**CONSTRAINING SOLAR SYSTEM BOMBARDMENT USING IN SITU RADIOMETRIC DATING.** 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 crater calibration record for the Moon. Surface ages record two fundamental planetary processes: differentiation and volcanism via internal heating, and impact cratering. Despite the ubiquity of these processes, little headway has been made in creating a common framework of absolute ages for these events across the Solar System, including the Late Heavy Bombardment, planetary volcanism, and windows of habitable environments on the Earth, Mars, and beyond.

The leading, but contentious, model for Solar System impact history includes a pronounced increase in large impact events between 4.1 and 3.9 Ga [1-4]. This cataclysm would have bombarded an Earth and Mars that had atmospheres, oceans, and continents, and may have influenced the course of biologic evolution. Dynamical models to explain such a phenomenon rearrange the architecture of our very Solar System and are invoked to explain the arrangement of exoplanets around other stars. Evidence for a cataclysm, and constraints on the rest of the solar system impact flux, come largely from geochronology of samples derived from multiple samples from the Moon and asteroids.

The older end of the flux curve is bounded by the large, nearside lunar basins. 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 [5-7]. 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 [8-10]. 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 [11]. These updated interpretations reopen the pre-Imbrian impact history to debate, which will only be solved by absolute chronology of samples definitively reset in lunar basins (e.g., SPA, Crisium, Nectaris, Orientale, Schrodinger).

Younger chronology is constrained by mare basalt flows and younger benchmark craters such as Copernicus, Tycho, Autolycus, and Aristillus [12]. Model ages of these craters generally agree with radiometric ages of the Apollo landing sites, but in some places can differ by a factor of 2-3, causing uncertainties in absolute age by up to 1 Gyr [13-15]. Newly-acquired U-Pb ages of samples from Aristillus are ~200 Myr younger than previously proposed ages and new Autolycus crater size-frequency distributions do not correspond to radiometric ages [16, 17]. Crater-density relationships imply that significantly older and younger basalts exist, expanding the active period of the Moon [13, 18]. Older basaltic clasts appear in lunar meteorites [19], but these lack known provenance. On the young end, controversial new results from the LRO mission suggest volcanism may have continued much longer than previously thought in the form of Irregular Mare Patches (IMPs). These areas exhibit a paucity of superposed impact craters that suggests they are younger than 100 Ma, or have physical properties that don’t support craters, and are instead billions of years old [20, 21]. Constraining the chronology of the post-basin era will require measuring radiometric ages of samples with well-established provenance, including young mare basalts and key stratigraphic craters.

Lunar meteorites provide another source of information about impact history from locations potentially far removed from Imbrium. Although relatively few crystallization ages have been determined for impact melt rock clasts, their distribution is broadly similar to that inferred from the Apollo samples and crater density studies of the lunar surface, with the oldest apparent ages around ~4.2 Ga, a peak at ~3.7 Ga, and a declining number of ages to ~2.5 Ga [22-24]. As many of the feldspathic lunar meteorites are regolith breccias, the longer tail to younger ages in the meteorite clasts compared to the Apollo melt rocks may reflect smaller or more localized impact events than the basins sampled by the Apollo sites.

Additional constraints come from impact ages of meteorites derived from asteroid parent bodies [25-27]. H-chondrites show a prominent group of reported 40Ar-39Ar ages between ~3.5 and 4.0 Ga, with the clast-poor, impact-melt rocks LAP 02240 and 031125 yielding especially well-defined plateau ages of 3.939 ± 0.062 Ga and 3.942 ± 0.023 Ga, respectively [26, 28]. Eucrites and howardites, believed to come from the asteroid 4 Vesta, have yielded numerous impact-caused Ar ages between 3.4 and 4.1 Ga, with groups of reliable ages at ~3.5 and 3.8-4.0 Ga, and few such ages between 4.1 and 4.5 Ga, but which may not be readily related to the crater density history revealed by missions like Dawn [25, 29-31]. Mesosiderites commonly yield Ar ages of 3.8 to 4.1 Ga [25], although the very slow cooling experienced by these meteorites following disruption and re-accretion of their parent body complicates the interpretation of these data.

Finally, the relative Martian chronology derived from stratigraphy is not yet tied to an absolute chronology. Confounding variables that contribute to the uncertainties associated with dating by crater density on Mars are the contributions of persistent volcanism
and fluvial and aeolian weathering to the preservation of impact craters on Mars. Absolute ages of Martian surface units are therefore uncertain by as much as a factor of two on older surfaces [32] and disagreements can be an order of magnitude or more on younger, lightly-cratered surfaces, limiting our ability to understand the timing or Martian evolutionary milestones [33, 34]. For example, we do not know whether the crucial Noachian-Hesperian boundary, where a warm, wet Mars became arid [35], occurred before, after or concurrent with the late heavy bombardment on the Moon and the oldest intact rocks on Earth, so Martian climate change cannot yet be put into the context of Solar System history.

Absolute ages are the primary driver for the 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. However, these missions are acknowledged to be large and costly. The Decadal Survey specifically recommends developing in situ dating capability: “New capabilities for in situ age dating are of particular importance, as they can help to provide constraints on models of surface and interior evolution of all the terrestrial planets.” The NASA Office of the Chief Technologist also includes in situ dating in its Planetary Science Technology Needs, specifically recommending maturing age dating to TRL 6 by 2020 and noting its potential use in Discovery, New Frontiers, and future Mars missions.

Multiple groups are developing dedicated in situ dating instruments [36-40]. 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 (±100 Myr) can provide meaningful constraints on geologic history. The capability for in situ geochronology on the Moon will open up the ability for this crucial measurement to be accomplished at multiple locations aboard stationary landers or mobile rovers. Discovery mission concepts and directed mission payloads that would take advantage of in situ dating for the Moon and Mars have been considered, developed, and proposed [41-44].

Multiple landing sites on the Moon, Mars, and asteroids such as Ceres and Vesta exist where these questions may be answered, whereas returning samples from all these places would be a daunting order. Though some questions will require the precision of laboratory measurements, many more are addressable with an accurate, though perhaps less precise, in situ age. For example, even a single mission to a key basin, such as Crisium or Nectaris, would add an enormous amount of clarity to understanding the cataclysm. A single mission to an IMP would resolve the wide disparity in interpretations of their origin. But countless missions could benefit from in situ dating capabilities, because geochronology is a fundamental measurement for the Moon and other planets. To develop a common framework for absolute ages across the solar system, in situ geochronology instruments should become a common tool, along with our imaging and compositional tools, for landers and rovers on the Moon, Mars, asteroids, and beyond.