



## Predicted recovery of Mercury's internal structure by MESSENGER

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[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  $\sim 800,000$  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  $\pm 23$  km,  $\pm 147$  kg m<sup>-3</sup>, and  $\pm 72$  kg m<sup>-3</sup>, respectively.

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### 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<sup>3</sup>) [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  $\gamma$ -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]:

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

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

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**Table 1.** Structural Model Parameters

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

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:

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

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

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

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 planetary 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:

$$P = \frac{3K_0}{2} \left[ \left( \frac{\rho}{\rho_0} \right)^{7/3} - \left( \frac{\rho}{\rho_0} \right)^{5/3} \right] \times \left[ 1 + \frac{3}{4} (K'_0 - 4) \left\{ \left( \frac{\rho}{\rho_0} \right)^{2/3} - 1 \right\} \right] + \alpha K_0 (T - T_0), \quad (5)$$

where  $P$ ,  $T$ ,  $T_0$ ,  $\rho_0$ ,  $K_0$ ,  $K'_0$ , and  $\alpha$  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  $\gamma$ -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  $\rho_0$ ,  $K'_0$ , and  $\alpha$  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,  $\chi_S$ , 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:

$$P(r) = \int_R^r \rho(x)g(x)dx, \quad (6)$$

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

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

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):

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

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  $\sim 0.02\%$ . 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  $\rho_m$ ) 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  $\rho_m$ .

### 3. Results

[11] We calculated approximately 800,000 individual internal structure models consistent with Mercury's bulk density of  $\rho_{bulk} = 5430 \pm 10 \text{ kg m}^{-3}$  [*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),  $\rho_m$  (2800–3600  $\text{kg m}^{-3}$ ),  $R_i/R_c$  (0–1), and  $\chi_{s,oc}$  (0–15 wt %). Ranges for  $\rho_m$  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 ( $\sigma$ ). These parameters and selected mean values include  $\rho_{bulk}$ ,  $\rho_{0,Fe,l}$  (7019  $\text{kg m}^{-3}$  @ 1811 K),  $\rho_{0,Fe,s}$  (7225  $\text{kg m}^{-3}$  @ 1700 K), and  $\rho_{0,Fe,s,l}$  (3900  $\text{kg m}^{-3}$  @ 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*].

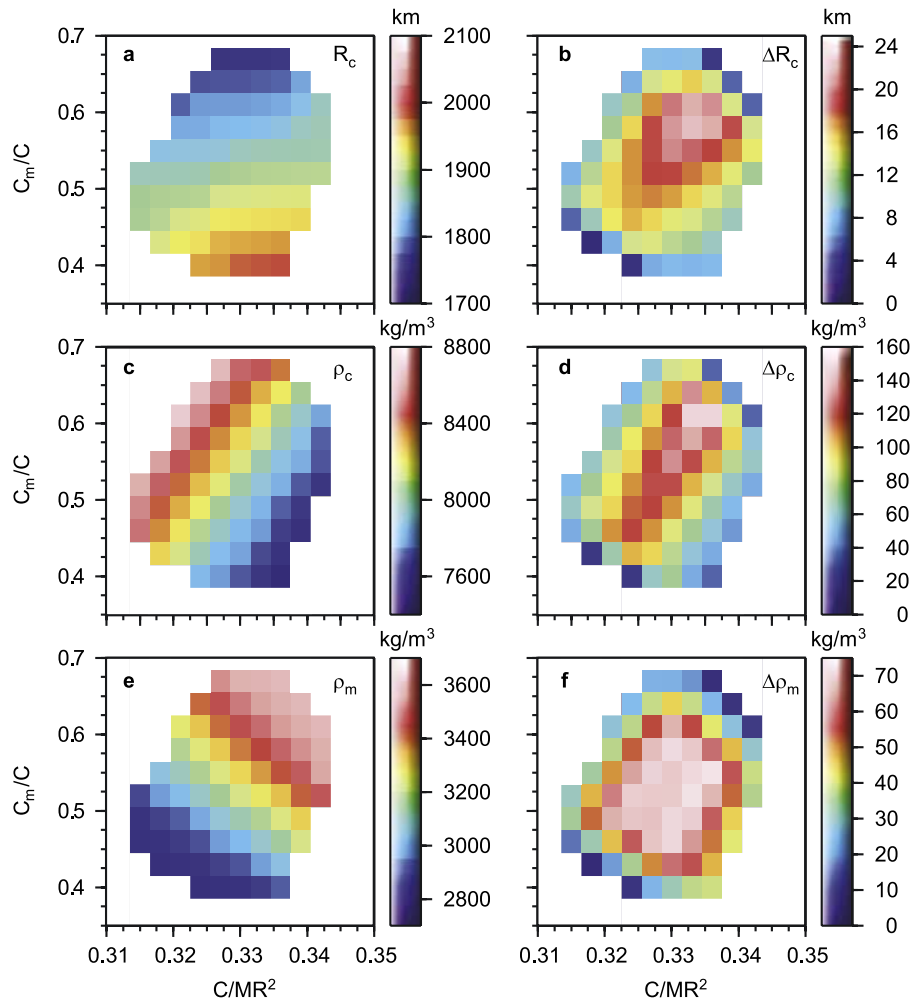
[12] As our primary goal is to understand how well the combination of Earth-based measurements [*Margot et al., 2007*] and future observations by MESSENGER may constrain Mercury's internal structure we consider the results of all the internal structure models in aggregate. Recent work suggests that data 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- $\sigma$  uncertainties. For statistical robustness we consider further only those average and 1- $\sigma$  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  $\sim 1750$ – $2000$  km across the entire parameter space. More importantly, the potential quality of the recovery is apparent in Figure 1b, where the maximum 1- $\sigma$  uncertainty in core radius  $\Delta R_c$  is  $\sim 23$  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- $\sigma$  values with maxima of  $\Delta \rho_c \sim 147 \text{ kg m}^{-3}$  (1.8%) and  $\Delta \rho_m \sim 72 \text{ kg m}^{-3}$  (2.3%). The results for  $R_c$ ,  $\rho_c$ , and  $\rho_m$  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- $\sigma$  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  $\sim 6\%$  improves the quality of the recovery of  $R_c$ ,  $\rho_c$ , and  $\rho_m$  by more than 50–170% compared with utilizing  $C/MR^2$  alone.

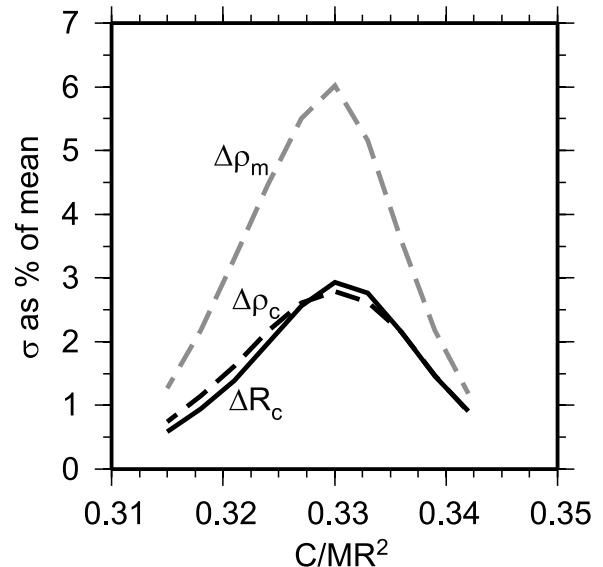
### 4. Discussion and Conclusion

[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  $R_c$ ,  $\rho_c$ , and  $\rho_m$  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  $\sim 43\%$  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  $\sim 49\%$  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  $\sim 120\%$  more uncertainty in  $\rho_m$  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  $R_c$ ,  $\rho_c$ , and  $\rho_m$  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  $C/MR^2$ .

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