Earth and Planetary Science Letters 377–378 (2013) 62–72

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The interior structure of Mercury constrained by the low-degree gravity field and the rotation of Mercury

A. Rivoldini *, T. Van Hoolst

Royal Observatory of Belgium, Avenue Circulaire 3, B-1180 Brussels, Belgium

ARTICLE INFO

Article history:
Received 23 November 2012
Received in revised form 4 July 2013
Accepted 16 July 2013
Available online 25 August 2013
Editor: Christophe Sotin

Keywords:
Mercury
interiors
geodesy
libration
obliquity

ABSTRACT

Among all the planets of the solar system Mercury stands out, because it has a relatively high average density compared to its size. To account for this high density, Mercury's core radius is thought to be larger than $\frac{3}{4}$ of its radius. Here, we use recent data about the second-degree gravity field coefficients and measurements about Mercury's rotation – obliquity and 88-day libration amplitude – to obtain constraints on Mercury's interior structure. By combining the gravity field data and the obliquity measurements, the mean moment of inertia of Mercury can be determined. If the coupling between the core and the mantle is neglected then the gravity field data together with the libration amplitude provide an estimate of Mercury's silicate shell moment of inertia. However, since the effect of core–mantle coupling on the 88-day libration amplitude can be about as large as the libration amplitude's uncertainty (Van Hoolst et al., 2012) we use as data the mean moment of inertia and the 88-day libration amplitude to infer knowledge about Mercury's interior structure.

We use two different interior modeling approaches. The first one is based on Rivoldini et al. (2009) and uses a set of 5 mantle mineralogies, a crust with a given thickness and density, and two mantle temperatures. In the second setting the density of the mantle, the thickness, and density of the crust, and the temperature of the core mantle boundary are parameters of the model. In both cases, we assume that the core is made of iron and the light element sulfur and use the temperature, pressure, and the concentration of sulfur in the core together with the melting temperature of iron–sulfur to determine the radius of the inner core.

Our results show that the data provide a strong constraint on the radius of the core and on its average density or equivalently on the fraction of sulfur in the core if sulfur is the only light element in the core. We find that Mercury has a core radius of 2004 ± 39 km, an average core density of 7233 ± 267 kg/m^3, and a sulfur fraction of 4.5 ± 1.8 wt%. The other parameters of the model, in particular the density of the mantle are however, only weakly constrained by the data. The geodesy data can also not distinguish between a fully liquid core and the existence of an inner core.

1. Introduction

Prior to the orbit insertion of the MESSENGER spacecraft only the mass and radius of Mercury provided a quantitative constraint on its interior structure. Other observations like the presence of a global magnetic field (Connerney and Ness, 1988) – observed by Mariner 10 – and the amplitude of its 88-days libration (Margot et al., 2007) provide support for a liquid part inside Mercury's core but did not allow constraining for example the core size and composition. By assuming that the core is made of iron and of the light element sulfur and five different mineralogies for the mantle Rivoldini et al. (2009) have shown that the mean density of Mercury implies that its core is larger than 1828 km and that the sulfur concentration of the core is smaller than about 11 wt% if the silicate shell of the planet is at least 240 km thick. Moreover, those interior structure models can have an inner core if their sulfur concentration is below 5 wt%, since for larger sulfur concentrations the melting temperature of Fe–FeS is below the core temperature. In the approach of Rivoldini et al. (2009) the size of an inner core is determined from the planet's thermal state, pressure, sulfur concentration, and from the melting temperature of Fe–FeS. In particular, the temperature at the core–mantle boundary was assumed to be between 1850 K and 2000 K. Similar results about the interior structure of Mercury have been obtained by Hauck et al. (2007) and Riner et al. (2008).

Further constraints on the interior structure of Mercury are provided by the polar moment of inertia of the planet and of its silicate shell. Both can now be estimated by combining the degree-two coefficients of Mercury's gravity field, recently determined by

* Corresponding author.
E-mail addresses: Attilio.Rivoldini@oma.be (A. Rivoldini), Tim.VanHoolst@oma.be (T. Van Hoolst).

0012-821X/$ – see front matter
http://dx.doi.org/10.1016/j.epsl.2013.07.021

tracking the MESSENGER spacecraft (Smith et al., 2012), and by radar measurements of Mercury's spin state (Margot et al., 2007). As moments of inertia are dependent on the planet's mass distribution they provide further constraints on the interior structure and in particular on the radius of the core and on the light element content of the core. According to the interior modeling of Smith et al. (2012), these data imply that the outer radius of the liquid part of the core is about 2040 ± 37 km. A more recent analysis by Hauck et al. (2013), using the newest rotation data by Margot et al. (2012), estimate that the core radius is 2020 ± 30 km (errors are one standard deviation).

Here we study to what extent the mass, radius, obliquity, 88-day libration amplitude, and second degree gravity field coefficients can constrain basic parameters of the interior structure of the planet. Unlike Smith et al. (2012) and Hauck et al. (2013) we do not use the silicate shell (crust and mantle) moment of inertia to constrain the interior models since coupling effects between the silicate shell and the core, in particular gravitational coupling between the shell and the inner core, on the libration amplitude can be as large as the uncertainty on the 88-day libration amplitude (Van Hoolst et al., 2012). Since the core–shell coupling effect on the libration amplitude depends on the details of the interior structure model the shell moment of inertia cannot be estimated independently from the model as it is the case when this coupling is neglected. In order to quantify the impact of the shell–core coupling on the parameter inferences we compare our results with those obtained when coupling is neglected. We use two different modeling approaches. The first approach uses detailed models in which all physical quantities of the interior like density and temperature are depth-dependent and in which the depth-dependent mantle mineralogy is derived from five different mantle compositions (Verhoeven et al., 2009; Rivoldini et al., 2009). For the temperature inside the mantle we consider both hot and cold temperature profiles. In the second approach, we consider the mantle to be homogeneous (uniform density), but assume a larger range for the mantle density and for the mantle temperature.

This article is organized as follows: In Section 2 we describe the two types of modeling approaches we use for the interior structure of Mercury. Section 3 discusses the relation between the data used to constrain the interior structure parameters and their relation to the low-degree gravity field and rotation measurements. Since the relation between the model parameters and the data is non-linear and since the number of parameters is larger than the number of data we use a Bayesian inversion method to infer knowledge about the parameters. The inversion method and the prior knowledge on the parameters are introduced in Section 4. The next section describes and compares the results for the considered cases. Finally, in the last section we present our conclusions.

2. Interior model

We assume a triaxial spheroidal planet, with a shape that can be represented by spherical harmonics of degree zero and two, with a rigid silicate shell – subdivided into crust and mantle – and a core which is in hydrostatic equilibrium with respect to the shell. The geometric flattenings of the surface and core are parameters of the model. Since the planet's mass and mean moment of inertia are invariant with respect to a degree-two deformation (Rochester and Smylie, 1974) the depth-dependent density profile is calculated for an equivalent – of same mass and mean moment of inertia – spherically symmetric interior model. In agreement with spin rate measurement and with the presence of a global magnetic field we only discuss models with at least a partially liquid core.

2.1. *Equivalent spherically symmetric model of the interior*

The crust of the spherical model is characterized by its average density and thickness. In the first approach we use 5 different mineralogies (denoted by FC, MA, TS, MC, and EC) for the Hermean mantle, as in Rivoldini et al. (2009). These mantle mineralogies have been derived from models about Mercury's bulk composition that are based on constraints provided by surface spectra measurements and from assumptions about Mercury's formation in the Solar System (Verhoeven et al., 2009; Rivoldini et al., 2009). However, the 5 considered mantle models provide only a limited set of density profiles for the mantle and models with quite different mantle densities are conceivable. Therefore, in the second approach we use a rather large range of average mantle densities to characterize the mantle of Mercury. Independent of the precise composition of the mantle, the pressure conditions in the mantle of Mercury are too low, below 8 GPa, for any of the principal mineral phase transitions in the lower mantle of the Earth or Mars to occur (e.g. Bertka and Fei, 1997). Hence, the variations of the density with depth are expected to be small. As the mantle is relatively thin compared to the radius of the planet, the resulting differences in the planet's and the shell's moment of inertia and on the 88-day libration amplitude between a model with a depth-dependent density and a model with a uniform density of the same mass are smaller than the measured uncertainties on those quantities. For the five considered mantle mineralogies the differences are smaller than 11% of the moment of inertia uncertainties.

Mercury's core is assumed to consist of iron and sulfur. Among the light elements sulfur has been found in many nickel–iron-meteorites, and is therefore ubiquitously invoked as a major candidate for light elements in planetary cores of terrestrial planets. Other possible light elements are silicon, oxygen, carbon, and hydrogen. The light element composition of the core depends principally on the pressure, temperature, and redox conditions during core formation. Under oxidizing conditions sulfur and oxygen are siderophile, but only sulfur is readily dissolved into liquid iron since at the expected pressures of Mercury's core formation the solubility of oxygen is small and remains below 1 wt% for pressures below 10 GPa (Tsuno et al., 2007). Given the likely reducing conditions at Mercury's formation (Malavergne et al., 2010; Nittler et al., 2011; Peplowski et al., 2011), other more lithophile light elements like silicon and carbon are expected to behave more siderophile at core formation and could also be included in certain amounts in the core. We will briefly address some of the implications of the addition of silicon in the core in the discussion section. However, the absence of accurate data on thermoelastic and melting properties of iron–silicon and iron–carbon compounds in iron–sulfur systems at Mercury's core conditions refrains their usage in precise models of Mercury's interior structure.

For the outer core we suppose an ideal Fe–FeS liquid solution with a sulfur concentrations below the Fe–FeS eutectic concentration. Since for those sulfur concentrations only a very small amount of sulfur can be dissolved in solid iron at Mercury's core temperature and pressure conditions (Li et al., 2001) we assume an inner core made of pure γ–Fe – the iron phase stable at Mercury's core conditions. The density of the core depends on its sulfur concentration and on the local pressure and temperature conditions. The radius of the inner core is determined from the Fe–FeS melting temperature, the pressure and temperature inside the core, and from the concentration of sulfur inside the core (Rivoldini et al., 2011). On cooling solid γ–Fe starts to crystalize out of the solution when the local temperature drops below the local liquidus temperature. With the melting temperature considered here, iron first solidifies at the core mantle boundary and precipitates inwards to form the inner core. For both the core and the inner core we assume that the heat transport is by convection and that no ra-