Surface abundances of K, Th, and U on Mercury and implications for planet formation and evolution. Patrick N. Peplowski[1], Larry G. Evans[2], David T. Blewett[1], Brett W. Denevi[1], David J. Lawrence[1], Larry R. Nittler[3], Edgar A. Rhodes[1], Sean C. Solomon[3], [1]Johns Hopkins University Applied Physics Laboratory (11100 Johns Hopkins Road, Laurel, MD 20723; Patrick.Peplowski@jhuapl.edu), [2]Computer Sciences Corporation, Lanham, MD 20706, [3]Carnegie Institution of Washington, Washington, DC 20015

Introduction: Models of the bulk composition of Mercury must account for the unusually high uncompressed density of the planet, thought to arise from a metal-to-silicate ratio at least twice that of Venus, Earth, and Mars [1]. The surface compositions predicted by such models [2] can be tested via measurements of the surface with the Gamma-Ray Spectrometer (GRS) on the MESSENGER spacecraft [3]. Inasmuch as competing composition models follow from different planetary formation scenarios, γ-ray spectrometry can shed light on the processes that occurred during Mercury's formation. Moreover, the abundances of the radioactive elements K, Th, and U provide important constraints on models for the thermal evolution of the planet.

MESSENGER has made three flybys of the planet Mercury on its way to orbit insertion in March 2011. GRS data from the flybys were used to make preliminary measurements of the surface abundances of Si, Fe, Ti, K, and Th [4]. This work extends that analysis for radioactive elements, where extrapolating the GRS measurements to surface abundances is less complicated than for stable elements whose γ-ray emissions rely on excitation by high energy galactic cosmic ray protons. The results derived here are compared to Mercury composition models, and are suggestive of the value of GRS results for studying Mercury's composition and formation, particulary when considering the improved coverage and statistical significance that will result from including orbital data.

Calculating surface abundances: Determining the abundances of elements on the surface of Mercury from GRS measurements is a two-step process. First the γ-ray flux at the detector for a given element must be determined. This includes fitting the corresponding γ-ray peak and correcting for background, detector efficiency, and spacecraft attenuation. The second step is to model the γ-ray flux coming from the planet. This includes propagating the surface γ-ray flux to the spacecraft via the altitude-dependent detector solid angle. The surface γ-ray flux for radioactive γ-decay is calculated in units of [$\gamma/(\mathrm{cm}^2$ min wt%)]. A comparison of the measured γ-ray flux to the expected flux per wt% yields the surface abundance.

As an example, consider the measured Th abundance. ^{232}Th decays with a half-life of 1.405×10^{10} yr in a decay chain resulting in ^{208}Pb. There is a 36% probability that a 2615-keV γ-ray will be emitted during this decay sequence. Starting with the known Th decay rate, the surface flux is calculated to be 11,542 [$\gamma/(\mathrm{cm}^2$ min wt%)] [5]. Using the spacecraft ephemeris and known detector response to calculate the expected GRS measured count rate during the first two Mercury flybys yields 3,635 cnts/(min wt%).

Examining data from the first two Mercury flybys reveals a 2615-keV peak [4]. After correcting for the background 2615-keV peak (0.07 cnts/min), the measured count rate is 0.43 +/- 0.24 cnts/min (1-σ error), giving a derived surface abundance of 1.2 ± 0.7 ppm. Similar calculations were carried out for K, resulting in a measured surface abundance of 800 ± 340 ppm.

Calculating the U abundance from the flyby data proved to be more challenging than for Th and K. Th and K each have a single dominant γ-decay, whereas U has many γ-decays with smaller fluxes. The highest-intensity γ-decays for U (295, 351, 609, 1120, 1765, and 2204 keV) were chosen for analysis. After correcting for the background and interference γ-ray peaks, and accounting for the limited statistics, a 3-σ upper limit for the U abundance of 10.5 ppm was established.

Comparisons to theory: K is moderately volatile and Th is refractory, so the K/Th ratio can in principle be viewed as an approximate proxy for the dominant temperature in the solar nebula in the vicinity of the solid material from which a planet accreted [6], and therefore its proximity to the Sun during its formation. Measured K/Th ratios for Mars, Earth, and Venus calculated from Mars Odyssey data [7], terrestrial measurements [8], and Soviet Venus lander data [9], respectively, are plotted with the K/Th ratio for Mercury as measured by the MESSENGER GRS (680 ± 470) in Fig. 1. The data indicate that the terrestrial planets likely formed in the order of solar distance observed today, suggesting that Mercury has not been subject to large migrations of its orbital parameters since its formation. Improved statistics from the MESSENGER orbital mission phase will provide a further test of this inference. This preliminary result should be viewed with caution, as surface alteration by space weathering processes as well as limited surface coverage during the flybys may be significant factors.

Measured Th and U abundances are compared to predictions from a variety of Mercury composition models in Fig. 2. Some previously proposed composition models differ from the measured Th abundance by 2-σ or 3-σ and can be downrated as a result (see figure caption for specifics). Because of the larger error in the U measurement, the upper limit on measured U abundance is consistent with all of the composition models to within 3-σ. Additional data from MESSENGER orbital observations are expected to narrow uncertainties considerably and will further test compositional models (Fig. 2).

Conclusions: Data from the MESSENGER GRS, collected during three flybys of Mercury, have been used to make preliminary measurements of the surface abundances of K, Th, and U. Despite being statistics-limited, these results provide tests of previous compositional models and implied formation mechanisms for the planet. An order of magnitude increase in data, achievable after just two weeks of orbital operations, will produce improved global K, Th, and U abundances (Fig. 2) that should be sufficient to rule out a number of proposed compositional models.

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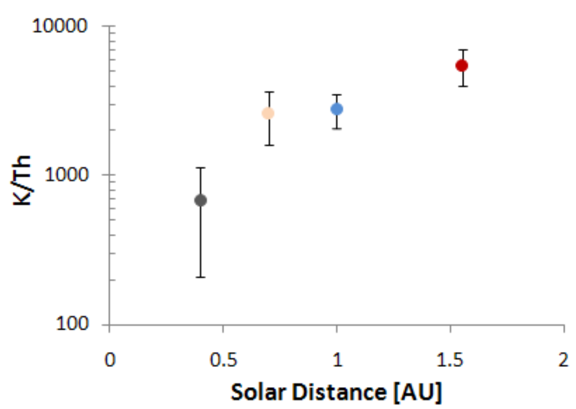

Figure 1. K/Th as a function of solar distance for the terrestrial planets: Mars – red, Earth – blue, Venus – tan, and Mercury – grey. Errors shown are 1-σ.

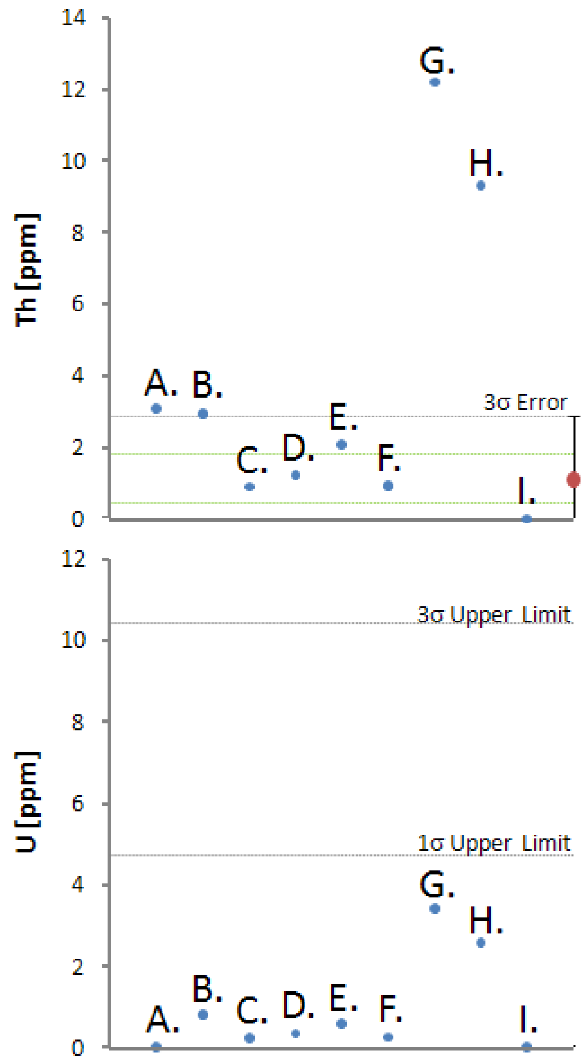

Figure 2. Comparison of Th (top) and U (bottom) abundances on the surface of Mercury measured by the MESSENGER GRS (red) to predictions of abundances from a variety of Mercury composition models. The models are A - Vaporization model [10], B - Refractory end-member [11], C - Preferred model [11], D - Model composition [12], E - Earth (39%) plus Refractory end-member (61%) [2], F - Average metal-rich chondrites [13], G - 10% partial melt of D [2], H - 10% partial melt of F [2], and I - 29% experimental partial melt of chondrites [2]. Models A-F are bulk compositions of the silicate portion of Mercury, whereas models G-I are surface lava flow compositions [2]. The impact of surface alteration via space weathering, coupled with the GRS depth sensitivity of ~ 10 cm complicate the interpretation of these results. Additionally, limited surface coverage during the two flybys may not accurately represent global elemental abundances. In the top figure, the green dashed lines are the expected 3σ error after two weeks of MESSENGER GRS data from orbit, suggestive of the statistical significance of a small fraction of the total GRS dataset as applied to surface composition.