MEASUREMENTS OF NEUTRON ABSORBING ELEMENTS ON MERCURY FROM THE THREE MESSENGER FLYBYS. David J. Lawrence[1], William C. Feldman[2], John O. Goldsten[1], Timothy J. McCoy[3], David T. Blewett[1], William V. Boynton[4], Larry G. Evans[5], Larry R. Nittler[6], Edgar A. Rhodes[1], Sean C. Solomon[6], [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD (David.J.Lawrence@jhuapl.edu); [2]Planetary Science Institute, Tucson, AZ; [3]National Museum of Natural History, Smithsonian Institution, Washington, DC; [4]University of Arizona, Tucson, AZ; [5]Computer Sciences Corporation, Lanham-Seabrook, MD; [6]Carnegie Institution of Washington, Washington, DC 20015, USA.

Introduction: Despite many measurements from Earth and from the Mariner 10 spacecraft, there is little definitive information about the elemental composition of Mercury's surface [1]. Specifically, there has been much debate about the Fe content of Mercury's surface materials [2,3]. For example, 1-µm absorption bands resulting from Fe^{2+} in silicates are either absent or very weak in reflectance spectra of Mercury at visible to near-infrared wavelengths. Taken at face value, these observations have been interpreted to imply that the FeO concentration of both the crust and the mantle of Mercury must be very low. This conclusion contrasts with the fact that the high uncompressed density of Mercury indicates that some 60% of the planet mass must be iron metal. The surface Fe content may be an important discriminator for testing whether Mercury's high bulk metal fraction stemmed from aerodynamic drag in the early solar nebula [4], from preferential vaporization of silicates by an early hot solar nebula [5,6], or from loss of the planet's original silicate crust and much of its mantle during a giant impact [7,8]. Although we have only limited information on the abundance of FeO in Mercury's crust, information on the abundances of other key elements (e.g., Ca, Si, Mg, K, Ti) that are concentrated in planetary crusts during differentiation is even more restricted. Ti may be particularly informative, because, like FeO, it appears to be low in abundance in Mercury surface silicates [9] but couples with iron in a variety of Fe-Ti-oxides in crustal rocks on other bodies.

The MESSENGER spacecraft has completed three flybys of Mercury on January 14, 2008 (M1), October 6, 2008 (M2), and September 29, 2009 (M3). Neutron data from the Neutron Spectrometer (NS) were collected during all three flybys. During these flybys the MESSENGER spacecraft executed rotation maneuvers that enabled thermal neutron enhancements to be measured using the Doppler filter effect [10]. Since thermal neutrons are sensitive to the surface abundances of neutron-absorbing elements Fe, Ti, Gd, and Sm, these Doppler filter measurements combined with neutron transport models of the spacecraft provide measurements of the absolute abundances of neutron-absorbing elements on Mercury's surface. In this study, we review the neutron measurements from each flyby and discuss implications of these measurements for our understanding of Mercury's surface.

Neutron Measurements from Mercury Flybys: NS data from the first and third Mercury flybys (M1 and M3) are shown in Figure 1. Data from one of the two thermal neutron detectors of the NS, lithium glass 2 (LG2) are shown as the black circles in Figure 1. The MESSENGER spacecraft executed rotation maneuvers that changed the orientation of the LG2 detector with respect to the spacecraft velocity vector for each flyby. For M1 and M3, these maneuvers occurred at 19:00 and 21:35 UTC, respectively. The counting rate peaks at these times show the thermal neutron enhancements due to the Doppler filter effect.

The colored lines in Figure 1 show modeled neutron counting rates for different assumed surface compositions ranging from a low neutron-absorbing-type soil (lunar ferroan anorthosite) to a high neutron-absorbing soil (Apollo 11 lunar soil). The soil that best fits the data is a Luna 16 soil that has relatively large amounts of Fe and Ti (13 wt.% and 2 wt.%, respectively). After a χ^2 fitting procedure, it has been further determined that within a 2-σ statistical uncertainty, the data are also consistent with neutron absorption for Apollo 11 and Luna 24 soils.

Interpretation of Thermal Neutron Measurements: Thermal neutrons do not allow measurement of individual elemental abundances, but rather of the bulk neutron-absorbing ability of a soil, which is expressed as a macroscopic neutron absorption cross section: $\Sigma_a = \Sigma \sigma_{a,i} f_i N_A / A_i$. Σ_a is a weighted sum over elements i, $\sigma_{a,i}$ is the microscopic absorption cross section for each element, f_i is the elemental weight fraction, A_i is the atomic mass, and N_A is Avogadro's number. In terms of Σ_a, the measured neutron absorption is 70 to 130 × 10^{-4} g/cm^2, where the uncertainties represent the 2-σ statistical uncertainties.

With this measured Σ_a, we can make direct comparisons with modeled estimates of Mercury's surface composition. Taylor and Scott [1] provided estimated compositions for three different models: a refractory-volatile mixture model [11], a metal-rich chondrite model, and a partial melt composition based on an enstatite bulk chondrite composition [12]. The Σ_a values for these models are Σ_a = 47 × 10^{-4}, 37 × 10^{-4}, 22 × 10^{-4}

g/cm^2, respectively. Our measurements of Σ_a rule out all of these model compositions as being appropriate estimates of Mercury's surface composition because of their low abundances of neutron-absorbing elements (see Figure 2).

We further conclude that the likely neutron-absorbing elements on Mercury's surface are Fe, Ti, Gd, and/or Sm. The reasons for this conclusion are twofold. First, for the types of soils considered, Fe, Ti, Gd, and Sm dominate the dynamic range of Σ_a. Second, although other elements do have microscopic absorption cross sections as high or higher than Fe and Ti, such as ^{35}Cl, ^{63}Cu, ^{55}Mn, and ^{58}Ni, their abundances in non-hydrated silicate planetary material are not expected to be as high as the few weight percent required to measurably affect Σ_a.

With these conclusions, we note that our results are consistent with the inference of Denevi et al. [13] that Mercury's color variations and visible and near-infrared reflectance spectra can be explained by substantial amounts of Fe-Ti oxides (e.g., ilmenite) on Mercury's surface. If the dominant sources of neutron absorption are Fe-Ti oxides, then the crust of Mercury may indeed have abundant Fe, even if not present to a measurable degree as FeO in silicate minerals. Thus, the non-detection of the 1-µm absorption feature in Mercury's soils does not lead directly to a low inferred total surface Fe abundance.

References: Taylor, G.J., Scott, E.R.D. (2003) In *Treatise on Geochemistry*, pp. 477; [2] Sprague, A. et al. (2007) *Space Sci. Rev*. 132, 399; [3] Boynton, W.V. et al. (2007) *Space Sci. Rev*. 131, 85; [4] Weidenschilling, S.J. (1978) *Icarus* 35, 99; [5] Cameron, A.G. (1985) *Icarus* 64, 285; [6] Fegley Jr., B., Cameron, A.G.W. (1987) *Earth Planet. Sci. Lett*. 82, 207; [7] Wetherill, G.W. (1988) In *Mercury*, Univ. of Ariz. Press, 670; [8] Benz W., et al. (1988) *Icarus* 74, 516; [9] Warell, J., Blewett, D.T. (2004) *Icarus* 168, 257; [10] Feldman, W.C., Drake, D.M. (1986) *Nuclear Instrum. Meth.* 245, 182; [11] Morgan J.W., Anders, E. (1980) *Proc. Natl. Acad. Sci.* 77, 6973; [12] McCoy T.J. et al. (1999) *Meteorit. Planet. Sci.* 34, 735; [13] Denevi, B.W. et al. (2009) *Science* 324, 613.

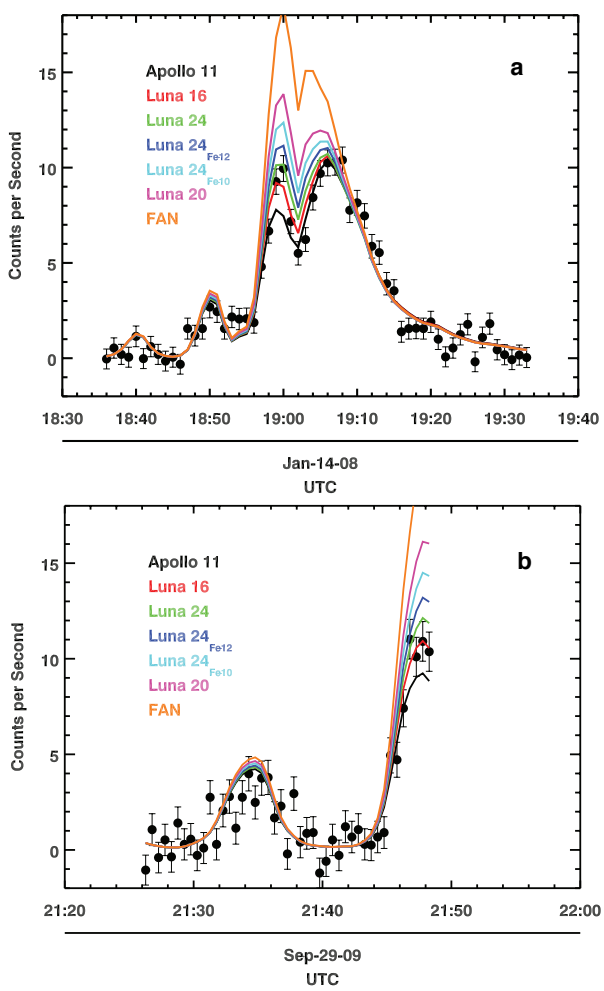

Figure 1. Time series NS data from the LG2 detector for the (a) M1 and (b) M3 flybys. Circles show data and colored traces show modeled counting rates for different model soils.

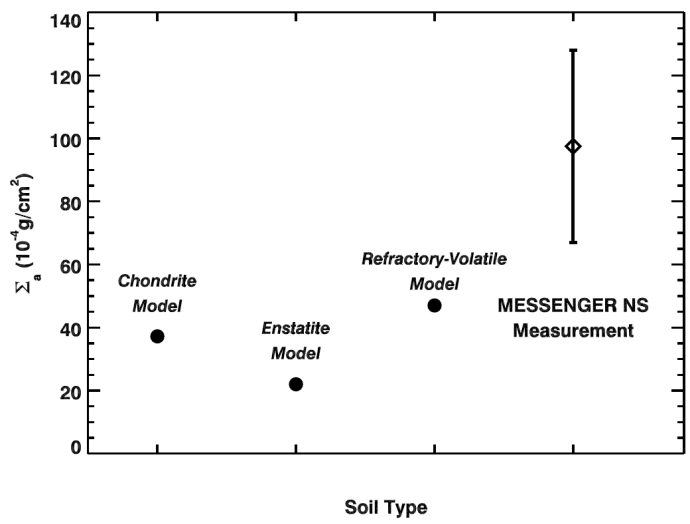

Figure 2. Summary of the macroscopic neutron-absorption cross sections, Σa, for modeled Mercury soils from Taylor and Scott [1] (closed circles), compared with the measured MESSENGER NS data (diamond). The error bar on the NS measurement depicts the range from Luna 24 to Apollo 11 and is between a 1-σ and 2-σ uncertainty.