Physics of the Earth and Planetary Interiors 224 (2013) 68–76

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Composition of Mars constrained using geophysical observations and mineral physics modeling

Yi Wang [a,*], Lianxing Wen [b,a], Donald J. Weidner [b]

[a] Laboratory of Seismology and Physics of Earth's Interior, University of Science and Technology of China, Hefei, Anhui 230026, China
[b] Department of Geosciences, State University of New York at Stony Brook, Stony Brook, NY 11794, United States

ARTICLE INFO

Article history:
Received 25 April 2013
Received in revised form 15 July 2013
Accepted 1 August 2013
Available online 21 August 2013
Edited by K. Hirose

Keywords:
Mars composition
Mean moment of inertial
Mineral physics modeling
Density distribution

ABSTRACT

We use the total mass, possible core radius and the observed mean moment of inertia factor of Mars to constrain mineralogical and compositional structures of Mars. We adopt a liquid Fe–S system for the Martian core and construct density models of the interior of Mars for a series of mantle compositions, core compositions and temperature profiles. The moment of inertia factor of the planet is then calculated and compared to the observation to place constraints on Mars composition. Based on the independent constraints of total mass, possible core radius of 1630–1830 km, and the mean moment of inertia factor (0.3645 ± 0.0005) of Mars, we find that Fe content in the Martian mantle is between 9.9 and 11.9 mol%, Al content in the Martian mantle smaller than 1.5 mol%, S content in the Martian core between 10.6 and 14.9 wt%. The inferred Fe content in the bulk Mars lies between 27.3 and 32.0 wt%, and the inferred Fe/Si ratio in Mars between 1.55 and 1.95, within a range too broad to make a conclusion whether Mars has the same nonvolatile bulk composition as that of CI chondrite. We also conclude that no perovskite layer exists in the bottom of the Martian mantle. Based on the inferred density models, we estimate the flattening factor and J_2 gravitational potential related to the hydrostatic figure of the rotating Mars to be $(5.0304 \pm 0.0098) \times 10^{-3}$ and $(1.8151 \pm 0.0065) \times 10^{-3}$, respectively. We also discuss implications of these compositional models to the understanding of formation and evolution of the planet.

1. Introduction

Compositions of the mantle and the core of the terrestrial planets are important for our understanding of the formation and evolution of the planets. There are two hypotheses on the evolution of the planets. One hypothesis states that the different mean densities of the terrestrial planets indicate different Fe/Si ratios in their bulk composition, which reflects an Fe/Si fractionation in the solar nebula according to the distances the planets are away from the Sun (Urey, 1952; Ganapathy and Anders, 1974). The other hypothesis states that the terrestrial planets all have the bulk composition with the same nonvolatile element abundances as those of CI carbonaceous chondrite (Ringwood, 1959). Later, this hypothesis is revised to be that the terrestrial planets consist of two chondritic components, with one completely reduced and the other oxidized, but both components have the same bulk composition of CI chondrite (Wanke and Dreibus, 1988). Based on this hypothesis, the terrestrial planets would have the same Fe/Si ratio, but different ratios between metallic Fe and the total Fe. Most geosciences studies conclude that it is possible for Earth to have the same bulk composition as that of chondrite (e.g. Allegre et al., 2001), but some studies suggest a different bulk composition of Earth (e.g. Javoy et al., 2010). Understanding the composition of other terrestrial planets can help us to evaluate these two hypotheses.

One obvious candidate planet is Mars. Many studies analyze the SNC (Shergottites, Nakhlites and Chassigny) meteorites to study bulk composition of Mars, including its major elements (e.g. Dreibus and Wanke, 1985) and isotopes (e.g. Lodders and Fegley, 1997; Sanloup et al., 1999; Mohapatra and Murty, 2003). The bulk compositional models from all these studies suggest that, comparing to Earth, Mars has more FeO in the mantle and more S in the core.

Physical data, such as mass, size, moment of inertia (MOI) factor can also be used to constrain bulk composition of Mars (Anderson, 1972; Mocquet et al., 1996; Bertka and Fei, 1998; Rivoldini et al., 2011). Recent missions to Mars have provided more precise measurements of the MOI factor. Previous study (Bertka and Fei, 1998) uses the polar MOI factor and mineral physics data to constrain Mars composition. The study assumes a solid core and a fixed mantle composition. They conclude that the bulk composition

* Corresponding author. Tel.: +86 551 63600715.
E-mail addresses: yiwang25@ustc.edu.cn (Y. Wang), Lianxing.Wen@sunysb.edu (L. Wen), dweidner@notes.cc.sunysb.edu (D.J. Weidner).

0031-9201/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.pepi.2013.08.005

of Mars is different from that of CI chondrite. A recent study, however, has suggested a liquid core in Mars (Yoder et al., 2003). Recent progress in mineral physics now also allows us to quantitatively predict velocity and density profiles for various mantle compositions, core compositions and temperature profiles within the planets (Weidner and Wang, 1998; Wang et al., 2006, 2008, 2009). In this study, we adopt a liquid Fe–S system in the core and test a variety of mantle compositions. Our mineral physics modeling method allows us to systematically search for possible compositions in the mantle and the core. We construct one-dimensional (1-D) density models of the interior of Mars for a series of compositions of the mantle and the core, and calculate the MOI factors. Comparing the calculated MOI factors with the observation, we place constraints on the mantle and core compositions in Mars. We discuss our methods in Section 2, modeling results in Section 3, and the effects of assumed crust model, temperature profile, as well as comparisons to previous studies, predictions of other geophysical parameters and non-existence of a perovskite layer in the bottom of the Martian mantle in Section 4.

2. Method

2.1. Moment of inertia (MOI) factor

MOI factor around a particular rotation axis is defined as $C = \int r^2 dm/MR^2$, where dm is mass integral, r the distance of dm to the rotation axis, M the total mass, and R the mean radius of the planet. Since Mars is not a perfect sphere, the MOI of the planet depends on the choice of axis. The polar MOI factor is the one with respect to the planets rotation axis. The mean MOI factor is defined as $I = \frac{1}{3}(A + B + C)$, where A and B are the principal equatorial MOI factors, and C is the polar MOI factor.

With the knowledge of a planets total mass, the mean radius R and the MOI factor, we can place constraints on density models inside the planet, which can be linked to its composition based on mineral physics modeling. Since our 1-D density models do not include the hydrostatic figures, we should use the inferred mean MOI factor instead of the polar MOI factor. Recent space missions provide us precise measurement of the MOI of Mars. Konopliv et al. (2011) calculate the mean MOI factor of Mars to be 0.3645 ± 0.0005 based on the measurements of Mars Reconnaissance Orbiter, Mars Global Survey, Odyssey, Pathfinder and Viking.

2.2. Mineral physics modeling

In mineral physics modeling, density distribution in the Martian mantle are calculated following the procedures outlined in Weidner and Wang (1998), Wang et al. (2006, 2008, 2009). In order to calculate the velocity and density for a certain mantle temperature and composition, we need to know the stable minerals and volume fraction, chemical composition and physical properties of each stable mineral under the condition of the mantle temperature, pressure and composition. We use phase equilibria data to define the stable assemblages at relevant pressures and temperatures, cation distribution data to define the chemical composition of each stable phase. This information, along with our current estimates of physical properties of these phases, provides a mineralogical model with volume fractions of each phase along with aggregate velocities and densities. In this study, we use the phase diagram for the earth upper mantle reported by Gasparik Chapter 10 in (Gasparik, 2003) as a template for defining the evolution of the system through mantle phase transformations, and consider both olivine and garnet components and their chemical interactions. In the phase diagram, we also ignore a low-pressure mineral, Al-rich pyroxene, and a phase transformation from Al-rich pyroxene to garnet occurring at 2 GPa (about 160 km depth), as the density difference between 50–160 km depth caused by the low-pressure mineral is less than 1%, and has small effect on MOI factor. Since in the mantle, most of Al is in garnet and perovskite, and the Al contents of other minerals are negligible, we assume that all Al is in garnet and perovskite with other minerals Al-free (Gasparik, 1990). For every mineral, we extrapolate their elastic properties to certain pressures and temperatures in the Martian mantle using the third order Birch–Murnaghan equation of state (Birch, 1947). Based on the volume and the mole fraction of every stable mineral, we calculate the volume fraction and density of each stable mineral, and then the combined density of the assemblage.

We use the temperature model from Fei and Bertka (2005) study as a reference temperature profile inside Mars.This reference temperature profile is below the mantle solidus and above the melting temperature of Fe–14.2 wt%S (Bertka and Fei, 1998 Martian core model) but below the melting temperature of pure Fe. So Mars has a solid mantle and a liquid/solid core based on this temperature profile. We also test the effects of different temperature profiles. We use the composition model of Wanke and Dreibus (1988) as a reference mantle composition model (Table 1), and test different Fe contents and Al contents in the Martian mantle. As a recent study (Yoder et al., 2003) suggests that the Martian core is liquid, we adopt a liquid Fe–S system in the Martian core. We calculate core density profiles for various S contents based on the measurements of elastic properties for pure liquid Fe (Anderson and Ahrens, 1994) and for liquid Fe with 10 wt% S (Balog et al., 2003; Sanloup et al., 2000) (Table 2), assuming the elastic properties of the system linearly change with S content. A recent study (Wieczorek and Zuber, 2004) estimates that the average crust thickness of Mars to be between 38 and 62 km, and the crust density between 2.7 and 3.1 g/cm^3. In our modeling, a Martian crust with a thickness of 50 km and a density of 3.0 g/cm^3 is adopted, but we also test the effects of the crust thickness and density in the reported range of parameters.

We calculate density profiles in the mantle and the core for a series of mantle and core compositions. Fig. 1 shows an example of mineral assemblages (Fig. 1b) and a density profile (Fig. 1a) inside Mars calculated based on Fei and Bertka (2005) temperature model, Wanke and Dreibus (1988) mantle composition model and a liquid Fe–S system with 12 wt% S in the core. For a particular mantle composition, core composition and temperature profile, only one core radius can be inferred to fit the total mass of Mars. For each density model, we calculate the MOI factors and use possible core radius (1630–1830 km) (Konopliv et al., 2011) and the inferred mean MOI factor (0.3645 ± 0.0005) (Konopliv et al., 2011) to place constraints on Mars composition.

3. Modeling results

Density in the Martian core is influenced by its S content. A higher S content results in a lower density in the core, and requires a larger core radius to fit the total mass (Fig. 2a). For a fixed mantle density, a less dense and larger core would result in a larger mean MOI factor. A lower S content would do the opposite (Fig. 2b).

Fe content in the mantle has significant effects on mantle density and the mean MOI factor of Mars. Increasing Fe content would increase the density of every mineral in the mantle. At the same time, increasing Fe content would also result in increasing

Table 1
Reference mantle composition model of Mars (Wanke and Dreibus, 1988).

	MgO	FeO	CaO	SiO_2	Al_2O_3
Wt%	30.20	17.90	2.45	44.40	3.02
Mol%	40.72	13.54	2.37	40.16	3.21