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Density profile of an SNC model Martian interior and the moment-of-inertia factor of Mars

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Abstract

The density profile of an SNC model Martian interior is calculated from the results of previous experimental work that determined the modal mineralogy of the model mantle up to Martian core–mantle boundary pressures. The moment-of-inertia factor of Mars is calculated as a function of core composition and crustal thickness using the SNC model mantle density profile as a constraint. Two sets of calculations are performed. In the first, the bulk composition of the planet is not constrained to a C1 chondrite composition. Assuming a Martian crust density of 2.7–3.0 g/cm^3, a crust thickness of 25–150 km, and the core composition proposed by Dreibus and Wänke, Fe 14 wt% S, the calculated moment-of-inertia factor ranges from 0.367 to 0.357. These models include a perovskite-bearing zone in the Martian interior. Considering core compositions ranging from pure Fe to pure FeS changes the moment-of-inertia factor by only ±0.001, but at higher S abundances, core size increases, such that the depth of the core–mantle boundary is shallower than the depth of perovskite stability. In the second set of calculations, the bulk composition of the planet is constrained to a C1 composition requiring a crust thickness of 180–320 km, assuming a crust density of 2.7–3.0 g/cm^3. The calculated moment-of-inertia factor is 0.354 and a perovskite-bearing layer is absent from the Martian interior. As it is unlikely that the thickness of the Martian crust is greater than 100 km, the bulk composition of Mars cannot be constrained to a C1 chondrite composition as proposed by the Dreibus and Wänke model (G. Dreibus, H. Wänke, Meteoritics 20 (1985) 367–382). In order to determine if the Martian mantle is more iron-rich than the Earth's mantle, we may need not only an improved estimate of the moment-of-inertia factor of Mars, but also tighter constraints on Martian crust thickness and density. The absolute degree of iron-enrichment, however, cannot be specified without also knowing the size of the Martian core. A moment-of-inertia factor of less than 0.342 is not geochemically feasible, because it requires that the mantle of Mars contains no iron. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Mars; planetary interiors; density; geophysical profiles

1. Introduction

Our understanding of the structure and composition of the Martian interior is limited by the absence of important geophysical constraints. The mass and radius of the planet is known, but the moment-of-inertia factor of Mars is uncertain, and we have no seismic data. The moment-of-inertia factor of Mars is uncertain because of the poor accuracy associated with measurements of the Martian spin pole precession rate. As a result, calculations of the mo-

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Table 1
Moment-of-inertia factor of Mars

Binder, 1969 [30]	0.370
Binder and Davis, 1973 [31]	0.377
Reasenberg, 1977 [3]	0.365
Kaula, 1979 [4]	0.365
Bills, 1989 [2]	0.345
Bills and Rubincam, 1995 [17]	0.325–0.365

Table 2
Bulk mantle compositions

	Earth	Mars		
	KLB [32]	Morgan and Anders [9]	Dreibus and Wänke [7]	MB This study
SiO_2	44.48	42.1	44.40	43.68
TiO_2	0.16	–	0.14	–
Al_2O_3	3.59	6.5	3.02	3.13
FeO	8.10	16.0	17.90	18.71
MnO	0.12	–	0.46	–
MgO	39.22	30.2	30.20	31.50
CaO	3.44	5.3	2.45	2.49
Na_2O	0.30	–	0.50	0.50
P_2O_5	0.03	–	0.16	–
Cr_2O_3	0.31	–	0.76	–
Mg#	89.6	77.1	75.0	75.0

Values are in wt%, except for Mg#.
Mg# = atomic $[Mg/(Mg + Fe^{2+}) \times 100]$.

ment-of-inertia factor are highly sensitive to models for the distribution of non-hydrostatic stresses about the Tharsis Plateau region of Mars [1]. Estimates of the moment-of-inertia factor of Mars are listed in Table 1. The larger values imply a denser or more iron-rich mantle than the lower values. Bills [2] has argued that the generally accepted moment-of-inertia value of 0.365 [3–5] may be too high and that a lower value, 0.345, which would imply a lower abundance of iron in the Martian mantle, may be possible. Although we may predict that the Martian interior includes a core, without more precise calculations of the moment-of-inertia factor there is a large uncertainty in core size, core composition, and mantle composition.

A successful completion of the Mars Pathfinder and/or the Mars Global Surveyor mission will result in a decrease in the uncertainty of the Martian moment-of-inertia factor from 10 to ~1% [1]. In addition, the topography and gravity data to be obtained from the Mars Global Surveyor mission will help constrain Martian crustal thickness, an important parameter in models of the interior structure of Mars that are derived using the moment-of-inertia factor. The purpose of this paper is to explore the relationship between one geochemical model for the composition of the Martian interior, the Dreibus and Wänke [6,7] model, and past and future estimates of the moment-of-inertia factor of Mars.

Most models for the composition of the Martian interior base their calculation of mantle iron content on an estimate of the moment-of-inertia factor [8–10]. These calculations suggest that the Martian mantle is more iron-rich than the Earth's mantle. The Dreibus and Wänke [7] model of Martian mantle composition is derived independent of the moment-of-inertia factor. Dreibus and Wänke [7] used element correlations between measured ratios in the SNC meteorites and chondritic abundances to derive a mantle composition that is also iron-rich compared with the Earth's mantle (see Table 2). The assumptions inherent in their approach are outlined in Refs. [11,12]. Bertka and Fei [11] performed high-pressure multi-anvil experiments with an analog of the Dreibus and Wänke [7] composition to determine its modal mineralogy up to core-mantle boundary pressures along a model areotherm, i.e. a P–T profile of the Martian interior. In this paper, we report the mantle density profile calculated from the results of these high-pressure experiments. We also report the results of calculations of the moment-of-inertia factor as a function of core composition and crustal thickness, using the SNC model mantle density profile as a constraint.

2. Density profile calculation

The modal mineralogy of an analog of the Dreibus and Wänke [7] mantle composition, denoted MB, was determined up to 23.5 GPa along a high-temperature areotherm [11]. The MB model upper mantle consists of olivine, garnet, clinopyroxene, and orthopyroxene. The dominant phase assemblage in the transition zone, which is marked by the appearance

Table 3
Parameters used for density profile calculations

Phases	V^0_{298} (cm^3/mol)	$\alpha(T) = \alpha_0 + \alpha_1 T + \alpha_2 T^{-2}$			K_0 (GPa)	K_T'	$(\partial K_T/\partial T)_P$ (GPa/K)
		α_0 (10^4)	α_1 (10^8)	α_2			
Olivine							
Mg_2SiO_4	43.60	0.3034	0.7422	−0.5381	129.0	5.37	−0.0224
Fe_2SiO_4	46.29	0.2386	1.1530	−0.0518	137.9	4.00	−0.0258
β-Phase							
Mg_2SiO_4	40.52	0.2893	0.5772	−0.8903	174.0	4.00	−0.0323
Fe_2SiO_4	43.15	0.2319	0.7117	−0.2430	166.0	4.00	−0.0215
Spinel							
Mg_2SiO_4	39.49	0.2497	0.3639	−0.6531	183.0	4.30	−0.0348
Fe_2SiO_4	42.03	0.2697	0.0000	−0.0000	197.0	4.00	−0.0375
Pyroxene							
$Mg_2Si_2O_6$ (ortho-)	62.67	0.2947	0.2694	−0.5588	107.0	4.20	−0.0200
$Fe_2Si_2O_6$ (ortho-)	65.94	0.3930	0.0000	−0.0000	101.0	4.20	−0.0200
$Mg_2Si_2O_6$ (clino-)	62.99	0.2947	0.2694	−0.5588	107.0	4.20	−0.0200
$Fe_2Si_2O_6$ (clino-)	65.89	0.3930	0.0000	−0.0000	101.0	4.20	−0.0200
$CaMgSi_2O_6$ (clino-)	66.04	0.3330	0.0000	−0.0000	113.0	4.80	−0.0200
$CaFeSi_2O_6$ (clino-)	67.87	0.2980	0.0000	−0.0000	119.0	4.00	−0.0200
Garnet–majorite							
$Mg_3Al_2Si_3O_{12}$	113.08	0.2311	0.5956	−0.4538	179.0	4.00	−0.0220
$Fe_3Al_2Si_3O_{12}$	115.43	0.1776	1.2140	−0.5071	175.0	4.00	−0.0220
$Ca_3Al_2Si_3O_{12}$	125.12	0.1951	0.8089	−0.4972	168.0	6.20	−0.0220
$Mg_4Si_4O_{12}$	114.32	0.2311	0.5956	−0.4538	161.0	4.00	−0.0220
Perovskite							
$MgSiO_3$	24.45	0.3156	0.9421	−0.3271	262.0	4.00	−0.0550
$FeSiO_3$	25.60	0.3156	0.9421	−0.3271	287.2	4.00	−0.0596
$CaSiO_3$	27.32	0.3156	0.9421	−0.3271	281.0	4.00	−0.0220
Magnesiowüstite							
MgO	11.25	0.3768	0.7404	−0.7446	160.3	4.13	−0.0272
FeO	12.25	0.3203	0.6293	0.0000	146.0	4.00	−0.0200
Iron–iron sulfide							
Fe (fcc)	7.09	0.7700	0.0000	−0.0000	170.0	4.00	−0.0200
FeS(IV) at 800 K	17.79	0.6852	0.0000	−0.0000	54.0	4.00	−0.0200

Data sources: Smyth and McCormick [33]; Fei et al. [34], Mao et al. [35], Boehler et al. [36], Fei et al. [37], Fei [38], and Knittle [39].

of γ-spinel at 13.5 GPa, is γ-spinel plus majorite. The lower mantle assemblage is Mg–Fe silicate perovskite, magnesiowüstite, and majorite. The mineral compositions and modal abundances of the MB high-pressure assemblages are given in Ref. [11]. These assemblages are used to calculate the density of the MB model mantle as a function of pressure and temperature with a Birch–Murnaghan equation of state. A detailed description of the calculations is given in Fei et al. [13]. The database for the end-member phases used in these calculations is given in Table 3. The calculated mantle density profile is shown in Fig. 1.

The mantle density profile shown in Fig. 1 assumes a crustal density of 3.0 g/cm^3 and a crust thickness of 50 km. Uncertainties in Martian crust density and thickness are discussed below. The density increase marking the beginning of the transition zone at 13.5 GPa is shown in Fig. 1, as is an increase in density at 17 GPa that is produced by the complete replacement of clinopyroxene by majorite and β-phase by γ-spinel. The density increase at 22.5

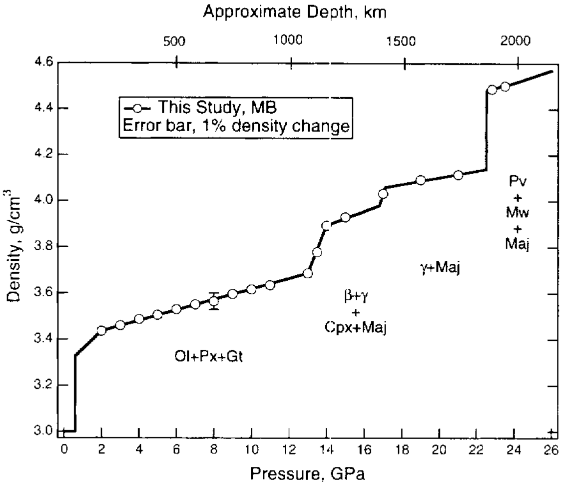

Fig. 1. Density profile of the Dreibus and Wänke [7] model Martian mantle. Mantle density calculated from the experimental results of [11] are shown with circles. The profile assumes a 50-km, 3.0-g/cm^3 crust.

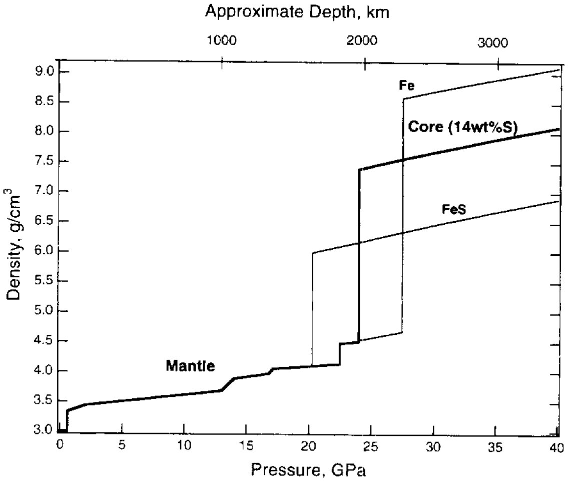

Fig. 2. Density profile of the Dreibus and Wänke [7] model Martian mantle and density profiles for a range of model core compositions, Fe to FeS. The mantle profile assumes a 50-km, 3.0-g/cm^3 crust.

GPa marks the transition of spinel to Mg–Fe silicate perovskite plus magnesiowüstite.

A complete density profile of the Martian interior will also include an increase in density at the core–mantle boundary. The composition and physical state of the Martian core is unknown. The weak magnetic field detected by the Russian mission [14] and the Phobos 2 mission [15] is consistent with either an entirely liquid or entirely solid Martian core [12,16]. The Martian core composition derived from the SNC meteorite model is sulfur-rich, consisting of Fe with 14.2 wt% S, 7.6 wt% Ni, and 0.4 wt% Co [7]. The density increase at the core mantle boundary is calculated by using P–V–T equations of state of high-PT phases of Fe (γ-Fe) and FeS (FeS(IV)). The results of these calculations are shown in Fig. 2. The database for the end-member phases used in these calculations is given in Table 3. The magnitude of the increase in density at the core–mantle boundary, as well as the depth of the boundary, depends on the core composition. The calculation of the depth of the core–mantle boundary is described below. Note that the presence of a very sulfur rich core, such as FeS, would result in the absence of the transition from spinel to Mg–Fe silicate perovskite plus magnesiowüstite in the Martian mantle.

3. Moment-of-inertia factor calculation

The mantle and core density profiles can be used to calculate the mass distribution of the planet. The mass inside a radius, r, is obtained via:

$$M(r) = 4\pi \int_0^r r^2 \rho(r) \mathrm{d}r \qquad (1)$$

where $M(r)$ and $\rho(r)$ are the mass and density as a function of radius (r), respectively. Having determined the density distribution which is necessary to satisfy the mass constraint for a given core composition, the mean moment of inertia, I, is calculated from the following relation:

$$I = 8/3\pi \int_0^R r^4 \rho(r) \mathrm{d}r \qquad (2)$$

The moment-of-inertia factor, MIF, is defined as:

$$\mathrm{MIF} = I/(MR^2) \qquad (3)$$

where M and R are the mass and radius of the planet, respectively.

These calculations were performed using the mantle density profile determined for the Dreibus and Wänke [7] model mantle and the core density profiles calculated for core compositions ranging from pure Fe to FeS. The effect of variation in the temperature profile of the Martian interior, as well as uncertainties in Martian crust thickness and density,

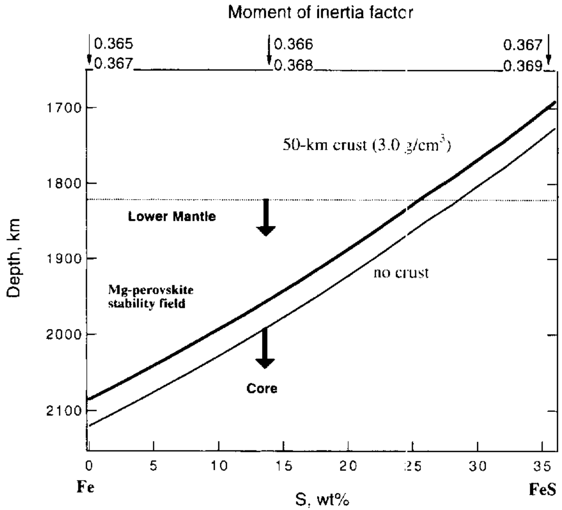

Fig. 3. Moment-of-inertia factor and depth to the core–mantle boundary as a function of core composition and crustal thickness. The dotted line marks the depth to the perovskite stability field, the beginning of the lower mantle. The bold curve illustrates the depth to the core–mantle boundary assuming a 50-km-thick crust, 3.0 g/cm^3, and the light curve the depth assuming no crust. The moment of inertia factor, calculated for three different core compositions, is also shown. The results for the model which includes a crust are shown in the upper row, and the results for the crust absent scenario in the bottom row.

were also evaluated. The results of these calculations are shown in Fig. 3.

In Fig. 3 the depth to the core–mantle boundary is shown as a function of core composition and crustal thickness. Assuming a zero crustal thickness, if the Martian core contains less than 30 wt% S, the interior will include a perovskite-bearing lower mantle. The moment-of-inertia factor calculated for a pure Fe core, a FeS core and the Dreibus and Wänke [7] preferred model of Fe with 14 wt% S is also shown. If the mantle density profile used in the calculation does not include a crust, then the Dreibus and Wanke [7] model of mantle and core composition yields a moment-of-inertia factor of 0.368. The addition of a crust, 50 km thick with a density of 3.0 g/cm^3, will lower the calculated moment-of-inertia factor by 0.002 and decrease the depth to the core mantle boundary by 35 km (increase the size of the core). The effect of temperature on the results shown in Fig. 3 was evaluated by recalculating the density of the mantle and core phases along a lower temperature PT profile of the Martian interior (see Ref. [11], fig. 1, profile c). At core–mantle boundary pressures the low-temperature profile yields a temperature 500°C lower than the high-temperature profile. The effect on the moment-of-inertia factor, however, is minimal. Assuming the low temperature PT profile increases the moment-of-inertia factor by only 0.001.

4. Discussion of results

The moment-of-inertia factor that we calculate for the SNC mantle and core composition model [7] without a crust, 0.368, is outside the range determined by Bills and Rubincam [17] to be consistent with geodetic and astrometric observations, $0.325 < \mathrm{MIF} < 0.365$. As shown above, the addition of a crust to this model lowers the calculated moment-of-inertia factor. Presently, however, the thickness and density of the Martian crust is not well constrained. When interpreting crustal structure from gravity and topography data, most workers assume a crustal density similar to that of the Earth's, 2.7–3.0 g/cm^3 (e.g. [18–21]). These models predict a mean thickness of the Martian crust ranging from a minimum value of 25 km to a maximum value of 150 km (for a review, see also [22,23]). As noted by Longhi et al. [12], these estimates of crust density may be too low if the SNC meteorites, whose densities are >3.0 g/cm^3, are representative of Martian crustal materials. In this case, the models underestimate crust thickness [12].

Assuming present-day estimates of a crust density of 2.7–3.0 g/cm^3, a mean crust thickness of 25–150 km, and an upper limit on the moment-of-inertia factor of 0.365, we have calculated the corresponding range in the moment-of-inertia factor that is allowable given the SNC model mantle and core density profiles. For a crust density of 2.7 g/cm^3 the calculated moment-of-inertia factor is 0.365–0.357 with a mean crust thickness of 42–150 km, respectively. For a crust density of 3.0 g/cm^3, the calculated moment-of-inertia factor is 0.365–0.362 with a mean crust thickness of 68–150 km, respectively. These models include a perovskite-bearing zone in the Martian interior. The thickness of the perovskite zone depends on the thickness and density of the crust. For example, assuming a 2.7-g/cm^3

crust with a thickness of 42–140 km, the perovskite-bearing zone ranges in thickness from 100 to 0 km, respectively.

The highest moment-of-inertia factor that the SNC model mantle and core density profiles can support, given the above constraints on crust thickness and density, is 0.367. If the Martian moment-of-inertia factor is greater than 0.367, then the Dreibus and Wänke [7] geochemical model underestimates the abundance of iron in the Martian mantle, or alternatively, the Martian crust is thinner than 25 km or has a density > 3.0 g/cm^3. If the Martian moment-of-inertia factor is lower than 0.357, then the Dreibus and Wänke [7] geochemical model overestimates the abundance of iron in the Martian mantle, or alternatively, the Martian crust is thicker than 150 km or has a density < 2.7 g/cm^3. Given the iron-rich basaltic nature of the SNC meteorites, the latter scenario, decreasing crust density, seems the least likely.

The moment-of-inertia factor that we calculate for the SNC Dreibus and Wänke [7] model mantle and core composition is significantly different from that calculated by Longhi et al. [12] for the same crust thickness and density. Longhi et al. [12] predicted the high pressure mineralogy of the SNC model composition from experimental work performed in simple systems. Although they do not report the modal abundances or compositions of the high-pressure phases used in their calculations, the mineralogy assumed is similar to that determined for the Dreibus and Wänke [7] composition by Bertka and Fei [11] and used in this study. Assuming a crust density of 2.7 g/cm^3 and a crust thickness of 100 km, Longhi et al. [12] calculated a moment-of-inertia factor of 0.353. Using the same crustal characteristics, we calculate a moment-of-inertia factor of 0.361. Our results are in good agreement with those of Kamaya et al. [24]. Kamaya et al. [24] experimentally determined the mineralogy of the Morgan and Anders [9] model Martian mantle composition. The Morgan and Anders [9] model has a mantle composition that is less iron-rich than the Dreibus and Wanke [7] mantle composition (see Table 1) and a sulfur-poor, iron–nickel alloy core. The moment-of-inertia factor that Kamaya et al. [24] calculate for the Morgan and Anders [9] mantle and core composition model is 0.364. This calculation does not include a crust. Assuming the mantle mineralogy determined for the Morgan and Anders model, they also calculate a moment-of-inertia factor for the Dreibus and Wänke [7] mantle and core composition model of 0.367, similar to our calculated value of 0.368.

Neither the calculations performed by Kamaya et al. [24] or our calculations constrain the planet's bulk composition to a C1 carbonaceous chondrite bulk composition, an original assumption of the Dreibus and Wänke [7] model. The iron content of the core plus the iron content of the mantle and crust in the Martian interior models presented above, is less than a C1 iron abundance. This is a result of the fact that the mass fraction of an Fe core with 14 wt% S is smaller in our calculations, 13.7–19 wt%, than in Dreibus and Wänke's [7] calculation, 21.7 wt%. In deriving the SNC Martian mantle composition, Dreibus and Wanke [7] used a mass balance calculation to distribute a C1 iron abundance between the core and mantle of the planet and thereby determine the mass fraction of the core. To constrain the overall bulk composition of the planet to a C1 chondrite composition, and maintain the total mass constraint, requires a crust thickness of 180–320 km, assuming a crust density of 2.7–3.0 g/cm^3, respectively. The mass fraction of the core in these two scenarios is 20.6 and 21.0 wt% (corresponding to 27.5 wt% bulk iron content), respectively, with a moment-of-inertia factor of 0.354. The core size is large enough in both of these scenarios that the core–mantle boundary occurs at a depth that is shallower than the depth necessary to stabilize perovskite, the mineral that defines the beginning of the lower mantle. Strictly speaking then, the Dreibus and Wänke [7] model, which was derived by assuming that Mars has a C1 bulk composition, requires crustal thickness to be greater than 180 km and implies the absence of a lower mantle in the Martian interior. Recently, Sohl and Spohn [25] calculated the moment-of-inertia factor for the Dreibus and Wänke [7] mantle and core composition while also constraining the Fe/Si ratio of the bulk planet to remain chondritic. They reached a result similar to that presented here. A 250-km-thick crust is necessary to maintain an overall bulk C1 composition. The mass fraction of the core in their model is 21 wt% and the moment-of-inertia factor is 0.357 [25]. Differences in the calculated crust thickness are largely due to differences in assumed crust density. However, as it is unlikely that the thickness of the Martian crust is greater than 100 km (e.g. Kiefer et al. [21]), the bulk composition of Mars cannot be constrained to a C1 chondrite composition as proposed by the Dreibus and Wänke [7] model.

An improved estimate of the moment-of-inertia factor will determine whether or not the mantle and core compositions proposed by Dreibus and Wänke [7] are plausible, but it will not uniquely define either the mantle or core density. Knowledge of the mean density of the planet and the moment-of-inertia factor can be used to specify only two of three variables, core density, core size, or mantle density. Without information about the size of the Martian core or its density, we cannot specify mantle density. Furthermore, this calculation is also sensitive to the choice of crustal characteristics. Even with knowledge of core density, for example, a range in mantle density is feasible depending on crust thickness and density. This is illustrated in Fig. 4 where the Mg# of the mantle is shown as a function of moment-of-inertia factor and crust thickness and density assuming a core composition of Fe 14 wt% S. The mantle density profiles used in the calculation of this diagram adopt the modal mineralogy and phase transitions determined for the Dreibus and Wänke [7] mantle

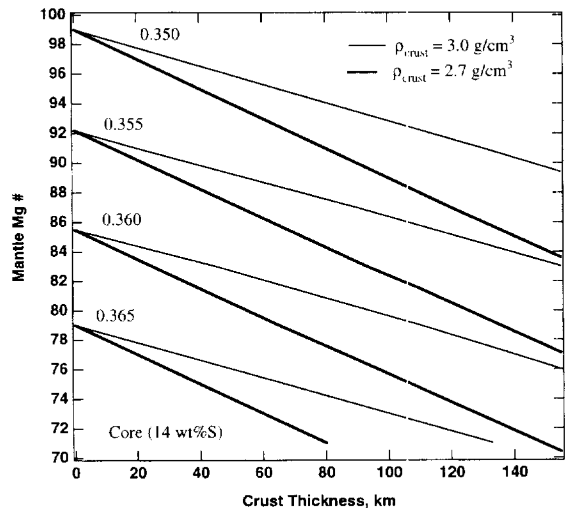

Fig. 4. Martian mantle Mg# as a function of crust thickness and density for a given moment of inertia factor, assuming a core composition of Fe 14 wt% S. See text for an explanation of calculations.

and core composition model while varying the iron content of the mantle mineral phases. Given a core composition of Fe 14 wt% S and a moment-of-inertia factor of 0.355, the mantle Mg# can range from 91 to 77 given a Martian crust 25–150 km thick with a mean density of 2.7–3.0 g/cm^3. This uncertainty in mantle Mg#, for a given moment-of-inertia factor, is slightly larger when the uncertainty in core composition is considered. Given a core composition between Fe and FeS, a moment-of-inertia factor of 0.355 is consistent with a mantle Mg# from 92 to 76.

Despite all of the uncertainty in our present day estimates of Martian geophysical parameters, we can conclude that a moment-of-inertia factor less than 0.342 is not geochemically feasible assuming a crust density of 3.0 g/cm^3 and a crust thickness of less than or equal to 150 km. A moment-of-inertia factor < 0.342 requires that the mantle of Mars contain no iron, an assumption which is not supported by the iron-rich nature of the SNC meteorites, products of partial melting of the Martian mantle, or by X-ray fluorescence analysis of the Martian surface [26]. Parent magma compositions for the SNC meteorites have been proposed by Longhi and Pan [27], but the absolute iron content of the mantle cannot be constrained from these proposed magma compositions. For example, Longhi and Pan [27] suggest that a parental liquid similar in composition to the groundmass of EETA79001A may be common to all the shergottites. Assuming olivine/liquid Fe/Mg equilibria, this liquid would be in equilibrium with an Mg# ~80 olivine [28]. In the unlikely event that these parental liquids were also primary melts (undifferentiated since their production in the source region), they may be partial melting products of a source region that was previously depleted. In this case the Mg# of the undepleted mantle could have been <80. The low modal abundance of olivine in the SNC meteorites, however, indicates that their parent magmas were evolved liquids, not primary melts, i.e. Ref. [29]. In this case, the Mg# of the primary melt from which the parent magmas evolved had a higher Mg# reflecting a source region olivine with Mg# > 80. This source region may, however, have been previously depleted so that the possibility for a source region with Mg# < 80 still cannot be ruled out (see [27]).

The payload of proposed missions to Mars does not presently include the seismic instrumentation necessary to determine the size of the Martian core. Mars Global Surveyor will, however, provide us with the gravity and topography data necessary to better constrain crustal characteristics. Tighter constraints on the moment-of-inertia factor, along with tighter constraints on Martian crust thickness and density, would allow us to address whether or not the Martian mantle is more iron-rich than the Earth's mantle. For example, given a moment-of-inertia factor of 0.360 with a 1% uncertainty, ±0.004, we would predict that the Martian mantle is more iron-rich than the Earth's mantle. The precise degree of iron-enrichment could not be specified, but the likelihood of iron-enrichment could be correlated to crustal thickness, the thicker the crust the lower the Mg# of the Martian mantle (see Fig. 4).

5. Conclusions

The moment-of-inertia factor calculated for the Dreibus and Wänke [7] Martian mantle and core composition model, constrained to maintain a C1 chondrite bulk composition, is 0.354. The C1 chondrite bulk composition constraint requires that the Dreibus and Wänke [7] model include a crust with a thickness of 180–320 km, assuming a Martian crust density of 2.7–3.0 g/cm^3, respectively. As it is unlikely that the thickness of the Martian crust is greater than 100 km (e.g. Kiefer et al. [21]), the bulk composition of Mars cannot be constrained to a C1 chondrite composition as proposed by the Dreibus and Wänke [7] model.

The moment-of-inertia factor calculated for the Dreibus and Wänke [7] Martian mantle and core composition model without a crust, and without the C1 chondrite bulk composition constraint, is 0.368. Assuming present day estimates of Martian crust density of 2.7–3.0 g/cm^3, and crust thickness of 25–150 km, the calculated moment-of-inertia factor is 0.367–0.357. In this model, the core–mantle boundary occurs at a depth slightly deeper than the depth necessary to stabilize perovskite in the Martian interior.

An improved estimate of the moment-of-inertia factor of Mars, and tighter constraints on Martian crust thickness and density, will allow us to address whether or not the Martian mantle is denser than the Earth's mantle. The degree of iron-enrichment in the Martian mantle, assuming an increase in density is due to an increase in iron content, however, cannot be specified without knowing the size of the Martian core.

A moment-of-inertia factor of less than 0.342, assuming a crust thickness of less than or equal to 150 km and a crust density of 3.0 g/cm^3, is not geochemically feasible because it requires that the mantle of Mars contain no iron.

6. Note added in proof

Folkner et al. [40] recently reported a new value for the moment-of-inertia factor of Mars based on an improved estimate of the Martian spin pole precession rate determined from Doppler and range measurements to the Mars Pathfinder lander. The value they report, 0.3662 ± 0.0017, is consistent with a Martian mantle that is more iron-rich than the Earth's mantle. Given a core composition of Fe 14 wt% S the Martian mantle Mg# can range from 60 to 78, assuming a Martian crust 25–150 km thick with a mean density of 2.7–3.0 g/cm^3 (see Fig. 4). As discussed above, the uncertainty in mantle Mg# is slightly larger when the uncertainty in core composition is considered.

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