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Introduction: Geochronology, or determination of absolute ages for geologic events, underpins many inquiries into the formation and evolution of planets and our Solar System. Bombardment chronology inferred from lunar samples has played a significant role in the development of models of early Solar System and extrasolar planet dynamics, as well as the timing of volatile, organic, and siderophile element delivery. Absolute ages of ancient and recent magmatic products provide strong constraints on dynamics of magma oceans and crustal formation, longevity and evolution of interior heat engines, and distinct mantle/crustal source regions. Absolute dating also relates habitability markers to the timescales of evolution of life on Earth. Major advances in planetary science can thus be driven by absolute geochronology in the next decade, calibrating body-specific chronologies and creating a framework for understanding Solar System formation, the effects of impact bombardment on life, and the evolution of planetary bodies and their interiors.

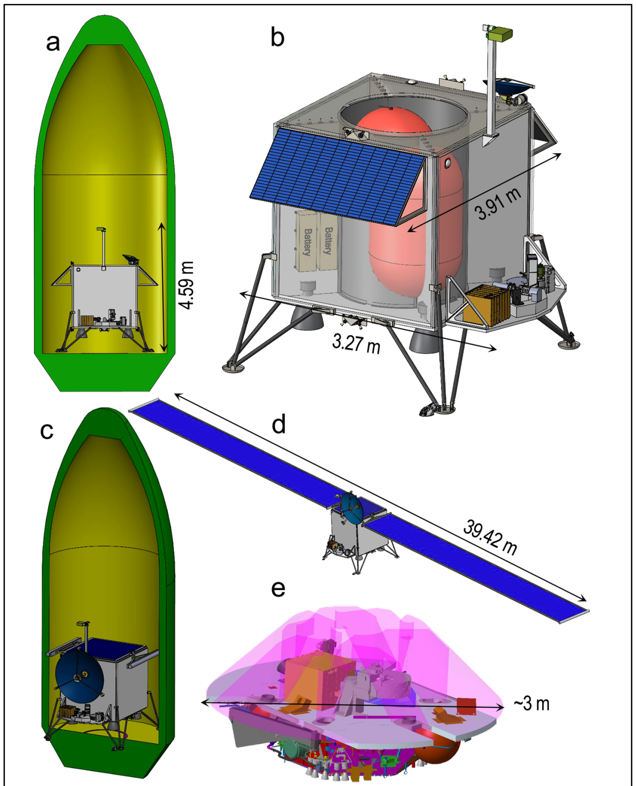

Figure 1: Views of geochronology landers for the Moon, Vesta, and Mars. a) Lunar lander in Falcon 9 Heavy 5m fairing; b) lunar lander structure accommodating the instrument deck; c) Vesta hopper with stowed solar arrays (lander and fairing dimensions are similar to the lunar lander); d) Vesta lander with unfurled solar arrays; and e) Instrument deck for a Phoenix-like lander in a 3m heat shield (pink envelope).

Absolute ages for multiple worlds are a desire in both the 2003 and 2013 Planetary Science Decadal Surveys, but only sample return was considered a viable method for geochronology. In preparation for the 2023 Planetary Science Decadal Survey, NASA commissioned several Planetary Mission Concept Studies (PMCS) including the one described here. This project investigated the viability of *in situ* dating techniques to accomplish longstanding geochronology goals for the Moon, Mars, and small bodies such as Vesta within a New Frontiers cost envelope. Our study team identified science goals and objectives, formed a notional payload, examined potential landing sites, and developed a spacecraft architecture for each destination. The full PMCS report [1] includes extensive details on the payload, spacecraft bus (Fig. 1), cost, and schedule.

Science Objectives: To formulate targeted Science Objectives for *in situ* geochronology investigations, we adopted a quantitative measurement requirement. The 2015 NASA Technology Roadmap identifies *in situ* dating as an important investment and targets measurement precision better than ±5% for rocks 4.5 Ga (approximately ±200 Myr, 2 σ). We explored specific scenarios where this level of uncertainty would resolve Science Objectives for to the Moon, Mars, and Vesta by tracing our objectives to LEAG, MEPAG, and SBAG goals documents.

Objective 1: Establish the chronology of basin-forming impacts by measuring the radiometric age of samples directly sourced from the impact melt sheet of a pre-Imbrian lunar basin. *In situ* dating precision of ±200 Myr may be sufficient to place some specific basins either within the canonical cataclysm (3.9 Ga) or as part of a declining bombardment in which most impacts are 4.2 Ga or older.

Objective 2: Establish the age of a very young lunar basalt to correlate crater size-frequency distributions with crystallization ages. *In situ* dating precision of ±200 Myr would reduce uncertainty in absolute model ages derived from crater size-frequency distribution measurements to <20% of current uncertainty among different lunar chronology functions.

Objective 3: Establish the age of a well-exposed Hesperian martian igneous terrain to correlate crater size-frequency distributions with crystallization ages. *In situ* dating precision of ±200 Myr would radically improve our understanding of Mars' volcanic history, assign absolute ages to widely-separated igneous provinces, and pin the absolute ages associated with late aqueous activity and the persistence of past habitability in middle and late martian history.

Objective 4: Establish the epoch of martian habitability by measuring the radiometric age of Noachian clay-bearing stratigraphies. *In situ* dating precision of ±200 Myr is sufficient to constrain the timing of Noachian unit formation. This would provide an important anchor for crater spatial densities of terrains hosting geologic evidence from Mars' most habitable period. This has concomitant implications for reconciling the timing of the development of life on Earth (~3.5 Ga for the oldest confirmed fossil evidence) and hypothesized spikes in early impact bombardment (~3.9 Ga).

Objective 5: Establish the radiometric ages of vestan samples with well-established provenance. *In situ* dating precision of ±200 Myr would constrain Vesta's geologic timescale by dating key stratigraphic craters and contiguous geologic terrains. This level of precision would not only reveal the ages of key basins but would also set firm constraints on the impactor flux estimates used throughout the Main Asteroid Belt.

Payload: For this study, measurement requirements for all goals and objectives would be met by carrying a single notional payload comprising representative instruments, all of which have substantial development and heritage. The notional payload would a) conduct *in situ* geochronology on samples, b) provide context to the samples and ages with imaging, mineralogy, and major- and trace-element geochemistry, and c) map the geology of the landing site and its lithologic units, relating it to crater counts determined from remote sensing.

We baselined two independently-developed *in situ* dating instruments that together can access both the Rb-Sr and K-Ar radiometric systems. The Chemistry and Dating Experiment (CDEX) [2-4] uses laser ablation-resonance ionization mass spectrometry to obtain elemental abundances and Rb-Sr dates. The Potassium-Argon Laser Experiment (KArLE) [5-7] uses a laser-induced breakdown spectroscopy and mass spectrometry to determine K-Ar ages. Rounding out the notional payload are an inductively-coupled plasma mass spectrometer, [8], a shortwave visible infrared imaging spectrometer [9], and a suite of geologic imagers [10, 11].

At present, geochronology measurements are not standoff or remote techniques; all share a common need for sample acquisition, manipulation, and analysis in a sealed and evacuated chamber to prevent escape of neutral particles and ions liberated from the sample. Therefore, a sample acquisition and handling system is a required payload element. For our study, we chose Honeybee Robotics' PlanetVac system [12].

Mission Architectures: We conducted three different studies on how to land the notional payload on the Moon, Mars, and Vesta. Each was conducted at Concept Maturity Level (CML) 4. We assumed that each mission would be a Class B, PI-led mission consistent with a New Frontiers Announcement of Opportunity. The payload mass would sum to approximately 180 kg, which includes 30% margin over the current best estimates. Peak power draws would come from laser operations during CDEX, KArLE, and ICP-MS analysis. Downlink needs would be driven by the imagers and imaging spectrometer.

Functionally, each mission must land, access surface and subsurface samples, and provide power and time for analysis. All versions of the geochronology mission in this study closed using a single lander [1], with the capability to hop to a second site implemented for the Vesta design. Landers carrying this payload to the Moon, Mars, and Vesta would likely fit into the New Frontiers cost cap in our study (~$1B). The goal to stay within a New Frontiers cost cap precluded mobility solutions on the Moon and Mars.

Conclusions: Feasible New Frontiers-class missions could carry a capable instrument payload to conduct *in situ* dating with the precision to answer community-identified Geochronology science goals. A mission of this type would provide crucial constraints on planetary history while also enabling a broad suite of investigations such as basic geologic characterization, geomorphologic analysis, ground truth for remote sensing analyses, analyses of major, minor, trace, and volatile elements, atmospheric and other long-lived monitoring, organic molecule analyses, and soil and geotechnical properties. ***The study team advocates that NASA include opportunities in the New Frontiers missions list for answering these compelling science questions, with the flexibility to meet them by sample return or in situ dating.***

References: 1] Cohen et al. (2020) *Final Report* https://science.nasa.gov/solar-system/documents [2] Anderson et al. (2020) *Planet Space Sci* **191**, 105007. [3] Anderson et al. (2015) *Rap Comm Mass Spect* **29**, 1457-1464. [4] Anderson et al. (2015) *Rapic Comm Mass Spect* **29**, 191-204. [5] Cho and Cohen (2018) *Rap Comm Mass Spect*. 10.1002/rcm.8214. [6] Cohen et al. (2014) *Geost Geoanal Res* **38**, 421-439. [7] Cohen et al. (2019) *Astrobiology* **19**, 1303-1314. [8] Arevalo Jr. et al. (2019) *EGU Gen Ass*, EGU2019-17077. [9] Fraeman et al. (2020) *Lunar Planet. Sci. Conf.*, 1610. [10] Maki et al. (2018) *Space Sci. Rev.* **214**, 105. [11] Yingst et al. (2020) *Lunar Planet. Sci. Conf.*, 1439. [12] Zacny et al. (2014) *2014 IEEE Aero. Conf.*, 1-8.