Chronology of Impact Bombardment in the Early Solar System: An Overview

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Most bodies without atmospheres in the solar system have heavily cratered surfaces, which give testimony to the importance of impacts as a geological process. Determining the chronology of this impact bombardment addresses whether the impact rate has been constant or variable over solar system history, and also may give insight to the origin of the impactors. To determine the absolute age of a given impact crater or cratered surface requires that radiometric age information be obtained on rock samples ejected by that crater or representative of that cratered surface. Lunar rocks returned to Earth constitute the largest data base for deciphering the chronology of solar system bombardment, although some meteorite data also contribute. Data on ages of specific lunar surfaces are combined with the numbers of craters of various diameters on that surface to define a linked impact cratering rate for the Moon over the past ~3.5 Gyr. This linked "impact-chronometer" for the Moon, adjusted for relative solar system position, has been applied to other planets and satellites to estimate the ages of their cratered surfaces. Although this process of determining surface ages is thought to work reasonably well for surfaces younger than ~3.5 Gyr, additional problems arise when the process is applied to older lunar surfaces. The impact rate prior to ~3.5 Gyr ago was apparently much higher, and the linked "impact-chronometer" breaks down. Old lunar surfaces begin to saturate with craters, and the surface ages become uncertain. From early analyses of lunar-returned samples, it became apparent that various radiometric ages (i.e., Ar-Ar, Rb-Sr, U-Pb) of most highland rocks had been impact reset after the Moon's formation, but prior to ~3.5 Gyr ago. This resetting was postulated to have been produced by an increased flux of impacting objects long after the Moon formed [1]. Another explanation offered was that the early age resetting was not the result of a spike in the bombardment rate, but rather of a long declining bombardment after the Moon's formation, in which radiometric ages were reset over an extended time period [2].

Four experimental approaches have been employed to determine the radiometric chronology of the early impact period, often referred to as an impact cataclysm or the late heavy bombardment (LHB). These approaches are: 1) determine the radiometric ages of individual lunar highland rocks, and examine the data statistically for the impact rate versus time; 2) age date lunar rock clasts and melts identified with a specific large crater or basin and presumably reset in age when ejected; 3) determine the ages of small impact melt samples in lunar meteorite breccias, and examine the data statistically for the impact rate versus time; 4) statistically characterize impact age resetting in meteorite samples. Many of these are Ar-Ar ages, which is the most sensitive to resetting. Dating many lunar highland rocks (approach #1) has given a range in ages mostly between 3.7 and 4.1 Gyr. Many fewer rocks give ages outside this range, and this was the initial observation that indicated impact resetting on the Moon was restricted to a relatively narrow time period. Meteorite impact melts (method #3) has yielded a much wider range of radiometric ages, ranging from <1 Gyr to ~4 Gyr, with perhaps an age concentration at ~3-4 Gyr [3]. Although few of these impact melts give ages >4 Gyr, the existence of many ages <3.5 Gyr indicates that many of these glasses were formed by impacts not associated with the LHB. Age determinations of tiny impact spheres in the lunar regolith also show a wide range, with most ages <1 Gyr [4]. The preponderance of young regolith ages may reflect a recent enhance flux of smaller impactors or a bias in the production and survivability of glass spheres in the regolith. Overall, there seems to be a correlation of smaller scale impact melts showing younger ages, reflective of formation in smaller events.

Radiometric dating of highland rocks thought to have been ejected by a specific lunar basin gives a somewhat narrower range of ages compared to highland rock ages as a whole. Based on samples of Apollo 15 and 17 impact melts, the Imbrium and Serenitatis basin ages appear to be relatively well determined at 3.85 ±0.02 Gyr and 3.89 ±0.01 Gyr, respectively [5]. The large abundance of ~3.85-3.9 Gyr ages among highland rocks occurs because the Apollo 14, 15 and 17 missions targeted ejecta from these basins. However, even among rocks identified with one of these two basins, some ages fall below and above these defined basin ages (see summary in [6]), suggesting incomplete age resetting by the basin events or resetting by later impacts. Because Imbrium and Serenitatis are the 3rd and 7th youngest of the ~42 large, recognized basins [7], formation of the last large lunar basin (Oriental) probably occurred ~3.7-3.8 Gyr ago. This is somewhat earlier than the apparent ~3.5 Gyr inflection in the age-crater density curve, and the younger reset ages of eucrites (discussed below).

Although Apollo 16 was supposed to have targeted rocks ejected by the Nectaris basin, ages of Apollo 16 rocks vary over a wide range and the formation age of Nectaris remains uncertain. The observation that Ap-16 rocks with higher K concentrations give Ar-Ar ages ~0.2 Gyr younger, on average, than rocks with smaller K concentrations [8] suggests that high-K ejecta from Imbrium may have contributed to these ages. Further, Ar-Ar ages of several Ap-16 impact melts gave an age distribution similar to Imbrium impact melts rocks, with a concentration of ages at ~3.86, but a total age spread of 3.75-4.19 [9].

Among meteorites, the eucrites are thought to derive from the large asteroid Vesta, and the common occurrence of breccias among eucrites attest to an active impact history. Essentially all brecciated eucrites show Ar-Ar ages of 3.4-4.0 Gyr, with very few ages lying outside this range [6 & unpublished data]. Presumably these ages were reset during the LHB; and they are suggestive of about three to five large impact events. Among ordinary chondrites, several also show reset Ar-Ar ages in the period of ~3.5-4.0 and also may reflect resetting in the LHB [6, 10, 11]. Because meteorite parent bodies are smaller than the Moon, impacts produced less heating and less resetting of radiometric ages, and affect the Ar-Ar chronometer more than other radiometric chronometers that are harder to reset. Reset ages among eucrites and chondrites in the approximate period 3.5-4.0 Gyr ago argues that the LHB affected not only the Moon-Earth system, but also the whole inner solar system.

An important parameter in defining the nature and time span of the LHB is the total range in lunar basin ages. Accepting the determined ages of Imbrium and Serenitatis means that nearly one-fifth of the recognized lunar basins formed after 3.9 Gyr ago. If the age of Nectaris is ~3.91 Gyr, as assumed by Ryder (2002), then at least one-third of the large basins formed long after the Moon formed. The origin and late arrival of so many large bodies constitutes a type of cataclysm and requires explanation. If the largest lunar basin, SPA, formed at 4.0 Gyr, as speculated by Ryder [12], then the LHB would have been entirely contained within a period of 200 Myr. However, the age of Nectaris may be considerably older than 3.91 Gyr, and the age of the oldest basin, SPA, is totally unconstrained. Thus, it may have been the case that large impacts struck the Moon over a period of many hundreds of Myr, and possibly dating back to lunar formation. This scenario might resemble the declining impact flux proposed by Hartmann [2], and it could be a challenge to explain the origin of these impacting bodies over such a long time period. Determination of the formation ages of Nectaris and SPA is important to resolve this question. A related question is when did the LHB end, shortly after formation of Imbrium ~3.85 Gyr ago or ~3.5 Gyr ago as suggested by the inflection in the lunar age-flux curve and meteorite data? Could smaller impacting objects have persisted after the large, basin-forming objects ceased? Another related question is whether the rarity, but not absence, of lunar rock ages >4.1 Gyr is due to LHB resetting, or continuous resetting over 4.4-4.1 Gyr, or even a much lower impact flux in this time span? If this earliest epoch was also a time of intense bombardment, why do some lunar rocks and meteorites still give radiometric ages in this period? Many questions about the chronology of impacts in the early Solar System are as yet unanswered.

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