Predicted recovery of Mercury's internal structure by MESSENGER

Steven A. Hauck, II,[1] Sean C. Solomon,[2] and Derek A. Smith[1]

Received 24 May 2007; revised 30 July 2007; accepted 13 August 2007; published 26 September 2007.

[1] Recent Earth-based and forthcoming MESSENGER spacecraft observations of the spin state and gravity field of Mercury will provide the opportunity to determine that planet's internal structure with unprecedented precision. These observations will provide estimates of the dimensionless polar moment of inertia and the ratio of the moment of inertia of the mantle plus crust to that of the planet. In order to understand how well these two parameters will constrain Mercury's internal structure we calculate ~800,000 Monte Carlo models of the planet's interior. Within the uncertainties currently predicted to be achieved by MESSENGER for these quantities we estimate that the radius and bulk density of an Fe-FeS core and the bulk density of the silicate shell can be determined to within ±23 km, ±147 kg m^{-3}, and ±72 kg m^{-3}, respectively.

Citation: Hauck, S. A., II, S. C. Solomon, and D. A. Smith (2007), Predicted recovery of Mercury's internal structure by MESSENGER, *Geophys. Res. Lett.*, *34*, L18201, doi:10.1029/2007GL030793.

1. Introduction

[2] One of the most persistent questions regarding the formation of the terrestrial planets is the origin of Mercury's large bulk density (5430 kg/m^3) [e.g., *Lewis*, 1988; *Wetherill*, 1988; *Solomon*, 2003]. This high density suggests that the planet has a larger ratio of metal to silicate than the other terrestrial planets, though neither the density nor other available data uniquely specify Mercury's composition. Indeed, typical solar nebula condensation and accretion models cannot account for Mercury's density [*Lewis*, 1988]. One or more additional processes such as aerodynamic sorting of metal and silicate grains in the early stages of the solar nebula [*Weidenschilling*, 1978], stripping of the crust and mantle by giant impact [*Wetherill*, 1988], or vaporization of the outer silicate shell in a hot nebula [*Fegley and Cameron*, 1987] are required. While these processes provide distinct geochemical predictions for Mercury's surface composition [e.g., *Solomon*, 2003], they do not constrain well the metal:silicate ratio or the internal structure of the planet.

[3] NASA's MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) spacecraft is scheduled to make the first of its three flybys of Mercury in January 2008 and to orbit Mercury in March 2011 [*Solomon et al.*, 2001]. MESSENGER data will be critical for building a new understanding of the planet, including the origin of its anomalous density. In particular, data from the spacecraft's suite of spectrometers and cameras [*Gold et al.*, 2001] will constrain elemental and mineralogical composition and measurement of gravity and topography will yield constraints on the planet's polar moment of inertia (C) and crustal thickness [*Gold et al.*, 2001; *Solomon et al.*, 2001].

[4] Measurement of the amplitude of Mercury's 88-day forced libration, if Mercury's core is at least partially molten, permits a determination as well of the ratio of the moment of inertia of the mantle plus crust to that of the planet (C_m/C) [*Peale et al.*, 2002]. Additional needed measurements are the planet's obliquity and the second-degree zonal and tesseral coefficients ($C_{2,0}$ and $C_{2,2}$) in the harmonic expansion of the planet's gravitational potential [*Peale et al.*, 2002]. Earth-based radar observations have recently been used to determine Mercury's obliquity and the amplitude of its forced libration, and even with the presently large uncertainties in $C_{2,0}$ and $C_{2,2}$ obtained from Mariner 10 a molten outer core is indicated at high confidence [*Margot et al.*, 2007].

[5] The combination of these Earth-based results with independent observations by MESSENGER to determine C and C_m will provide two more constraints on Mercury's internal structure than have been used in models to date [e.g., *Harder and Schubert*, 2001]. Moreover, recent experimental work on potential core-forming alloys, especially Fe-FeS, has provided equations of state for liquids and demonstrated a strong dependence of compressibility on sulfur content [*Sanloup et al.*, 2000, 2002; *Balog et al.*, 2003], data unavailable for earlier models [*Harder and Schubert*, 2001]. Therefore, we model the internal structure of Mercury with the goal of understanding how future measurements of the planet's moments of inertia will elucidate its structure and composition.

2. Approach

[6] Mercury's radial density distribution must be consistent with the planet's mass and moments of inertia. By generating a suite of models of the planet's internal structure constrained only by current estimates of Mercury's mass, M, and radius, R, we aim to outline the range of reasonable models and understand the ability of forthcoming measurements of C/MR^2 and C_m/C to constrain further the interior of Mercury. We assume a generalized structure for the interior with an outer silicate shell, a liquid Fe-FeS outer core, and a solid γ-Fe inner core. The internal density distribution resulting from this basic structure is used 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., *Turcotte and Schubert*, 2002]:

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

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

[1] Department of Geological Sciences, Case Western Reserve University, Cleveland, Ohio, USA.

[2] Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC, USA.

0094-8276/07/2007GL030793

Table 1. Structural Model Parameters

Parameter	Symbol	Value	Units
Bulk density of planet	ρ_{bulk}	5430 ± 10	kg m^{-3}
Radius of planet	R_p	2440	km
Mantle density	ρ_{m}	2800–3600	kg m^{-3}
Outer core sulfur content	$\chi_{s,oc}$	0–15	wt %
Solid Fe density	$\rho_{0,\mathrm{Fe},s}$	7225 ± 72	kg m^{-3}
Liquid Fe density	$\rho_{0,\mathrm{Fe},l}$	7019 ± 175	kg m^{-3}
Liquid FeS density	$\rho_{0,\mathrm{FeS},l}$	3900 ± 98	kg m^{-3}
Solid bulk modulus	$K_{0,\mathrm{Fe},s}$	1.27×10^{11}	Pa
Liquid bulk modulus coefficient	K_{0a}	5.54×10^{11}	Pa
Liquid bulk modulus coefficient	K_{0b}	-3.91×10^{11}	Pa
Liquid bulk modulus coefficient	K_{0c}	8.13×10^{10}	Pa
Pressure derivative of K_0	$K'_{0,\mathrm{Fe},s}$	2.2	-
Pressure derivative of K_0	$K'_{0,\mathrm{Fe},l}$	4.6	-
Pressure derivative of K_0	$K'_{0,\mathrm{FeS},l}$	5.0	-
Coefficient of thermal expansion	$\alpha_{0,\mathrm{Fe}}$	9.2×10^{-5}	K^{-1}
Coefficient of thermal expansion	$\alpha_{0,\mathrm{FeS}}$	1.1×10^{-4}	K^{-1}
Core heat capacity	c_c	850	J kg^{-1} K^{-1}

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

$$\frac{C_m}{C} + \frac{C_c}{C} = 1. \tag{3}$$

[7] We may calculate C_m/C from equation (3) supplemented by (2) plus

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

where R_c is the core radius.

[8] The density structure, $\rho(r)$, is not known a priori, but Mercury's large bulk density suggests a large core, consisting dominantly of iron, and a comparatively thin silicate shell. Though a pure iron core would be entirely solid by the present [*Siegfried and Solomon*, 1974], the addition of a light alloying element, such as in Earth's outer core, would depress the melting temperature and raise the likelihood that the outer core is currently molten. Such a melting point depression would also lead to limited inner core growth [*Schubert et al.*, 1988; *Hauck et al.*, 2004], consistent with the limited planetary contraction inferred from images of lobate scarps acquired by Mariner 10 [*Strom et al.*, 1975; *Watters et al.*, 1998] and the detection of an internal magnetic field [*Ness et al.*, 1975], possibly the result of dynamo action within a molten outer core [*Stevenson*, 2003]. We assume that sulfur is the major light alloying element in Mercury's core, on the grounds that it displays highly siderophile behavior at the low pressures of planetesimal formation and has a high cosmochemical abundance [e.g., *Hillgren et al.*, 2000]. This assumption is also in accord with existing models of the planet's interior structure and evolution [*Schubert et al.*, 1988; *Harder and Schubert*, 2001; *Hauck et al.*, 2004]. Further, Fe-S alloys are better characterized at the relevant pressures and temperatures [*Fei et al.*, 1997; *Hillgren et al.*, 2000] for Mercury's interior than other candidate compounds (e.g., Fe-C, Fe-Si).

[9] The radial dependence of density structure [e.g., *Harder and Schubert*, 2001] can be captured by supplementing equations (1–4) with equations of state for appropriate materials. We assume a constant, average density for the silicate shell and implement a third-order Birch-Murnaghan equation of state [e.g., *Poirier*, 2000] for the core:

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

where P, T, T_0, ρ_0, K_0, K_0', and α are the local pressure, local and reference temperatures, reference density, isothermal bulk modulus and its pressure derivative, and volumetric coefficient of thermal expansion, respectively. Table 1 lists values of these parameters for both the solid and liquid portions of the core. The inner core is assumed to be pure, solid γ-Fe, and the outer core a liquid Fe-FeS alloy [e.g., *Anderson and Ahrens*, 1994; *Sanloup et al.*, 2000; *Balog et al.*, 2003]. To understand the role of variations in core sulfur content we employ a linear parameterization as a function of sulfur content for ρ_0, K_0', and α and a quadratic fit ($K_0 = K_{0a}\chi_S^2 + K_{0b}\chi_S + K_{0c}$) for the bulk modulus as a function of sulfur mass fraction, χ_S, from the data of *Sanloup et al.* [2000], extrapolated from 0–10 wt % to 15 wt % S. To implement, the pressure distribution is calculated from the assumption of hydrostatic equilibrium:

$$P(r) = \int_R^r \rho(x) g(x) dx, \tag{6}$$

where x is a variable of integration and the gravitational acceleration is given by:

$$g(r) = \frac{4\pi G}{r^2}\int_0^r \rho(x) x^2 dx. \tag{7}$$

The equation of state is augmented by assuming an adiabatic thermal profile in the outer core, pinned by an assumed temperature at the core-mantle boundary (CMB):

$$T(r) = T_{cmb}\exp\left[\frac{\alpha}{\bar{\rho}_c c_c}\left(P(r) - P_{cmb}\right)\right], \tag{8}$$

where $\bar{\rho}_c$ is the average core density, c_c is the core specific heat, and P_{cmb} is the CMB pressure. The inner core is taken to be isothermal, with the temperature determined by the adiabatic temperature at the inner core boundary. We solve equations (1)–(8) using an iterative procedure for the density structure of the core, based on (5), for a given set of a priori assumptions regarding the thicknesses and properties for each of the individual layers and bulk properties of the planet. The radius of the planet is enforced in our formulation, so an individual model is considered successful if the model bulk density of the planet matches a given value within ~0.02%. By investigating a wide range of possibilities for unknown parameters we can outline the breadth of possibilities for Mercury's internal structure.

[10] Approaches to outlining the range of possible planetary internal structures include both grid searches [e.g., *Hauck and Solomon*, 2004] and Monte Carlo methods [e.g., *Harder and Schubert*, 2001]. A grid search is an efficient way of mapping the range of possible structures and illustrating the relationships among parameters (e.g., the variation in C/MR^2 with ρ_m) with a specified resolution, while a Monte Carlo approach is useful for understanding how the underlying uncertainties in model parameters will affect the quality of the recovery of internal structures based upon the model. We use the Monte Carlo method to outline both the range of possible internal structures at Mercury and the ability of anticipated future measurements (e.g., by MESSENGER) to constrain the interior. This approach utilizes large numbers of models with randomly distributed parameters, within known uncertainties or physically reasonable limits, to estimate the propagation of error through the model. As the internal structural models are predicated on the density distribution, the reference densities of assumed core materials clearly are critical parameters, as is the observed bulk density of the planet. Other important, though unknown, parameters are T_{cmb}, the fractional radius of the inner core R_i/R_c, the sulfur content of the outer core $\chi_{s,oc}$, and the mean density of the silicate shell ρ_m.

3. Results

[11] We calculated approximately 800,000 individual internal structure models consistent with Mercury's bulk density of $\rho_{bulk} = 5430 \pm 10$ kg m^{-3} [*Anderson et al.*, 1987] and a broad range of material and structural parameters. Model parameters for which there are no independently determined preferred values with associated estimates of uncertainty were randomly selected from a uniform distribution between two end-member values; these parameters include T_{cmb} (1700–2100 K), ρ_m (2800–3600 kg m^{-3}), R_i/R_c (0–1), and $\chi_{s,oc}$ (0–15 wt %). Ranges for ρ_m and R_i/R_c are conservative estimates; T_{cmb} and $\chi_{s,oc}$ are broader ranges than recent thermal modeling [*Hauck et al.*, 2004] suggests are likely and consistent with the idea that Mercury's magnetic field is the product of a core dynamo. For critical parameters that have been determined from observations, possible values are taken to be distributed normally about mean values with some standard deviation (σ). These parameters and selected mean values include ρ_{bulk}, $\rho_{0,\mathrm{Fe},l}$ (7019 kg m^{-3} @ 1811 K), $\rho_{0,\mathrm{Fe},s}$ (7225 kg m^{-3} @ 1700 K), and $\rho_{0,\mathrm{FeS},l}$ (3900 kg m^{-3} @ 1473 K) [*Kaiura and Toguri*, 1979; *Anderson and Ahrens*, 1994; *Harder and Schubert*, 2001]; assumed uncertainties on the liquid and solid densities are 2.5% and 1%, respectively [*Kaiura and Toguri*, 1979; *Sanloup et al.*, 2000; *Harder and Schubert*, 2001].

[12] As our primary goal is to understand how well the combination of Earth-based measurements [*Margot et al.*, 2007] and future observations by MESSENGER may constrain Mercury's internal structure we consider the results of all the internal structure models in aggregate. Recent work suggests that data collected from both sources by the end of MESSENGER's primary mission will allow estimates for C/MR^2 and C_m/C to be known to an accuracy of approximately 1% and 6%, respectively [*Peale et al.*, 2002; *Margot et al.*, 2007]. Under the conservative assumption that these uncertainties are uniformly distributed about their central values we calculate the mean and standard deviation of structural parameters that give a particular set of C/MR^2 and C_m/C, within 1-σ uncertainties. For statistical robustness we consider further only those average and 1-σ values that are based on more than 100 individual models, though in practice most are based on tens of thousands of individual results. In Figure 1a, the recovery of R_c as a function of C_m/C and C/MR^2 is shown with a range of ~1750–2000 km across the entire parameter space. More importantly, the potential quality of the recovery is apparent in Figure 1b, where the maximum 1-σ uncertainty in core radius ΔR_c is ~23 km (1.2% of the mean value). Figures 1c–1f illustrate the results for the average core and mantle densities, which also have small 1-σ values with maxima of $\Delta\rho_c \sim 147$ kg m^{-3} (1.8%) and $\Delta\rho_m \sim 72$ kg m^{-3} (2.3%). The results for R_c, ρ_c, and ρ_m are the only robustly recoverable parameters in this analysis; uncertainties on R_i/R_c and $\chi_{s,oc}$ are at least 50% of the mean, or more. A negative result for the latter parameters is consistent with the distinct tradeoff between the radius of the pure iron inner core and outer core sulfur content that leads to similar values for bulk core density. So, while the size and bulk density of the core can be deduced, further insight into the size of the inner core and the amount of sulfur cannot be reasonably determined.

[13] The results in Figure 1 are indicative of the ideal case where both C_m/C and C/MR^2 are recovered with reasonable accuracy. Though Earth-based radar observations have demonstrated that Mercury likely has a liquid outer core [*Margot et al.*, 2007], a 5–10% possibility remains that core and mantle are coupled and a value for C_m/C will not be recoverable by the experiment. To demonstrate the added value of a well-determined value of C_m/C, Figure 2 shows the 1-σ uncertainty relative to the mean values for the case where C/MR^2 is known to 1% but C_m/C is not known. Although in the absence of a value for C_m/C the range of possible structural parameters is quite broad (Figure 1) the most likely values are still relatively well determined (Figure 2), due in large part to the fact that Mercury is predominantly core. Knowledge of C_m/C to ~6% improves the quality of the recovery of R_c, ρ_c, and ρ_m by more than 50–170% compared with utilizing C/MR^2 alone.

4. Discussion and Conclusion

[14] Mercury's interior holds important clues to understanding fundamental questions about the planet, particularly its bulk composition and the dynamics of the interior. The recent determination by *Margot et al.* [2007] of Mercury's obliquity and physical libration amplitude led to the important inference that the outer core is molten, a result that is consistent with, though does not require, a dynamo origin for the magnetic field. With these new, ground-based results the primary ambiguity in ascertaining Mercury's internal density structure comes from uncertainties in $C_{2,0}$ and $C_{2,2}$ (up to 50%) [*Anderson et al.*, 1987] from Mariner 10 tracking. Future observations by MESSENGER will substantially improve these uncertainties to less than a percent [*Solomon et al.*, 2001], which will

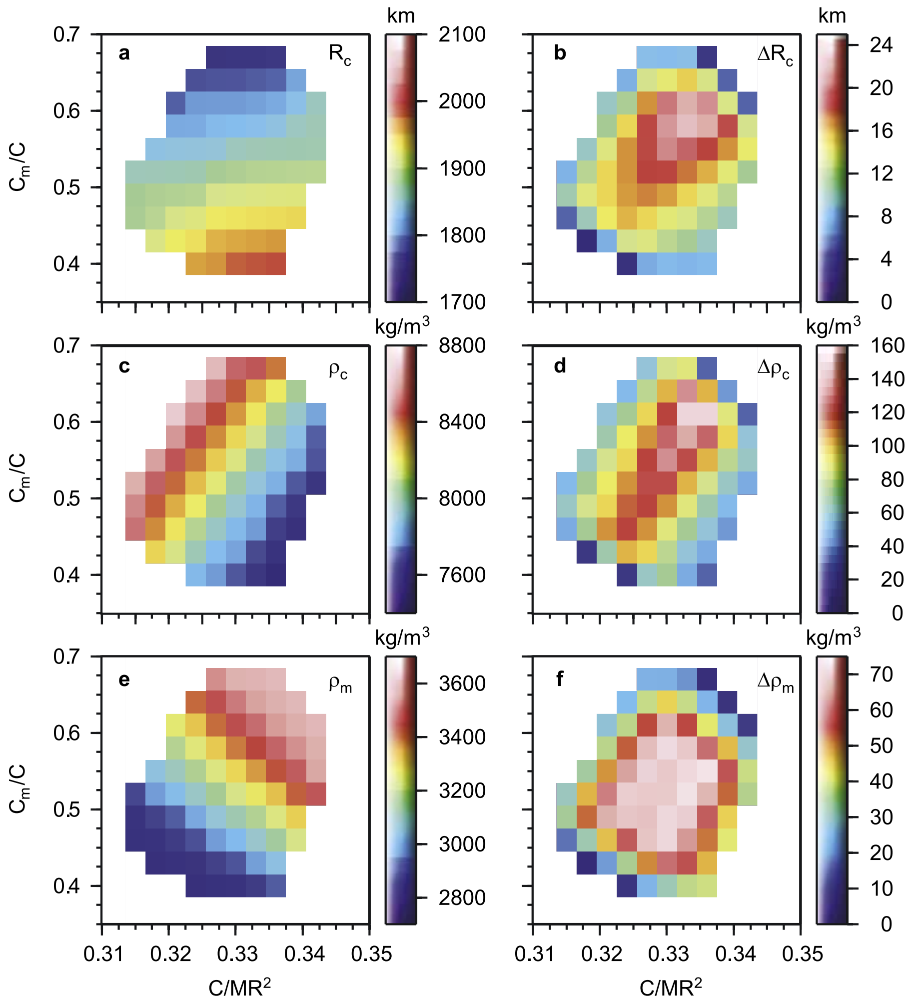

Figure 1. Recovery of internal structure parameters as functions of C_m/C and C/MR^2: (a–b) core radius and uncertainty, (c–d) core bulk density and uncertainty, and (e–f) mantle bulk density and uncertainty.

allow both the determination of core-mantle coupling with greater confidence and inferences on R_c, ρ_c, and ρ_m with significant precision. Beyond constraining the origin of the magnetic field, internal structure results will also inform studies of mantle convection in Mercury's interior. Parameterized convection models suggest that mantle convection may have ceased by the present [*Hauck et al.*, 2004], though more recent mantle convection models call into question the strength of that conclusion [*Breuer et al.*, 2007; *Redmond and King*, 2007]. Mercury's mantle may be near the critical point for convection to occur, and accurate knowledge of the thickness of the mantle shell is necessary because the Rayleigh number (the ratio of buoyancy forces to viscous forces) is proportional to the cube of the mantle thickness. Moreover, studies of mantle convection at Mercury have not adequately addressed how the presence of a crust that may be as much as one-half the thickness of the silicate shell [*Nimmo*, 2002] may affect stability against convection. Models of the bulk internal structure and analysis of crustal thickness variations from MESSENGER gravity and topography data should provide critical new information on this subject.

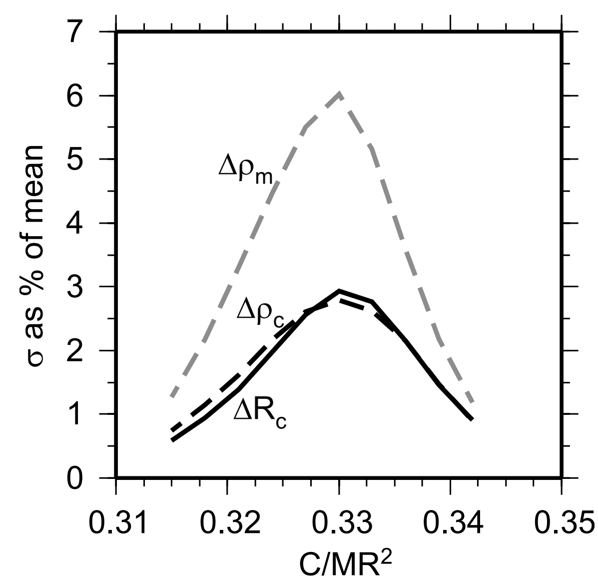

Figure 2. Fractional uncertainty in internal structure parameters as functions of C/MR^2 alone.

[15] The quality of these internal structure recoveries varies with the uncertainties in C/MR^2 and C_m/C, where the latter is dominated by uncertainty in the libration amplitude given precise values for $C_{2,0}$ and $C_{2,2}$ from MESSENGER [*Margot et al.*, 2007]. Errors in R_c scale with C_m/C, with up to ~43% more uncertainty at $\Delta(C_m/C)$ = 10%, but are not sensitive to $\Delta(C/MR^2)$. In contrast, $\Delta\rho_c$ is negligibly affected by increases in $\Delta(C_m/C)$ compared with $\Delta(C/MR^2)$ = 5%, which results in ~49% more uncertainty relative to Figure 1. The sensitivity of $\Delta\rho_m$ to the observational parameters is similar, where increases to $\Delta(C_m/C)$ = 10% and $\Delta(C/MR^2)$ = 5% lead to ~120% more uncertainty in ρ_m compared with the nominal case. Improvements in ground-based radar observations to near the limit of current techniques [*Peale et al.*, 2002] could reduce errors in the amplitude of the physical libration [*Margot et al.*, 2007] to a level that would improve C_m/C by a factor of three and recoveries for R_c, ρ_c, and ρ_m by at least a factor of two.

[16] Taking the predicted uncertainties in estimates of C/MR^2 and C_m/C from ground-based radar and spacecraft observations [*Solomon et al.*, 2001; *Peale et al.*, 2002; *Margot et al.*, 2007] at face value, our recoveries of internal structure (Figure 1) may be considered to be conservative. For example, in order to bracket the effects of the unknown internal temperatures we use a very broad range for T_{cmb} relative to recent thermal models [*Hauck et al.*, 2004]; the magnitude of T_{cmb} has more influence than the distribution (i.e., adiabatic versus isothermal). A notable aspect of our models is that several parameters are assumed to have a uniform distribution about their mean, e.g., C/MR^2 and C_m/C. Use of formal uncertainties and a distribution of probabilities may allow a tighter estimation of internal structure parameters. Gravity, topography, compositional, and mineralogical observations by MESSENGER should yield information on crustal thickness and composition, which in turn will provide additional constraints on the density distribution in the planet's silicate shell. Our results do rely on the assumption that the outer core is an Fe-S alloy. Other light elements (i.e., C or O) may produce alloys with different solid-liquid partitioning behavior and bulk moduli, which could result in different internal structures. However, sulfur is the best-characterized potential alloying element [e.g., *Fei et al.*, 1997; *Sanloup et al.*, 2000; *Kavner et al.*, 2001], highly siderophile, and cosmochemically abundant, consistent with it being commonly assumed to be the dominant light element in Mercury's core [e.g., *Schubert et al.*, 1988; *Harder and Schubert*, 2001; *Hauck et al.*, 2004; *Van Hoolst and Jacobs*, 2003].

[17] The prospect that robust determinations of C/MR^2 and C_m/C for Mercury will be made in the near future [*Solomon et al.*, 2001; *Margot et al.*, 2007] provides a special opportunity to understand the planet's internal structure. The additional knowledge gained by having a well-determined value for C_m/C substantially improves the determination of internal density structure relative to knowing only C/MR^2.

[18] **Acknowledgments.** Comments by H. Harder and an anonymous reviewer are appreciated. This research was supported by NASA grants NNG05GH12G and NNG04GI64G.

References

Anderson, J. D., G. Colombo, P. B. Esposito, E. L. Lau, and G. B. Trager (1987), The mass, gravity field, and ephemeris of Mercury, *Icarus*, *71*, 337–349.

Anderson, W. W., and T. J. Ahrens (1994), An equation of state for liquid iron and implications for the Earth's core, *J. Geophys. Res.*, *99*, 4273–4284.

Balog, P. S., R. A. Secco, D. C. Rubie, and D. J. Frost (2003), Equation of state of liquid Fe-10 wt % S: Implications for the metallic cores of planetary bodies, *J. Geophys. Res.*, *108*(B2), 2124, doi:10.1029/2001JB001646.

Breuer, D., S. A. Hauck, II, M. Buske, M. Pauer, and T. Spohn (2007), Interior evolution of Mercury, *Space Sci. Rev.*, in press.

Fegley, B., Jr., and A. G. W. Cameron (1987), A vaporization model for iron/silicate fractionation in the Mercury protoplanet, *Earth Planet. Sci. Lett.*, *82*, 207–222.

Fei, Y., C. M. Bertka, and L. W. Finger (1997), High-pressure iron sulfur compound, Fe_3S_2, and melting relations in the Fe-FeS system, *Science*, *275*, 1621–1623.

Gold, R. E., et al. (2001), The MESSENGER mission to Mercury: Scientific payload, *Planet. Space Sci.*, *49*, 1467–1479.

Harder, H., and G. Schubert (2001), Sulfur in Mercury's core?, *Icarus*, *151*, 118–122.

Hauck, S. A., II, and S. C. Solomon (2004), Mercury: Determination of internal structure and evolution, *Lunar Planet Sci.* [CD-ROM], *35*, abstract 1921.

Hauck, S. A., II, A. J. Dombard, R. J. Phillips, and S. C. Solomon (2004), Internal and tectonic evolution of Mercury, *Earth Planet. Sci. Lett.*, *222*, 713–728.

Hillgren, V. J., C. K. Gessman, and J. Li (2000), An experimental perspective on the light element in the Earth's core, in *Origin of the Earth and Moon*, edited by R. M. Canup and K. Righter, pp. 245–263, Univ. of Ariz. Press, Tucson.

Kaiura, G. H., and J. M. Toguri (1979), Densities of the molten FeS, FeS-Cu_2S and Fe-S-O systems—Utilizing a bottom balance Archimedean technique, *Can. Metal. Q.*, *18*, 155–164.

Kavner, A., T. S. Duffy, and G. Shen (2001), Phase stability and density of FeS at high pressures and temperatures: Implications for the interior structure of Mars, *Earth Planet. Sci. Lett.*, *185*, 25–33.

Lewis, J. S. (1988), Origin and composition of Mercury, in *Mercury*, edited by F. Vilas, C. R. Chapman, and M. S. Matthews, pp. 651–666, Univ. of Ariz. Press, Tucson.

Margot, J. L., S. J. Peale, R. F. Jurgens, M. A. Slade, and I. V. Holin (2007), Large longitude libration of Mercury reveals a molten core, *Science*, *316*, 710–714.

Ness, N. F., K. W. Behannon, R. P. Lepping, and Y. C. Whang (1975), The magnetic field of Mercury: 1, *J. Geophys. Res.*, *80*, 2708–2716.

Nimmo, F. (2002), Constraining the crustal thickness on Mercury from viscous topographic relaxation, *Geophys. Res. Lett.*, *29*(5), 1063, doi:10.1029/2001GL013883.

Peale, S. J., R. J. Phillips, S. C. Solomon, D. E. Smith, and M. T. Zuber (2002), A procedure for determining the nature of Mercury's core, *Meteorit. Planet. Sci.*, *37*, 1269–1283.

Poirier, J. P. (2000), *Introduction to the Physics of the Earth's Interior*, 2nd ed., 312 pp., Cambridge Univ. Press, Cambridge, U. K.

Redmond, H. L., and S. D. King (2007), Does mantle convection currently exist on Mercury?, *Phys. Earth Planet. Inter.*, in press.

Sanloup, C., F. Guyot, P. Gillet, G. Fiquet, M. Mezaouar, and I. Martinez (2000), Density measurements of liquid Fe-S alloys at high-pressure, *Geophys. Res. Lett.*, *27*, 811–814.

Sanloup, C., F. Guyot, P. Gillet, and Y. Fei (2002), Physical properties of liquid Fe alloys at high pressure and their bearings on the nature of metallic planetary cores, *J. Geophys. Res.*, *107*(B11), 2272, doi:10.1029/2001JB000808.

Schubert, G., M. N. Ross, D. J. Stevenson, and T. Spohn (1988), Mercury's thermal history and the generation of its magnetic field, in *Mercury*, edited by F. Vilas, C. R. Chapman, and M. S. Matthews, pp. 429–460, Univ. of Ariz. Press, Tucson.

Siegfried, R. W., II, and S. C. Solomon (1974), Mercury: Internal structure and thermal evolution, *Icarus*, *23*, 192–205.

Solomon, S. C. (2003), Mercury: The enigmatic innermost planet, *Earth Planet. Sci. Lett.*, *216*, 441–455.

Solomon, S. C., et al. (2001), The MESSENGER mission to Mercury: Scientific objectives and implementation, *Planet. Space Sci.*, *49*, 1445–1465.

Stevenson, D. J. (2003), Planetary magnetic fields, *Earth Planet Sci. Lett.*, *208*, 1–11.

Strom, R. G., N. J. Trask, and J. E. Guest (1975), Tectonism and volcanism on Mercury, *J. Geophys. Res.*, *80*, 2478–2507.

Turcotte, D. L., and G. Schubert (2002), *Geodynamics*, 2nd ed., 472 pp., Cambridge Univ. Press, Cambridge, U. K.
Van Hoolst, T., and C. Jacobs (2003), Mercury's tides and interior structure, *J. Geophys. Res.*, *108*(E11), 5121, doi:10.1029/2003JE002126.
Watters, T. R., M. S. Robinson, and A. C. Cook (1998), Topography of lobate scarps on Mercury: New constraints on the planet's contraction, *Geology*, *26*, 991–994.
Weidenschilling, S. J. (1978), Iron/silicate fractionation and the origin of Mercury, *Icarus*, *35*, 99–111.
Wetherill, G. W. (1988), Accumulation of Mercury from planetesimals, in *Mercury*, edited by F. Vilas, C. R. Chapman, and M. S. Matthews, pp. 670–691, Univ. of Ariz. Press, Tucson.

S. A. Hauck, II, and D. A. Smith, Department of Geological Sciences, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106, USA. (hauck@case.edu)

S. C. Solomon, Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd., N.W., Washington, DC 20015, USA.