Curie: Constraining Solar System Bombardment Using In Situ Radiometric Dating

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Introduction: Establishing an absolute lunar chronology has important ramifications for understanding the early structure of the Solar System and the dynamical evolution and composition of planetary bodies. The age distribution of lunar impact breccias inspired the idea of a catastrophic influx of asteroids and/or comets about 4 billion years ago and motivated new models of planetary dynamics. The dynamical models 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 exoplanets around other stars. This event would also have affected the Earth at a time when other evidence shows that continents, oceans, and perhaps even life already existed.

Linking lunar samples to specific basins underpins the concept of a putative lunar cataclysm. Until relatively there was a broad consensus among lunar geologists about the relationships of samples collected by the Apollo missions to the Imbrium (Apollo 14), Serenitatis (Apollo 17), and Nectaris (Apollo 16) basins [1]. Today, most of these relationships have been questioned and are under active debate. The best available age for Imbrium appears to be 3.92 ± 0.01 Ga from KREEP-rich breccias and melt rocks collected at the Apollo 12 and 14 sites [2-5]. Analysis of LRO images of boulder tracks verified that the boulders sampled at the Apollo 17 site originated in outcrops within the North Massif walls, which had been interpreted as Serenitatis ejecta [6, 7]. However, the overlying Sculptured Hills deposits may be more closely related to Imbrium than Serenitatis [8, 9]. U-Pb dating of Carphosphates in Apollo 17 melt breccias appears to support an Imbrium origin for these rocks, while the Ar distribution is less straightforward [10, 11]. The aluminous Descartes breccias from Apollo 16, which have been interpreted as either Imbrium or Nectaris ejecta, range in age from 3.9 to 4.1 Ga, leading to a proposed old age for Nectaris [12, 13]. However, subsequent studies showed that the youngest population of clasts in these breccias is coeval with the KREEP-rich, crystalline melt rocks that are the best candidates for Imbrium ejecta, supporting geological observations that favor emplacement of the Descartes breccias as Imbrium ejecta [14]. Luna 20 fragments interpreted to be Crisium impact melt have radiometric ages ranging from ~3.84 Ga to 3.895 Ga [15-17]. Updated Apollo 17 sample ages, also interpreted as representing
around Nectaris or Crisium, so their impact-melt deposits should be aluminous and possibly slightly iron-rich [17, 28]. Such samples would be readily distinguished from KREEPy Imbrium and basaltic mare materials, though multiple measurements of impact-melt candidate rocks would be required to provide confidence in both the origin and age of an impact-melt lithology.

Assessing the onset of a putative lunar cataclysm using the age of the Nectaris or Crisium basins requires only coarse precision. If the measured basin age were ~3.9 Ga (as suggested for Crisium), it would lend credence to at least a terminal cataclysm, with Crisium and Imbrium as large impact events occurring closely spaced in time significantly later than solar system formation. If the measured basin age were ~4.1 Ga (as suggested for Nectaris), a more expansive epoch of bombardment would be allowable for the nearside basins, with significant periods of time occurring between basin-forming events. If either basin proved even older, there may have been no unusual spike in flux but rather a declining rate of bombardment over time. These intervals can be recognized with ages ±100 Myr (or less), currently achievable with in situ techniques [29-31].

A stationary lander could retrieve small rock samples from the regolith, using technologies similar to that developed for the proposed MoonRise mission [13]. Samples of interest would be dated using K-Ar techniques using LIBS to measure the K abundance and to release noble gases; mass spectrometry to measure the evolved Ar, and optical measurement of the ablated volume. These components would provide essential measurements to understand the origin and evolution of the samples (complete elemental abundance, evolved volatile analysis, microimaging) as well as in situ geochronology [29].

The Curie mission would constrain the existence of the putative cataclysm by determining the age of samples directly sourced from the impact melt sheet of a major pre-Imbrium lunar basin. The measurements would also enable further understanding of lunar evolution by characterizing new lunar lithologies far from the Apollo and Luna landing sites, including the very low-Ti basalts in Mare Crisium and potential olivine-rich lithologies in the margins of both Mare Nectaris and Mars Crisium [32]. Equipped with a mass spectrometer and a LIBS, Curie would also be well-placed to survey volatile components of the lunar regolith, including surface-bound hydrogen [33,34].