THE POTASSIUM-ARGON LASER EXPERIMENT (KArLE): IN SITU GEOCHRONOLOGY FOR MARS AND BEYOND. B. A. Cohen, NASA Marshall Space Flight Center, Huntsville AL 35812 (Barbara.A.Cohen@nasa.gov)

Introduction: The search for life in the solar system depends upon discovering the right moments in planetary evolution: when habitable environments existed, when they declined, and when geologic processes operated to preserve traces of life after death. However, an incomplete knowledge of absolute Martian geochronology limits our ability to understand the timing of Martian evolutionary milestones, major climate changes, and stratigraphic epochs [1, 2]. Absolute dating relates these habitability markers to planetary-wide geologic, atmospheric, and climate history places, and ties their occurrence to the history of the solar system, especially the Earth-Moon system and the timescale of evolution of life on Earth.

KArLE is being developed to anchor the relative timeline of geological events to an absolute chronology that puts Mars into a wider solar system context. KArLE makes its measurements on rock samples that can be obtained by landers or rovers and inserted into a small, mechanically simple chamber. KArLE interrogates the samples using laser-induced breakdown spectrocopy (LIBS), mass spectrometry, and optical imaging. The KArLE experiment is flexible enough to accommodate any partner providing these instrument components, a creative approach that extends the ability of mission payloads to accomplish an additional highly-desirable science measurement for low cost and risk and minimal extra hardware.

Breadboard Results: We have validated the KArLE approach using breadboard component-level and end-to-end testing on Martian analog samples (Fish Canyon Tuff, 28.305 ± 0.036 Ma [3]; Boulder Creek Granite, 1700 ± 40 Ma [4, 5]). We cut samples into cores 8 mm in diameter to provide a curved reference surface similar to a mission drill core. We computed a whole-rock density for each sample using the bulk composition for each lithology, converted to a normative composition (2.59 g/cm^3 for Fish Canyon and 2.65 g/cm^3 for Boulder Creek). Visual investigation of both samples sample showed very low porosity and the mineralogy did not indicate excess volatiles or alteration, so the computed densities were adopted.

We collected simultaneous LIBS and QMS measurements on multiple spots on both samples by moving the sample under the laser in discrete steps and firing the laser for 300 shots each time, without attempting to confine the laser ablation to a single mineral or phase or vary the ablation parameters based on the K content. We then removed the samples to the laser confocal microscope for pit volume analysis and downsampled the data to the MAHLI camera resolution. The best-fit isochrons (using a least-squares fit weighted in both x and y) for Fish Canyon defines an age of 20.6 ± 9.7 Ma, within ~25% of the accepted crystallization age of 28.0 Myr, and for Boulder Creek, 1.54 ± 0.6 Ga, which is within 10% of the accepted crystallization age (Fig. 1). This result is in line with the predicted uncertainty (Fig. 2) for samples of such a young age. Note that individual shots in both samples are systematically too old, but the nonzero intercept of the isochron fit reveals the presence of a trapped atmospheric Ar component, yet the slope of the isochron line yields the age regardless of the contribution of the trapped component.

Flight Performance: While K-Ar ages increase logarithmically with the Ar/K ratio, uncertainty in the age increases as a quadratic combination of the relative errors. This means that for fixed measurement uncertainties, the uncertainty in age becomes a smaller fraction of the age (more precise) as ages increase (Fig. 2), a feature for planetary samples, which are generally older than terrestrial samples. Conservative uncertainty goals for each measurement can be set based on established instrument performance and laboratory demonstration – σA=5%, σL=10%, σρ=5%, and σV=10% – or 15% in the combined 40Ar/40K ratio (σAr/K=15%). Using multiple measurements to construct an isochron of at least six points will further decrease the combined uncertainty from what it would be with a single measurement (1/√(N-2) for a straight line). These performance levels enable KArLE to determine the age of planetary samples 2 Ga and older to ±100 Myr, sufficient to address a wide range of geochronology problems in planetary science.

The extensive flight and laboratory-based work that has been conducted using the KArLE components [6-13] establishes the limits of detection (LOD) for rocks

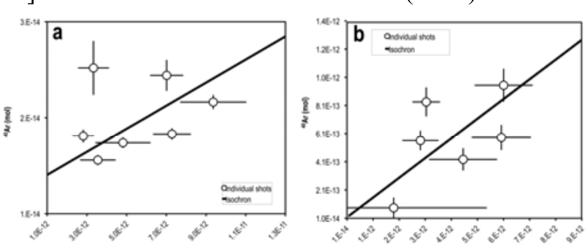


Figure 1: KArLE isochron results.

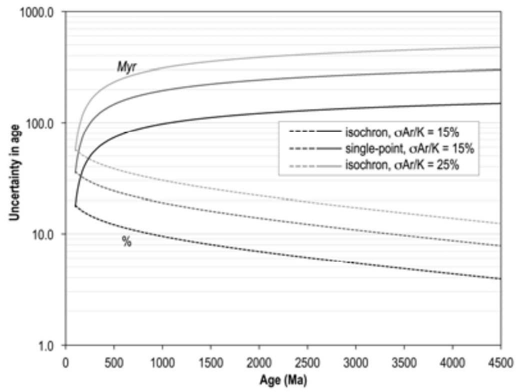
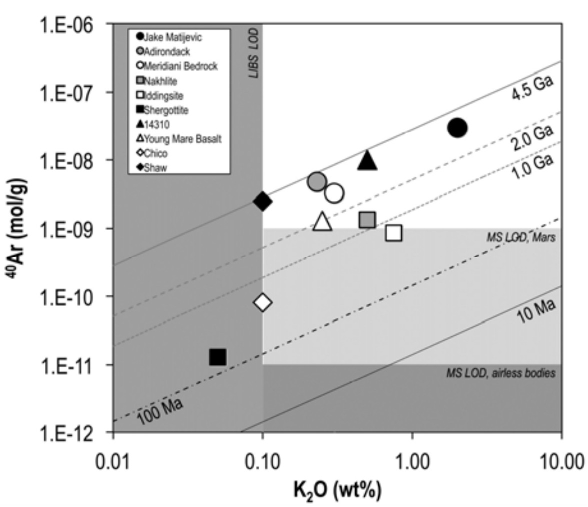


Figure 2: KArLE predicted uncertainties.

datable by KArLE. For K, the LOD = 0.1 wt% using the 769.89 nm line. For Ar, the limit is set by the ability of the mass spectrometer for airless bodies, or by the background Ar level for Mars. The SAM chamber reaches ~10^{-6} torr on Mars, which would contain ~10^{-9} mol ^{40}Ar from the Martian atmosphere, leading to an anticipated LOD of 10^{-9} mol ^{40}Ar. On airless bodies, the LOD can be much lower, depending on the sensitivity of the mass spectrometer – as low as 10 picomoles. Figure 3 shows the expected ability of KArLE to measure the age of rocks encountered by Spirit, Opportunity, and Curiosity, high-K and low-K lunar rocks, and ordinary chondrites. KArLE will be able to accurately date the majority of these samples with a level of precision for single K-Ar analyses comparable to current efforts on Curiosity rocks or Martian meteorites [14, 15].

Conclusions: Fundamentally important scientific objectives on the Moon, Mars, and other rocky bodies can be met with in situ dating using the KArLE approach. Each component of the KArLE experiment (LIBS, MS, density, and volume) has been individually developed for application in a flight environment, yielding accurate measurements with 5-10% precision. End-to-end testing on planetary analog samples yields good results, giving ages with 25% uncertainty on very young samples (<50Ma) and 10% uncertainties on older samples. These performance results predict that for planetary samples older than 2 Ga, precision will be on the order of ±100 Myr, in line with expectations set by the NASA Space Technology Roadmaps. Our component-level proof-of concept tests and our end-to-end KArLE experiments on analog samples bring the KArLE experiment to Technology Readiness Level (TRL) 4. We plan to further develop the KArLE concept into a well-characterized flight prototype that can be tested in relevant environments.

Figure 3: KArLE levels of detection are sufficient to date a wide variety of rocks on Mars.



Each KArLE component (LIBS, MS, camera) helps make measurements that give necessary contextual information to interpret the geochronology measurement. For example, the surface textures of the rock can be characterized with the imager. The LIBS ablation will provide a complete elemental analysis of the rock. The MS could also be used for volatile-element analysis, or plumbed to other sample inlets such as for atmospheric measurements or laser desorption experiments. These dual-use components make KArLE a highly attractive way to integrate geochronology into a payload capability rather than dedicated isotopic instruments. The flight heritage of the KArLE components strongly suggests that the finished instrument will be able to fit on rovers as well as landers and the operational concept is applicable to Mars, the Moon, and asteroids, as well as virtually any rocky surface.

In situ dating does not obviate sample return, just as current missions have not obviated the need for return sample-based trace element abundances and microanalysis. However, in situ dating with an instrument such as KArLE can help elucidate the relationship between specific samples and the stratigraphy of the landing site, adding important information to choose the most relevant samples for return and ensuring that returned samples are representative of major surfaces at a landing site.

References: [1] Doran et al. (2004) *Earth-Science Reviews*, 67, 313–337. [2] Bibring et al. (2005) *Science*, 307, 1576-1581. [3] Renne et al. (2010) *GCA*, 74, 5349–5367. [4] Peterman et al. (1968) *JGR*, 73, 2277-2296. [5] Anderson et al. (2012) 2844. [6] Devismes et al. (2013) EPSC2013-71. [7] Devismes et al. (2012) 7608. [8] Cho et al. (2013) 878. [9] Cho et al. (2012) #1093. [10] Stipe et al. (2012) *Spectrochim. Acta B,* 70, 45-50. [11] French et al. (2014) 1936. [12] Cohen et al. (2013) Abstract #2363. [13] Cohen et al. (2012) Abstract #1018. [14] Bogard (2009) *MAPS*, 44, 3-14. [15] Farley et al. (2014) *Science*, 343.