. Multiple groups are developing dedicated in situ dating instruments [40-44]. These instruments are on track to demonstrate TRL 6 readiness by 2020 and will need to be selected in the 2020's and 2030's for competed and directed flight missions to relevant destinations where *in situ* precision can provide meaningful constraints on geologic history.

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