CONSTRAINTS ON THE INTERNAL STRUCTURE OF MERCURY AFTER THREE MESSENGER FLYBYS. Steven A. Hauck, II[1], Sean C. Solomon[2], Stanton J. Peale[3], Jean-Luc Margot[4], Roger J. Phillips[5], David E. Smith[6], Maria T. Zuber[6], [1]Dept. of Geological 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 Physics, University of California, Santa Barbara, CA 93106, [4]Dept. of Earth and Space Sciences, University of California, Los Angeles, CA 90095, [5]Planetary Science Directorate, Southwest Research Institute, Boulder, CO 80302, [6]Dept. of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02129.

Introduction: A persistent issue in our understanding of the formation of the terrestrial planets has been the enigmatically large bulk density of Mercury of 5430 kg m^{-3} [e.g., 1]. A bulk density this large implies that the mass fraction of iron in Mercury's interior is considerably greater than in the other terrestrial planets. Data available to date have not permitted the opportunity to robustly estimate Mercury's internal structure. However, much recent work has focused on understanding how measurements to be made by MESSENGER and BepiColombo will constrain knowledge of Mercury's interior [2-4].

Recent Earth-based radar observations have determined Mercury's obliquity and forced libration amplitude, resulting in the conclusion that Mercury's core is likely at least partially molten at present [5]. However, this result alone does not provide a significant constraint on the interior structure of the planet [2-4]. In order to improve constraints on Mercury's radially varying density structure, knowledge of the planet's moment of inertia, in addition to its mass and radius, is generally required. Fortunately, due to the molten state of the core, measurement of Mercury's 88-day forced libration, obliquity, and the second-degree gravitational field harmonics C_{20} and C_{22} permits determination of the normalized polar moment of inertia, C/MR^2 and the ratio of the polar moment of inertia of the mantle plus crust to that of the planet, C_m/C [6].

Since January 2008, the MESSENGER spacecraft has executed a series of three flybys of Mercury. Each of these flybys, with approximately equatorial trajectories, has provided the opportunity to determine Mercury's low-order gravity field, especially the product of the planet's mass and the gravitational constant, GM, and C_{20} and C_{22} [7]. Whereas the uncertainty in the degree-two gravitational harmonics provided by data from the flybys is greater than that expected from the upcoming orbital phase of the MESSENGER mission [7], the relative improvement over Mariner 10 results [8] permits a preliminary estimate of the internal density structure of Mercury's interior.

Approach: Our approach to modeling the interior of Mercury directly follows our earlier effort [2], which aimed to outline how well the internal structure may be constrained by the MESSENGER orbital phase. We model the planet's interior as a three-layer structure consisting of a compressible γ-Fe inner core and liquid Fe-FeS alloy outer core and a single uniform-density silicate layer of mantle plus crust. As Mercury's silicate layer is likely thin, the influence of compressibility in the mantle plus crust layer is not as significant as it is for the large core in the calculation of the moments of inertia.

Modeling: We calculate a large suite of Monte Carlo 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 use the internal density distribution to calculate the planetary mass (M), polar moment of inertia (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]:

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

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

where $\rho(r)$ is the radial density distribution and R is the radius of the planet. The moments of inertia of the mantle plus crust (C_m) and core (C_c) are related by:

$$\frac{C_m}{C} + \frac{C_c}{C} = 1 . \qquad (3)$$

We may calculate C_m/C from Equation (3) supplemented by (2) and

$$C_c = \frac{8\pi}{3} \int_0^{R_c} \rho(r) r^4 dr , \qquad (4)$$

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

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

where P, T, T_0, ρ_0, K_0, K_0', and α are the local pressure, the local and reference temperatures, reference density, the isothermal bulk modulus and its pressure derivative, and the volumetric coefficient of thermal expansion, respectively (see [2] for details).

Observational constraints on Mercury's internal state: Recent work has demonstrated that Mercury occupies a Cassini state [5] which in principle allows for the determination of the normalized polar moment of inertia C/MR^2 as a function of C_{20}, C_{22}, and the planet's orbital parameters, including the obliquity [6-7]. Whereas C_{22} has been well-determined by the equatorial geometry of MESSENGER's flybys, the value of C_{20} is less constrained. This fact limits the ability to place useful, independent bounds on C/MR^2 and C_m/C at present [7]. However, following [6] we can estimate C_m/MR^2 with greater fidelity than was previously possible because of the precise determination of the amplitude of the physical libration [5] and C_{22} [7] through the relations:

$$\frac{C_m}{(B-A)}\frac{(B-A)}{MR^2} = \frac{C_m}{C}\frac{C}{MR^2} = \frac{C_m}{MR^2}. \qquad (6)$$

The first term on the left-hand side is determined from the amplitude of the physical libration, and the second term is equal to $4C_{22}$. The value of C_m/MR^2, and associated uncertainties, can be compared with the models of Mercury's interior described above.

Preliminary results: Our preliminary results are based upon the ~800,000 Monte Carlo models of [2] as well as the known value of $(B\text{-}A)/C_m = (2.03 \pm 0.12) \times 10^{-4}$ [5] and of $(B\text{-}A)/MR^2 = (3.24 \pm 0.1) \times 10^{-5}$ given the value of C_{22} from the HgM001 gravity model of [7] from the first two MESSENGER flybys of Mercury. From these data, $C_m/MR^2 = 0.16 \pm 0.018$. In Figure 1 we show how these new data compare with models of Mercury's interior by plotting the core radius as a function of C_m/MR^2 for all ~800,000 models with the color indicating the density of the silicate mantle plus crust. The MESSENGER and Earth-based radar-derived value of C_m/MR^2 and associated 1-σ uncertainties outline approximate limits on the internal structure. This formalism also provides a basis for estimating other internal structure parameters, such as the radius of the core and densities of the core and silicate mantle plus crust. Additional data, from MESSENGER's third flyby of Mercury and from Mariner 10, if available, may sharpen these constraints in anticipation of a reanalysis once observations from the MESSENGER orbital mission phase are underway.

References: [1] Solomon S. C. (2003) *EPSL, 216,* 441. [2] Hauck, S. A., II et al. (2007) *GRL, 34,* L18201. [3] Riner, M. A. et al. (2008) *JGR, 113,* E08013. [4] Rivoldini, A. et al. (2009) *Icarus, 201,* 12. [5] Margot, J.-L. et al. (2007), *Science, 316,* 710. [6] Peale, S. J. et al. (2002), *MAPS, 37,* 1269. [7] Smith, D. E. et al. (2009) *Icarus,* submitted. [8] Anderson J. D. et al. (1987) *Icarus, 71,* 337. [9] Turcotte, D. L. and G. Schubert (2002) Geodynamics, 2nd edition, Cambridge University Press.

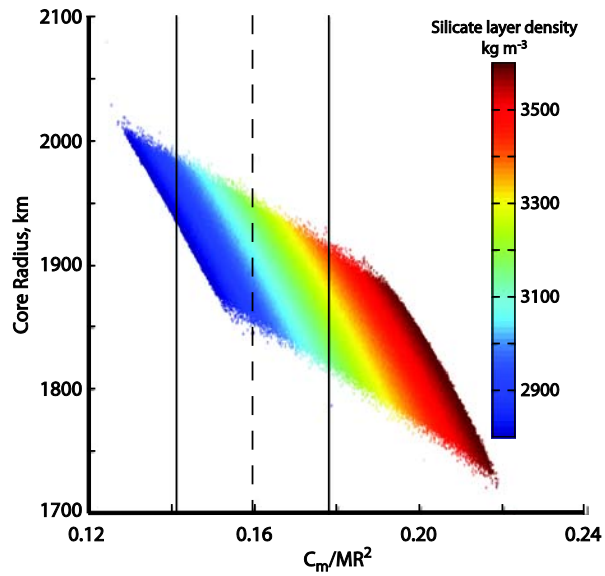

Figure 1 Relationship between the radius of Mercury's core and the normalized polar moment of inertia of the mantle plus crust for ~800,000 Monte Carlo models of the planet's interior. Also shown in color is the density of the silicate layer that includes the mantle and crust. The vertical dashed line represents the MESSENGER and radar derived value for C_m/MR^2 and the solid lines outline the 1-σ uncertainties.