COMPRESSIBLE MERCURY – INSIGHTS INTO ITS COMPOSITION AND INTERIOR STRUCTURE.

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Introduction: Mercury is unique among the terrestrial planets for its low mass (3.302×10^{23} kg) and high average density (5.427 g/cc) that together imply an iron-rich composition. Meaningful interplanetary comparisons of bulk composition, through bulk density, require the removal of self-compression effects to determine decompressed density (zero pressure and 300K, STP). The methodologies used in past estimates of planetary decompressed densities (Table 1) are not well documented in the scientific literature and rarely include uncertainty estimates. We present a detailed calculation of Mercury's decompressed density including elucidation of assumptions, methodology, and an estimate of uncertainty.

	g/cc
Mercury	5.3-5.31
Venus	3.95-4.0
Earth	4.0-4.05
Mars	3.71-3.75

Table 1 - Commonly cited decompressed densities for the terrestrial planets [e.g. 1-3]

Background: The relatively high average density and low mass of Mercury indicates an unusual bulk composition and thus provides an important constraint for the initial temperature of the solar nebula, the degree of radial mixing, and the extent of condensation and evaporation [e.g. 4]. The high iron content of Mercury could be the result of chemical and thermal gradients in the solar nebula or partial removal of the silicate portion of a differentiated planet by giant impact or vaporization. These hypotheses lead to different predications, by numerous authors, of the bulk chemistry of Mercury, particularly the abundance of volatile elements.

Little is directly known of Mercury's composition and internal structure, however its high average density suggests a high metal to silicate ratio. Remote sensing suggests low FeO in the crust [5-8] and mantle [9]. The presence of an intrinsic magnetic field, possibly generated by a hydromagnetic dynamo, has led many researchers to postulate that Mercury has a molten outer core, thus demanding an alloying element, possibly sulfur, to lower the melting temperature [e.g. 10-11]. Sodium and potassium are present in the exosphere of Mercury, but it is not clear if their source is endogenic or exogenic [12]. Volatiles in the exosphere together with the intrinsic magnetic field demand consideration of a range of volatile abundances for Mercury.

Simple models of Mercury's interior have been presented based on the total mass, total radius and cosmochemical arguments of plausible planetary compositions [13-15]. But none of these studies have presented calculations of the decompressed density.

Methods: We model Mercury's interior under adiabatic self-compression using the Adams-Williamson equation with the second order Birch-Murnaghan finite strain equation of state (EOS) to estimate its decompressed density. We assume the thermal profile is adiabatic except for a thermal boundary layer at the core mantle boundary, modeled as a temperature difference between the adiabats for the core and the mantle extrapolated to zero pressure.

Our model is constrained by the total mass and radius (2440km) of Mercury along with cosmochemical constraints on densities and physical properties of likely core and mantle materials. We ignore the uncertainties in the total mass and total radius because they are much less significant than the uncertainties in the core and mantle densities and interior structure. The moment of inertia for Mercury is not accurately known and thus is not used as a constraint.

We obtained a suite of results by randomly varying six input parameters within the ranges shown in Table 2 and adjusting the core density, within the allowable range, to match the observed mass of Mercury. We assume constant thermal expansion coefficient ($\alpha_k = 2.5 \times 10^{-5}$ K^{-1}) and second Grüneisen parameter ($\delta_{Sk} = 4$) for the core.

	value
ρ^o_m	3.35 ± 0.25 g/cc
ρ^o_k	6.85 ± 1.35 g/cc
R_c	1900 ± 300 km
K^o_{Sm}	165 ± 45 GPa
K^o_{Sk}	145 ± 75 GPa
ΔT_{Sk}	500 ± 500 K

Table 2 - Input parameters and ranges for our Mercury model. From top to bottom: STP mantle [16] and core densities [16-19], core radius, STP mantle [16] and core bulk moduli [16-19], temperature difference between the core and mantle adiabats.

The composition, size, and phase of Mercury's core are poorly known, thus we consider solid and liquid cores with compositions ranging from Fe to Fe-FeS (10wt%S). We compiled bulk modulus (K) estimates of Fe and Fe-alloys, liquid and solid, from multiple studies and normalized them to STP and K'=4. The extreme high and low values set the range of core K values. We assume intermediate values of core density and bulk moduli represent intermediate compositions or layered cores. The core density and K are not independent, so we assume coupled core density and K inputs: low density (Fe-FeS cores, <7.0 g/cc) must have low K (<150GPa) and high density cores (Fe, >7.0 g/cc) must have high K values (>100GPa).

Results: Of ~17,250 cases of random input parameters meeting our requirements, 12,035 converged to match the mass of Mercury and are thus considered plausible interior structures. The plausible interior structures have decompressed densities in the range, 4.8-5.2 g/cc (Fig. 1), significantly lower than the commonly cited value of 5.3 g/cc. The range of interior structures of Mercury is illustrated with two end member models, a solid Fe core and a molten Fe-FeS (10wt%S) core (Fig. 2). Our decompressed density estimates are correlated with and most sensitive to the core K. The decompressed density estimate is most sensitive to properties of the core rather than the mantle because most of Mercury's mass (>60%) is in the core. We find that dramatic changes in the pressure derivative of K (±50%) do not result in significant changes to the decompressed density (≤1%) justifying the use of the second order EOS.

Discussion: Given our current knowledge of the composition and interior structure of Mercury and the density and elastic properties of plausible core materials, our analysis yields a mean decompressed density for Mercury of 5.1 g/cc ± 0.08 (1σ). Higher density cores (Fe) correspond to higher incompressibilities and thus result in higher decompressed densities. Likewise lower density cores correspond to molten (or partially molten) cores and/or cores with a light alloying element (here assumed to be S). These cores have lower incompressibilities and yield lower decompressed densities. The shape of the histogram of decompressed densities is sensitive to the assumed coupled core density and K inputs. However the mean mercurian decompressed density value is consistently ~5.1 g/cc as long as both Fe and Fe-FeS cores are considered.

Previous work has proposed that due to Mercury's relatively small mass, the density correction for self-compression is small and subject to little uncertainty [e.g. 1-2]. Our model indicates maximum interior pressures that are high enough for significant self-compression. For our plausible mercurian interiors, central pressures are between 30 and 45 GPa resulting in ~10-30% increase in core density from the core mantle boundary to the center of mass (Fig. 2). This result means that the decompressed density can vary significantly from the average density and there is uncertainty in decompressed density estimates.

Given the mantle and thermal conditions shown in Fig. 2, the smallest possible core (Fe) is 1770 km (~70% planet radius) and a liquid Fe-FeS (10 wt% S) core is 2170 km (~90% planet radius).

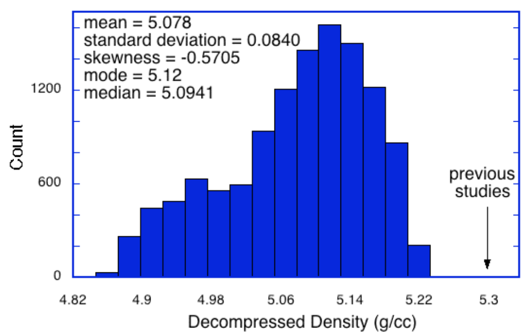

Fig. 1 - Decompressed densities from 12035 random Mercury self-compression models.

Given our input parameters, the canonical decompressed density value for Mercury (5.3 g/cc) is not obtained for any plausible interior structure. Models with a decompressed density of 5.3 g/cc require a low density, Fe-FeS liquid core (5.5 g/cc) with high incompressibility (K= 200 GPa) or a high density solid Fe core (8.1 g/cc) with an unreasonably high incompressibility (K= 520 GPa).

Models of planet accretion, low surface FeO, an intrinsic magnetic field, and the volatile-rich exosphere provide constraints on the bulk composition of Mercury. Geophysical modeling, while suffering from broad constraints, does constrain the metal content of Mercury but not the volatile content. However, our results are consistent with, but do not require, a Mercury that is not wholly depleted in volatiles. Solid Fe, solid Fe-FeS and liquid Fe-FeS cores are all plausible interior structures within our parameter space.

Better constraints on the composition, phase, and size of Mercury's core may provide insight into planet formation and the solar nebula, planetary core formation processes, including the Earth, and generation of planetary magnetic fields. Updated interior models of Mercury, incorporating results from recent high-pressure experiments can enhance the scientific return of upcoming spacecraft missions to Mercury.

Summary: We have applied new results from high-pressure experiments to model Mercury's interior and found a mean decompressed density of 5.1 g/cc (plausible range 4.8-5.2 g/cc), significantly lower than the canonical value of 5.3 g/cc.

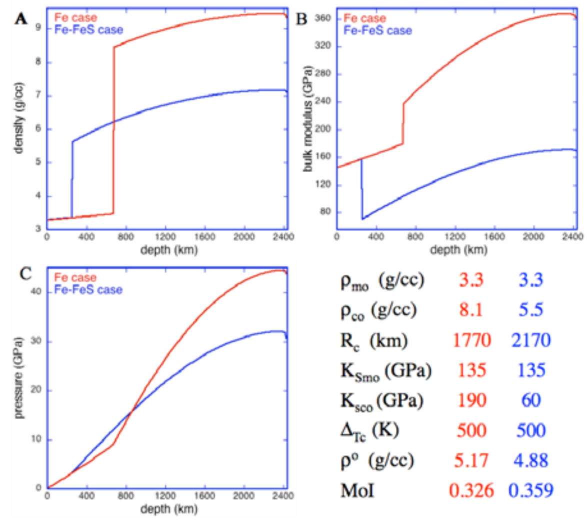

Fig. 2 - Density (A), bulk modulus (B), and pressure (C) as a function of depth for our two end-member models. The red model has a pure solid iron core [16] and the blue model has a liquid Fe-FeS core (10 wt% S) [19]. Both models have the same mantle and thermal parameters. The low pressure, low temperature input parameters and resulting decompressed density and moment of inertia for each model are shown.

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