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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 recently 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 Ca-phosphates 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 Imbrum 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 Crisium impact-melt rocks, range from 3.88 to 3.93 Ga [7]. The crater density data for Crisium ejecta similarly vary in their model ages from 3.99 Ga to 3.94 Ga [18, 19]. It is clear that there is little consensus on what samples represent impact melt from basins other than Imbrium, reopening the pre-Imbrian impact history to debate.

The Decadal Survey twice recognized the importance of understanding the lunar cataclysm by recommending sample return from the South Pole-Aitken (SPA) basin, which would enable high-precision measurements by laboratory methods to resolve sample petrology and ages. However, if an SPA sample-return mission is not selected, it may be possible to understand the formation age of a nearside basin using *in situ* dating in a Discovery-class package. We are currently developing Curie, a potential Discovery mission concept that would directly constrain the onset of the cataclysm by new *in situ* dating of Nectaris or Crisium – both stratigraphically critical lunar basins.

Although the Nectaris and Crisium basins have experienced both basaltic infill and erosion, their original multiring morphologies are still recognizable. Updated geologic maps of the Nectaris basin and its surrounding terrain have identified small plains near inner-basin ring massifs and inter-massif “draped” deposits as possible remnants of the Nectaris basin impact melt sheet [20, 21]. Similar efforts also identified kipukas of the Crisium basin impact melt sheet, based on their morphology and composition [22]. In both Nectaris and Crisium, these exposures occur between the inner and outer basin rings and exhibit cracked and fissured morphologies consistent with those at both fresh craters (e.g., Tycho and King craters [23]) and older impact melts (e.g., Orientale [24, 25]), as well as embayment by subsequent mare basalt flows. The composition of these areas is less mafic than the surrounding basalts, a reflection of the lunar highlands target materials. If these are indeed areas of preserved Nectaris or Crisium impact melt, such sites would be unique among basins as in situ impact melt exposures.

In contrast to attempts to identify impact melt rocks ejected from the basin to distant sites like Apollo 17 or Luna 20, regolith formed atop an impact melt substrate should contain a majority of impact-melt rocks – similar to the dominance of basaltic materials in the regolith developed over Mare Tranquilitatis at Apollo 11 [26, 27]. There is no KREEP-rich compositional halo 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].

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