MERCURY'S INTERNAL STRUCTURE AS CONSTRAINED BY MESSENGER OBSERVATIONS.

Steven A. Hauck, II[1], Sean C. Solomon[2], Jean-Luc Margot[3], Frank G. Lemoine[4], Erwan Mazarico[5], Stanton J. Peale[6], Mark E. Perry[7], Roger J. Phillips[8], David E. Smith[5], Maria T. Zuber[5], [1]Dept. of Earth, Environmental and Planetary Sciences, Case Western Reserve University, Cleveland, OH 44106 (hauck@case.edu); [2]Dept. of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015; [3]Dept. of Earth and Space Sciences, University of California, Los Angeles, CA 90095; [4]NASA Goddard Space Flight Center, Greenbelt, MD 20771; [5]Dept. of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139; [6]Dept. of Physics, University of California, Santa Barbara, CA 93106; [7]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723; [8]Planetary Science Directorate, Southwest Research Institute, Boulder, CO 80302.

Introduction: A longstanding question regarding the formation of the terrestrial planets is the origin of the large bulk density (5430 kg m^{-3}) of Mercury [e.g., 1]. A bulk density this large implies that the mass fraction of iron in Mercury's interior is substantially greater than in the other terrestrial planets. Until recently, a lack of additional constraints on Mercury's interior has limited the ability to constrain the internal structure that gives rise to this unusual bulk density [2-5].

Earth-based radar observations constrain Mercury's spin state and the amplitude of its forced libration in longitude [6]. The spin state results confirmed that the planet occupies a Cassini state in which the axis of rotation is nearly perpendicular to the orbital plane and the spin and orbital precession rates are equal. The large amplitude of Mercury's forced libration indicates that the solid exterior of the planet is decoupled from the deeper interior by a liquid layer. This result is interpreted to indicate the presence of a metallic core at least part of which is molten at present.

Since MESSENGER entered orbit about Mercury on 18 March 2011, Doppler tracking of radio signals has been used to determine the planet's gravity field [7]. Two of the second-degree harmonics of Mercury's gravity field, C_{20} and C_{22}, provide important constraints on how mass is distributed radially within the planet's interior. Because Mercury occupies the Cassini state, knowledge of these two parameters in concert with the obliquity and amplitude of the forced libration permits the determination of two key measures of Mercury's internal structure. The normalized polar moment of inertia, C/MR^2, where M and R are Mercury's mass and radius, is a gauge of how mass is radially distributed within the planet. The ratio of the polar moment of inertia of the outermost solid shell to that of the entire planet, C_m/C, is particularly sensitive to the outer radius of the liquid portion of the core.

Observations of Mercury by MESSENGER's suite of sensors sensitive to the elemental and mineralogical composition of surface materials provide important additional clues to the makeup of the planet's interior. MESSENGER X-ray Spectrometer (XRS) measurements [8] indicate a surface with less than ~ 4 wt % Fe, as well as comparably low concentrations of Ti and Al. These observations are suggestive of a relatively modest bulk density for the portions of the silicate mantle that served as source regions for surface volcanic material. The XRS measurements also indicate a surface S content nearly an order of magnitude larger than for Earth or the Moon. The combination of low Fe and high S contents are consistent with Mercury having formed from highly-reduced components [8]. This highly-reducing environment would favor the partitioning of Si, possibly in addition to S, into the metallic materials that make up Mercury's core [9, 10].

Here we use the estimates of C/MR^2 and C_m/C, along with geochemical constraints, to explore models of Mercury's interior structure.

Approach: Our approach to modeling the interior of Mercury generally follows our earlier effort [3], which outlined how well the internal structure could be constrained by MESSENGER's orbital measurements. We model the planet's interior as a multiple-layer structure consisting of compressible solid inner and liquid outer cores and uniform-density silicate crust and mantle layers. As Mercury's silicate shell is thin, the influence of compressibility in the outer solid layers is not as important as it is for the large core in the calculation of the moments of inertia.

Modeling: We performed Monte Carlo calculations of large suites of internal structure models consistent with Mercury's mean radius, bulk density, and a wide range of material and internal structural parameters. For each candidate structure we used the internal density distribution to calculate M, C, and the ratio C_m/C. For a spherically symmetric planet, M and C are related to the internal structure by [e.g., 9]:

$$M = 4\pi \int_0^R \rho(r) r^2 dr \tag{1}$$

$$C = \frac{8\pi}{3} \int_0^R \rho(r) r^4 dr \tag{2}$$

where $\rho(r)$ is the radial density distribution. The polar moments of inertia of the solid exterior C_m and core C_c are related by:

$$\frac{C_{\mathrm{m}}}{C}+\frac{C_{\mathrm{c}}}{C}=1. \tag{3}$$

We may calculate C_{m}/C from equation (3) supplemented by (2) and

$$C_{\mathrm{c}}=\frac{8\pi}{3}\int_0^{R_c}\rho(r)r^4dr\ , \tag{4}$$

where R_{c} is the core radius. The depth dependence of the density structure can be captured by supplementing equations (1-4) with a third-order Birch-Murnaghan equation of state for the appropriate core materials

$$\begin{gathered}P=\frac{3K_0}{2}\left[\left(\frac{\rho}{\rho_0}\right)^{7/3}-\left(\frac{\rho}{\rho_0}\right)^{5/3}\right]\times \\ \left[1+\frac{3}{4}\left(K_0'-4\right)\left\{\left(\frac{\rho}{\rho_0}\right)^{2/3}-1\right\}\right]+\alpha K_0\left(T-T_0\right)\end{gathered}\ , \tag{5}$$

where P, T, T_0, ρ_0, K_0, K_0', and α are the local pressure, the local and reference temperatures, the reference density, the isothermal bulk modulus and its pressure derivative, and the volumetric coefficient of thermal expansion, respectively.

Results: From the MESSENGER-derived C_{20} and C_{22} values [7] as well as the Earth-based radar measurements of the libration amplitude [6] and a recent update to the obliquity [11], we find that $C/MR^2 = 0.353 \pm 0.0172$ and $C_{\mathrm{m}}/C = 0.452 \pm 0.0353$. We have calculated several suites of models containing nearly 10^6 models per case that span a variety of core compositions (i.e., Fe-S, Fe-Si, Fe-C core alloys) and solid outer shell density structures. The most robust results from these models are that the boundary between the solid outer shell and the liquid portion of the core lies at a radius of 2030 ± 37 km and that the bulk density of the solid outer shell is 3650 ± 225 kg m^{-3} (Fig. 1).

Discussion: These model comparisons indicate that Mercury has a larger and lower density core than previously considered likely [cf. 2] and a dense solid outer shell. The latter result is surprising given the XRS measurements [8] indicating low surface abundances of Fe, Ti, and Al. A reservoir of high-density material deeper than the source regions of surface volcanic material is required to account for the large density. One possibility is a dense, possibly Fe-bearing, silicate layer that did not substantively participate in the generation of Mercury's crust. Alternatively, Mercury may have a solid layer of FeS at the top of the core. The highly reducing chemical conditions implied by the low Fe and high S contents of Mercury's surface [8] is consistent with a core containing an Fe-S-Si alloy. Such alloys have two immiscible liquids at pressures less than 15 GPa [12], resulting in sequestration of S-rich liquids near the top of the core. Over a wide range of compositions, solid FeS may remain more buoyant than the residual liquids, resulting in a solid FeS layer at the base of a silicate mantle. We consider the robustness of such models and their implications for the structure, composition, and evolution of Mercury.

References: [1] Solomon, S. C. (2003) *EPSL*, 216, 441-455. [2] Harder, H., and G. Schubert (2001) *Icarus*, 151, 118-122. [3] Hauck, S. A., II, et al. (2007) *GRL*, 34, L18201. [4] Riner, M. A., et al. (2008) *JGR*, 113, E08013. [5] Rivoldini, A., et al. (2009) *Icarus*, 201, 12-30. [6] Margot, J. L., et al. (2007) *Science*, 316, 710-714. [7] Smith, D. E., et al. (2012) *Science*, submitted. [8] Nittler, L. R., et al. (2011) *Science*, 333, 1847-1850. [9] McCoy, T. J., et al. (1999) *MAPS*, 34, 735-746. [10] Malavergne, V., et al. (2010) *Icarus*, 206, 199-209. [11] Margot, J.-L., et al. (2011) *AGU Fall Mtg.*, abstract P44B-01. [12] Morard, G., and T. Katsura (2010) *GCA*, 74, 3659-3667.

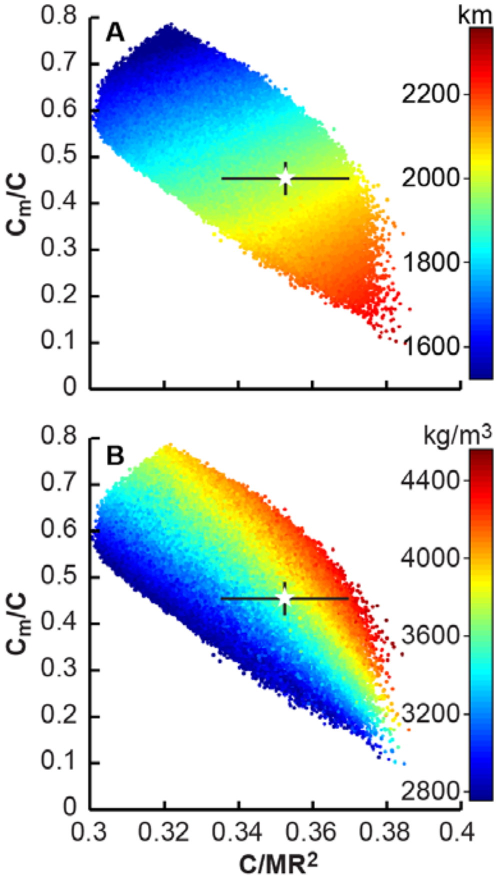

Figure 1. C_{m}/C versus C/MR^2 for ~10^6 internal structure models consistent with Mercury's radius and bulk density are compared with the MESSENGER-derived values (white star with ±one standard deviation in black). Color coding in (**A)** depicts the outer radius of the liquid portion of the core, whereas that in (**B**) indicates the bulk density of the outer solid shell of the planet.