New Insights into Mercury's Interior with the MESSENGER Mission. A. Genova[1,2], S. Goossens[2,3], E. Mazarico[3], F. G. Lemoine[3], G. A. Neumann[3], W. Kuang[3], T. J. Sabaka[3], D. E. Smith[1] and M. T. Zuber[1], [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA (antonio.genova@nasa.gov); [2]Center for Research and Exploration in Space Science and Technology, University of Maryland, Baltimore County, Baltimore, MD 21250, USA; [3]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

Introduction: The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission addressed key scientific objectives focused on the interior of the planet with dedicated magnetic and gravity investigations. The measurement of the magnetic field offset and amplitude, for example, allowed the characterization of some properties of the outer core [1]. In addition, the combination of the planet's orientation (obliquity -- angle between spin and orbital axis -- and physical longitudinal librations) with gravity measurements (degree 2 in spherical harmonics) have constrained the size of the molten outer core [2, 3].

However, there are still open questions concerning the mass distribution within the different layers of the planet interior and, in particular, nature of the solid inner core. The analysis of the entire MESSENGER radio science dataset, which includes the low-altitude campaign, enabled us to substantially improve the knowledge of Mercury's gravity field and obliquity of the spin axis. These geophysical quantities are necessary to refine the polar moment of inertia of the whole planet which bears on the level of differentiation [4].

Data and Method: We analyzed the full MESSENGER mission, e.g., the three Mercury flybys (January and September 2008, and September 2009) and the entire orbital phase (March 2011- April 2015). The radio tracking data (both range rate and range) were processed with a novel technique that is based on the co-integration and co-estimation of both the MESSENGER and Mercury orbits. This method allowed us to obtain measurements of general relativity and heliophysics parameters with substantially improved accuracies [5].

The geophysical results also greatly benefit from a better understanding of Mercury's ephemeris. Our solution provides improved accuracies of the MESSENGER orbits leading to an accurate map of the gravity anomalies and refined estimates of the spin axis coordinates (right ascension and declination). Figure 1 shows the new gravity model's (denoted HgM008) free-air gravity anomalies, shaded by Mercury Laser Altimeter (MLA) topography [6].

The estimated right ascension and declination of the pole results in a lower obliquity compared to previous estimates, which were tied to measurements of Mercury's surface [3, 6]. Our estimation of the planet's orientation permits the retrieval, for the first time, of the average obliquity of the *whole* planet, which we find in perfect agreement with the Cassini state.

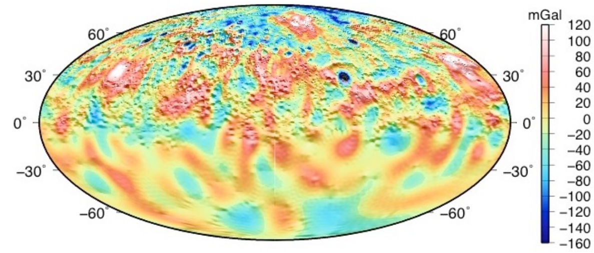

Figure 1. Free-air gravity anomalies (HgM008) on shaded MLA topographic relief.

The normalized polar moment of inertia, *c,* resulting from the new obliquity is significantly lower than the previous estimate of 0.346±0.014 [7] and with an uncertainty improved by a factor of 3 [8]. Our refined estimate of the polar moment of inertia suggests that Mercury is much more differentiated than initially thought.

To determine the interior structure of Mercury with these geophysical constraints, we implemented a Markov-chain Monte Carlo (MCMC) algorithm using two different models for Mercury's interior. Both MCMC approaches obtain solutions that match bulk density and radius and our latest estimates of the normalized polar moment of inertia, *c*, and the fractional polar moment of inertia, C_{c+m}/C.

First, we considered a 5-layer planet (inner core, two layers for the outer core, mantle, and crust) with the only two assumptions being that the density and the radius of the layers increase and decrease with depth, respectively. The parameters that are perturbed with random-walkers are:

- inner (r_{icb}) and outer (r_{cmb}) core radii;
- crust (ρ_m), mantle (ρ_m), inner (ρ_{ic}) and outer (ρ_{oc}) core (both layers) densities;
- thickness of the crust (d_c) and of the outer layer of the core (d_{oc}).

The second approach (*Multi-Layer*) also assumes a 5-layer interior, but it uses 1-km thick sub-layers for the integration of the Equation of State (EoS). This more sophisticated method retrieves models of the interior that are self-consistent and physically realistic in terms of their pressure, temperature and density profiles [9]. The parameters perturbed in this second approach are the same as in the 5-layer case, except that the densities of the inner and outer core are defined by the integration of the EoS. Instead, the Multi-layer cases used two additional parameters, the temperature at the Core-Mantle-Boundary (CMB), and the weight fraction of light elements in the core. To solve the EoS, we need to assume the elements that form an Fe-alloy in the core. For this reason, we studied several scenarios independently, with S or Si weight fractions in the core.

Results: The 5-layer MCMC approach provides internal models with moments of inertia that are fully consistent with our estimates. Figure 2 shows the ratio between the inner and outer core radii as a histogram for the samples of models that are in agreement with the measured moments of inertia. This ensemble suggests the presence of a large solid inner core with a $r_{icb} \approx 0.3\text{-}0.6\ r_{oc}$.

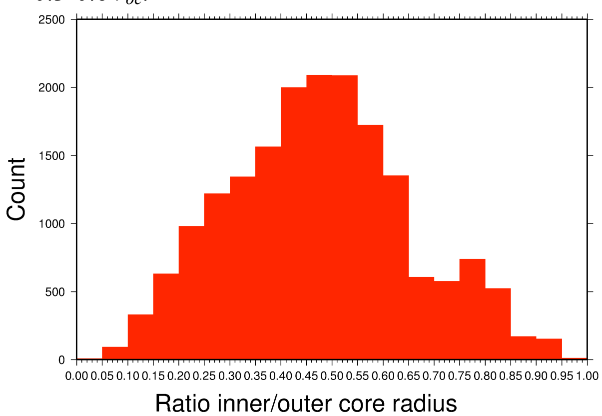

Figure 2. Ratio between the inner and outer core radii as a histogram for the samples of the 5-layer MCMC solutions.

The Multi-layer approach requires an initial assumption on the light element that is present in the core. A possible scenario is an inner and outer core of Fe-Si alloy, and a solid Fe-S layer underneath the CMB (Figure 3). Figure 4 shows the r_{icb}/r_{oc} as a histogram for the Multi-layer ensemble. These results still suggest the presence of a solid inner core with a $r_{icb} \approx 0.3\text{-}0.7\ r_{oc}$. The assumption of one light element in the different layers of the solid and liquid core may also limit the interpretation of these results since a mixture of elements, such as S, Si and Ni, is expected [10].

Summary: Our new measurements of the polar moments of inertia of the whole planet and of the outer layers (crust+mantle) suggest a more differentiated internal structure for Mercury. These geophysical quantities improve the constraint on the size of the solid inner core. The MCMC method enables us to retrieve the properties of the different layers of the interior including the size of the core. Furthermore, simulations of Mercury's magnetic field dynamo confirm that the presence of a solid inner core with a $r_{icb} \leq 0.5\ r_{oc}$ is consistent with the magnetic field, thus providing an additional constraint on the size of the solid inner core.

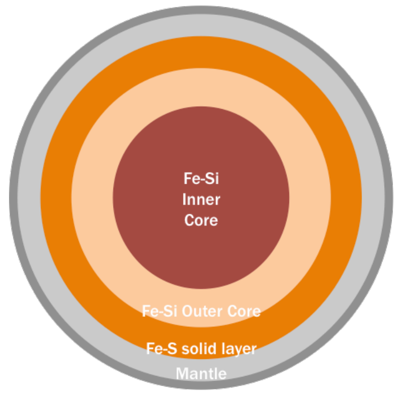

Figure 3. Interior modeling for the Multi-layer MCMC case [9].

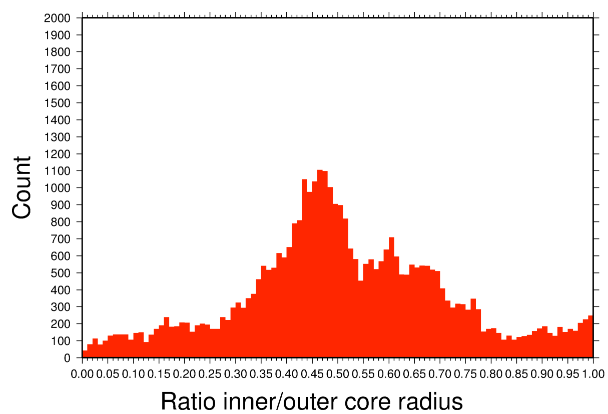

Figure 4. Ratio between the inner and outer core radii as a histogram for the samples of the Multi-layer MCMC solutions.

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