Powering Mercury's dynamo

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[1] The presence of the global magnetic field of Mercury has implications for the interior structure of the planet and its thermal evolution. We use a thermal evolution model to explore the conditions under which excess entropy is available to drive a convective dynamo. The current state of the core is strongly affected by its sulfur concentration and the viscosity of the overlying mantle. A present-day dynamo is difficult to achieve. The minimum rate of entropy production required to drive a dynamo is attained in only the most optimistic models, and requires present-day mantle convection. An additional entropy source such as the addition of a radiogenic heat source in the core increases the probability of a present-day dynamo. Given the uncertainty, more specific characterization of the planet's interior and magnetic field is required to alleviate ambiguities in the original Mariner 10 observations. **Citation:** Williams, J.-P., O. Aharonson, and F. Nimmo (2007), Powering Mercury's dynamo, *Geophys. Res. Lett.*, *34*, L21201, doi:10.1029/2007GL031164.

1. Introduction

[2] Mercury is a rather enigmatic planet for a variety of reasons and presents a challenge to our general understanding of the terrestrial planets. It is the smallest planet in the solar system, with a radius $R_p \sim 2440$ km, smaller than the moons Ganymede and Titan, yet has the highest uncompressed density from which it is inferred to have the largest fractional core size, of radius 0.74–0.76 R_p [*Schubert et al.*, 1988; *Harder and Schubert*, 2001]. The high density results in a surface gravity comparable to Mars. Its ancient, heavily cratered surface indicates that internal geologic activity ceased earliest among the inner planets; however, it possesses a global magnetic field with an apparent dipolar signature [*Ness*, 1979; *Connerney and Ness*, 1988]. A hydromagnetic dynamo is a possible source of the magnetic field and requires cooling of a liquid iron-rich core at a rate capable of driving convective motions. It is not clear whether a convective dynamo can be maintained presently for Mercury since there is no plate tectonics to aid in cooling the core. Mercury does currently possess at least a partially molten core as revealed by the amplitude of the planet's libration [*Margot et al.*, 2007]; however, simple models predict that the core should have solidified or significantly cooled by now [*Cassen et al.*, 1976; *Solomon*, 1976; *Schubert et al.*, 1988]. Numerical simulations have demonstrated that both thin-shell [*Stanley et al.*, 2005] and thick-shell [*Heimpel et al.*, 2005] dynamo geometries can reproduce the relatively weak dipole signature characteristic of the observed field. Alternate geometries are capable of producing appropriately weak magnetic fields at the outer shell boundary such as dynamos operating beneath a stably stratified liquid outer core [*Christensen*, 2006]. Such a stratified core, however, would inhibit core cooling and less power would be available for driving a dynamo.

[3] An additional constraint on Mercury's thermal history is provided by the surface geology. An apparent system of compressional tectonic structures, appearing as lobate scarps, records ~1–2 km global radial contraction associated with interior cooling [*Strom et al.*, 1975; *Watters et al.*, 1998]. However, how strong a constraint on the thermal history the contraction provides is not yet clear [*Pritchard and Stevenson*, 2000; *Dombard et al.*, 2001].

2. Model

[4] We have developed a thermal evolution model for Mercury to explore the conditions under which a present-day convective dynamo is energetically possible. Our model, previously employed for Earth [*Nimmo et al.*, 2004] and Mars [*Williams and Nimmo*, 2004], and adapted here for Mercury, calculates the rate of entropy production within the core as a function of time by using the methods of *Gubbins et al.* [1979], *Gubbins et al.* [2003], and *Gubbins et al.* [2004]. The rate of entropy production is related to the power available to drive a dynamo. Temperature changes in the core result from the heat flux into the mantle, and if present, core solidification and radioactive heating. Heat fluxes across the conductive boundary layers of the core-mantle boundary (CMB) and the lithosphere are determined by a parameterized convection model [*Nimmo et al.*, 2004] (see *Davies* [2007] for an alternate formulation of the CMB heat flux). A stagnant lid [*Solomatov*, 1995] is assumed throughout the planet's history. The thickness of the boundary layers, and hence, the heat flux across the boundaries, are determined by the temperature-dependent mantle viscosity, $\eta = \eta_o \exp[-\zeta(T_m - T_{ref})]$, where ζ is related to the activation energy and η_o is the viscosity at a reference temperature T_{ref}. As a result, dynamo activity is intimately related to the thermal history of the mantle.

[5] The energy balance in the mantle is described by

$$H_m M_m - Q_m + Q_c = M_m C_{pm} dT_m/dt, \tag{1}$$

where subscript m and c denote mantle and core, respectively, H is the internal heating per unit mass, M is mass, C_p is the specific heat capacity (1200 J kg^{-1} K^{-1} and 800 J kg^{-1} K^{-1} for the mantle and core, respectively), and T_m is the temperature half way through the mantle. The quantity Q is the heat extracted from the layer and is determined by the heat flux across the appropriate

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conductive boundary layer (lithosphere and CMB). The energy balance of the core is described similarly by

$$H_c M_c - Q_c + Q_L + Q_g = M_c C_{pc} dT_c/dt, \quad (2)$$

where T_c is the core temperature at the CMB. The terms Q_L and Q_g result from core solidification where Q_L is latent heating and Q_g is heating resulting from the change in gravitational energy from sequestering of lighter elements in the outer liquid core.

[6] The rate of entropy production in the core is given by

$$\Delta E = E_R + E_s + E_L + E_H + E_g - E_k, \quad (3)$$

where E_s, E_L, E_H, and E_g, are the specific heat, latent heat, heat of solution, and gravitational energy terms respectively and depend on the rate of core cooling, dT_c/dt, and E_R is the entropy due to radioactive heating in the core and depends on H_c. E_k is the conductive contribution and is a function of the core adiabat, and hence the core's specific heat capacity, C_{pc}, and thermal expansivity, α_c, taken here to be 3×10^{-5} K^{-1}. A core conductivity of 40 W m^{-1} K^{-1} is assumed. The actual rate of entropy production required to drive a dynamo is not known [*Roberts et al.*, 2003]. Here we assume that a dynamo can occur for any $\Delta E > 0$, i.e. Ohmic dissipation within the core is assumed to be negligible. Parameter values, adapted from *Nimmo et al.* [2004] and *Hauck et al.* [2004], are tabulated in the auxiliary material.[1]

[7] The location of the inner core boundary is where the core liquidus and adiabat are equivalent. The liquidus is derived from empirical results [*Fei et al.*, 1995, 1997, 2000]

$$T_m = T_{m0}(1 - \theta\chi)\left(1 + T_{m1}P + T_{m2}P^2\right) \quad (4)$$

and is a function of pressure, P, and mass fraction of a light alloying element, χ, where T_{m0}, T_{m1}, and T_{m2} are constants and θ accounts for the depression of the Fe melting temperature by the alloying element. We assume $\theta = 2$ is constant, however θ does vary with S content due to curvature of the liquidus [e.g., *Fei et al.*, 2000]. Larger values of θ will result in slower inner core growth, dR_i/dt, and therefore smaller values for E_L, E_H, and E_g. The core adiabat, following *Stevenson et al.* [1983], is given as a function of pressure by

$$T_c(r) = T_{cmb}\left[\frac{1 + T_{a1}P(r) + T_{a2}P^2(r)}{1 + T_{a1}P_{cmb} + T_{a2}P^2_{cmb}}\right], \quad (5)$$

where T_{a1} and T_{a2} are determined by fitting the exponential expression of *Labrosse et al.* [2001] for the adiabatic temperature of the core. The core radius is fixed at 1850 km along with the pressure at CMB, P_{cmb} = 8 GPa, and the planet's center, P_{cen} = 40 GPa. The core density is linearly interpolated between liquid density end-members as a function of sulfur content with $\rho_{o,Fe}$ = 7019 kg m^{-3} [*Anderson and Ahrens*, 1994] and $\rho_{o,FeS}$ = 5333 kg m^{-3} [*Sanloup et al.*, 2000]. The bulk modulus is determined from the quadratic fit to data employed by *Hauck et al.* [2006]. The length scale of compression [*Labrosse et al.*, 2001] is then determined using the logarithmic equation of state of *Poirier and Tarantola* [1998]. We determine the accumulated radial contraction of the planet, ΔR, over the last 4 Gyr resulting from volumetric changes of a cooling lithosphere, mantle, and core, and the liquid-solid phase change of a freezing inner core following *Hauck et al.* [2004]. Relevant parameter values for the ΔR calculations similarly follow *Hauck et al.* [2004].

3. Core Sulfur Content

[8] Many early studies of Mercury's thermal history predicted rapid freezing of the core that is inconsistent with a present-day dynamo [e.g., *Siegfried and Solomon*, 1974; *Solomon*, 1976]. The incorporation of a light alloying element, which lowers the melting temperature, provides a plausible way to retain a partially molten core [*Cassen et al.*, 1976; *Stevenson et al.*, 1983; *Schubert et al.*, 1988]. Sulfur is the most reasonable candidate, and although equilibrium condensation models [e.g., *Lewis*, 1972; *Grossman*, 1972] predict negligible amounts of S, *Stevenson et al.* [1983] argue that radial mixing within the solar nebula of planetesimals would result in Mercury accreting bodies containing S. The addition of sulfur to the core results in a strongly depressed Fe-S eutectic inhibiting complete core solidification [*Boehler*, 1996; *Fei et al.*, 1995, 1997, 2000]. Previous models by *Stevenson et al.* [1983] and *Schubert et al.* [1988] that incorporated subsolidus convection in the Mercurian mantle have found that a fluid outer core is possible at present with a modest abundance of sulfur (>1wt%).

[9] Model results are shown for a representative example with initial fractional sulfur concentration χ_o = 0.03 (Figure 1). The sulfur inhibits complete core solidification after 4.6 Gyr. Temperatures and heat fluxes decline with time with a present day mantle potential temperature ~1530 K similar to the Earth. An initial mantle CMB temperature of 2100 K is used to coincide with the mantle solidus at 8 GPa [*Herzberg et al.*, 2000]. An initial core CMB temperature of 2150 K is selected, although the results after 4.6 Gyr are relatively insensitive to the precise temperature chosen as early cooling of the interior is relatively rapid. This model results in a radial contraction, $\Delta R = -16.6$ km, and a present-day entropy production rate, ΔE = -4.51 MW K^{-1}, inconsistent with the modest contraction (~1–2 km) implied from the observed lobate scarps and a present-day dynamo. An increase in χ_o reduces liquidus temperatures, delaying the onset of core solidification resulting in a smaller inner core, and thus, less contraction. The rate of inner core growth is initially rapid and declines over time as S is sequestered into the declining volume of the outer core, further reducing the liquidus temperature. The inner core radius and ΔE for χ_o = 0.06 is shown in Figure 1a for comparison. As can be seen, the overall increase in entropy resulting from inner core solidification is smaller for later core formation as the core cooling rate, dT_c/dt, on which E_s, E_L, E_H, and E_g depend, declines over time. Additionally, E_H becomes increasingly negative with larger χ_o since heat is absorbed in the disassociation of S and Fe at the inner core boundary. As a result, there is a specific χ_o at which maximum present-day entropy is achieved where the timing of the "jump" in

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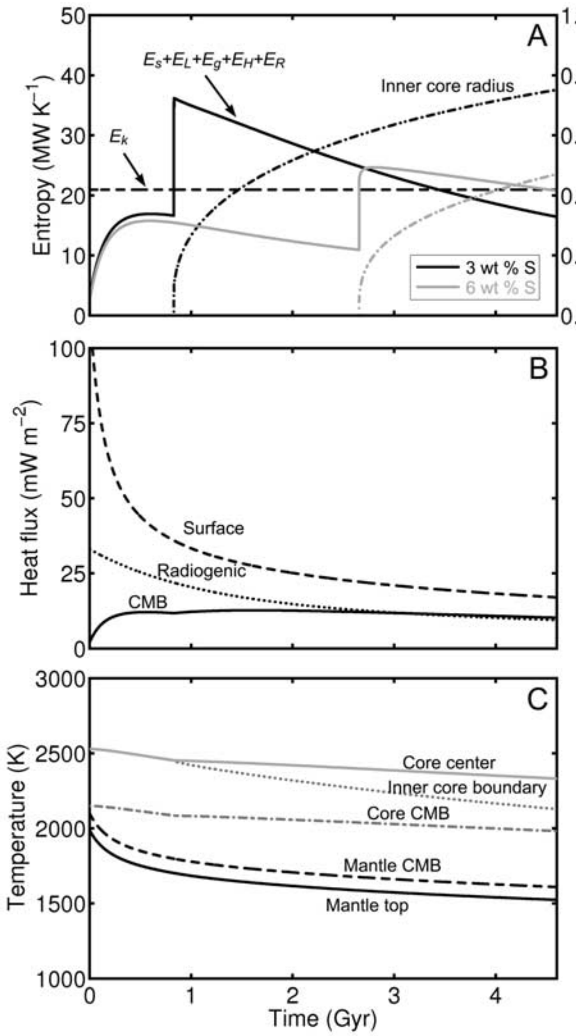

Figure 1. Representative thermal evolution and resulting entropy generation in the core as a function of time for Mercury with 3 wt% core S. (a) The entropy production (solid) decreases over time as the planet cools with a large increase occurring with the onset of core solidification. The thermal diffusive entropy value (dash) represents the minimum entropy value required for a dynamo to be present. A large inner core (dash-dot) develops, however the sulfur inhibits complete solidification. Additionally, results for 6 wt% core sulfur concentration are shown (gray curves). (b) Evolution of the heat fluxes from the core (solid) and mantle (dash) and the heat generated by radioactive decay in the mantle (dot) with time for the 3 wt% sulfur case. (c) Evolution of temperatures at the top (solid black) and bottom (dash black) of the mantle, the top of the core (dot-dash dark gray), the inner-outer core boundary (dot gray), and the core center (solid gray).

entropy from core solidification is balanced by the decrease in magnitude of the jump with time (Figure 2). Running models with $\chi_o = 0$ to 0.08 in increments of 0.005, this was found to occur when χ_o = 0.065. This model yields a fractional present-day inner core radius 0.39 R_c and ΔR = −2.79 km. The present-day entropy production value however, only marginally exceeds E_k (ΔE = +1.82 MW K^{-1}) and with the uncertainty in actual rate of excess entropy production required to drive a dynamo [*Roberts et al.*, 2003], the feasibility of a dynamo in this case remains ambiguous.

4. Mantle Viscosity

[10] The thermal history of the core is influenced by the mantle's viscosity as it determines the efficiency of the mantle at removing heat from the core. The temperature dependent viscosity determines the thickness of the boundary layers and, thus, the heat flux [e.g., *Nimmo and Stevenson*, 2000]. Figure 3 illustrates the trade-off between final inner core radius and final entropy after 4.6 Gyr as a function of mantle reference viscosity, η_o, for varying χ_o. For small inner core sizes, increasing η_o results in smaller inner cores and lower rates of entropy production as core cooling is slower. For large inner core sizes decreasing η_o results in more rapid core cooling, however entropy production decreases as outer core mass becomes small. An optimal inner core size for entropy production occurs where the trade-off between outer core mass and cooling rate are maximized at $R_i/R_c \sim 0.7$. For the nominal reference viscosity, $\eta_o = 10^{20}$ Pa s, the maximum $\Delta E \sim 0$ is achieved at 6–7 wt% S. With these parameters, present-day viscosities of the order 10^{20} Pa s result. In order to obtain $\Delta E > 0$ lower viscosities are required. Present-day viscosities for the Earth's upper mantle range from 10^{20} to 10^{21} Pa s [e.g., *Mitrovica and Forte*, 1997; *Peltier and Jiang*, 1996]. Mercury's mantle, because of its refractory nature, is expected to have a higher viscosity than that of the Earth's at corresponding temperatures and pressures [*Schubert et al.*, 1988] thus $\eta_o = 10^{20}$ Pa s likely represents a lower limit. Higher viscosities inhibit core cooling and ΔE does not

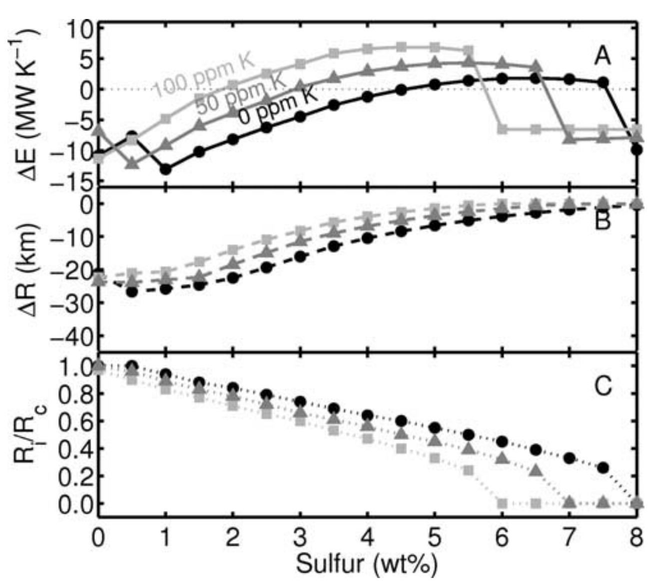

Figure 2. (a) The present-day entropy production rate, (b) accumulated radial contraction of the planet over the last 4 Gyr, and (c) the non-dimensional inner core radius as a function of core S wt% for 0, 50, and 100 ppm K in the core. The drop in entropy production at higher S concentrations is due to the absence of core solidification. Elevated values of ΔE at 0 and 0.5 wt% S result from an increase in E_s with complete core solidification.

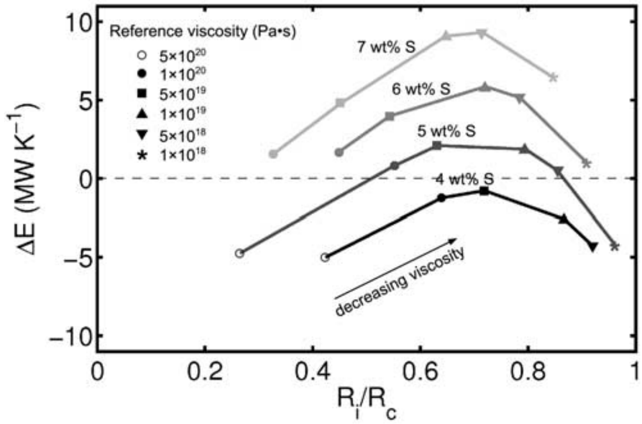

Figure 3. Present-day entropy production rate versus inner core radius for varying core sulfur concentrations and mantle reference viscosities.

exceed the thermally diffusive value. From this, we conclude that if subsolidus convection is not occurring in the mantle, i.e. it is in a conductive regime where $\eta > 10^{23}$ Pa s, a core dynamo is not possible.

5. Potassium

[11] If dynamo action is the source of the magnetic field, an additional entropy source may be required such as tidal heating [*Schubert et al.*, 1988], dissolution of elements such as Si (D. J. Stevenson, personal communication, 2006) or precipitation of Fe [*Hauck et al.*, 2006] at the CMB. Here we consider the inclusion of a radioactive heat source, ^{40}K, providing additional entropy production in the core. A growing body of experimental evidence suggests that potassium should partition into liquid iron planetary cores [*Gessmann and Wood*, 2002; *Murthy et al.*, 2003; *Lee and Jeanloz*, 2003; *Bouhifd et al.*, 2007]. Concentrations of a few hundred ppm K are estimated for the Earth's core [*Gessmann and Wood*, 2002]. Lower concentrations of K would be likely for Mercury's core as the partition coefficient is observed to decrease with lower S core content [e.g., *Bouhifd et al.*, 2007].

[12] The heat generated by the radioactive decay of ^{40}K reduces the inner core size and ΔR for a given χ_o. The reduction in entropy corresponding to the slower rate of cooling is offset by the entropy generated by the additional heat source, resulting in a larger ΔE. Figure 2 includes results for models with 50 ppm and 100 ppm potassium in the core. The presence of potassium relaxes the constraints on the thermal evolution enabling the entropy requirements for a dynamo to be attained for a wider range of core S concentrations. However, whether enough K is present to permit a dynamo is not clear as its partition coefficient between silicate and Fe-rich metal melts is found to vary by nearly four orders of magnitude depending on experimental conditions (pressure, temperature, oxygen fugacity, etc.) [*Bouhifd et al.*, 2007].

6. Conclusions

[13] We find that inner core growth and mantle convection are necessary but not sufficient conditions for a dynamo. This precludes a pure Fe core which would freeze in its entirety after 4.6 Gyr. We find an optimal core sulfur content (~6–7 wt %), and thus optimal inner core size, exists where the present-day core entropy production rate is maximized. The addition of K in the core lowers the S content at which this maximum occurs. Without an additional entropy source, minimum entropy requirements ($\Delta E > 0$) for a dynamo are difficult to achieve, and become even more challenging if significant Ohmic dissipation takes place. Radiogenic heating from potassium in core concentrations likely appropriate to Mercury only marginally increases the entropy and does not guarantee the existence of a present-day dynamo. Potassium does however, reduce ΔR as the optimal inner core size for a dynamo occurs at smaller R_i, and permits a dynamo to operate at higher mantle viscosities. Ultimately more observations are needed.

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