CORE EVOLUTION AND MAGNETISM OF THE TERRESTRIAL PLANETS. D. J. Stevenson, G. Schubert, Dept. Earth and Space Sciences, U.C.L.A., Los Angeles, CA 90024, and P. Cassen, R. T. Reynolds, NASA-Ames Res. Ctr., Moffett Field, CA 94035.

Core evolution necessarily depends on the heat transport processes in the overlying mantle and no meaningful conclusions concerning the rate of cooling or freezing of a terrestrial planetary core can be made without modelling the core and mantle as a coupled system. All terrestrial planetary mantles (including the lunar mantle) are likely to be undergoing subsolidus convection (1) and their thermal states are thus determined by the strongly temperature-dependent mantle rheology and the convective efficiency, essentially in accordance with the self-regulation concept introduced by Tozer (2). For realistic rheologies, the resulting present day deep mantle temperatures are substantially less than the freezing points of pure iron, so the existence of partially fluid cores (a necessary but not sufficient condition for planetary dynamos) requires alloying constituents (e.g. sulphur) which reduce the freezing points. Since substantial radiogenic heat sources are likely to be absent from the cores (3,4), the core convective motions necessary for a dynamo are driven either by cooling the fluid from above or by the energy release (latent and gravitational) of inner core growth. The models reported here incorporate all of the above considerations and are aimed at understanding the dynamic and thermal evolution of terrestrial cores. Possible explanations for the substantial magnetic fields of the Earth and Mercury, and the likely absence of substantial fields in Venus and Mars arise naturally from these models.

The calculations assume subsolidus whole mantle convection parameterized by a simple Nusselt-Rayleigh number relationship (1). This simple parameterization permits consideration of a wide range of models and parameter space. The mantle is assumed to be adiabatic (apart from boundary layers), the fluid part of the core is initially adiabatic (with negligible boundary layers) and radiogenic heating is confined to the mantle. The evolutions are initiated after complete separation of core from mantle (assumed to be a rapid process). The energy balance equations for mantle and core are

$$4\pi R_m^2 F_m - 4\pi R_c^2 F_c = \frac{4}{3}\pi (R_m^3 - R_c^3)\left[Q - \rho_m c_m \frac{d\bar{T}_m}{dt}\right] \qquad (1)$$

$$4\pi R_c^2 F_c = -\frac{4}{3}\pi R_c^3 \rho_c c_c \frac{d\bar{T}_c}{dt} + (L + E_G)\frac{dm}{dt} \qquad (2)$$

Subscripts m and c refer to mantle and core, respectively. R is the outer radius of the region, F is the heat flux at that position, Q is the radiogenic heat production per unit volume (approximated by $Q_o e^{-\lambda t}$ where λ is appropriate to a chondritic mixture and t is time); ρ, c and $\bar{T}$ are the average values of density, specific heat and temperature, respectively. L and E_G are the latent heat and gravitational energy release per unit inner core mass m. F_m and F_c are related to the temperature drops across the appropriate boundary layers and to the Rayleigh number of the mantle convection, in accordance with the Nusselt-Rayleigh number prescription. Some models incorporated breakdown of the lower (high temperature, hence low viscosity) boundary layer. The inner core size is determined by the intercept of the core adiabat and core freezing curve. The core alloy is assumed to be on the iron-rich side of the eutectic, and allowance is made for both the depression of the melting point and the upward migration of light elements during core freezing. A large number of models have been run; the general features are described below for each of the planets.

Earth. The constraints at $t \simeq 4.5 \times 10^9$ yrs. are the surface heat flux ($\simeq 4 \times 10^{20}$ erg/sec, of which about 10% is crustal), the mantle viscosity inferred from post-glacial rebound ($\sim 10^{22}$P) the inner core size ($\simeq$1215 km), and the upper mantle temperature ($\simeq$1650 K at 150 km depth, but with substantial uncertainty). Models were constructed which satisfied these constraints for a variety of choices of $L + E_G$ in the range 5×10^9 to 2×10^{10} erg/g (5,6) and for various freezing curves. For initially "hot" models ($T \sim 5000$ K at the Earth's center at $t = 0$, but the results are insensitive to this choice) it was found that the Earth has no inner core for the first 2 - 3 billion years, but that the core heat flux during this epoch is ample for thermal convection and dynamo generation. The core heat flux F_c initially drops rapidly with time, but after inner core growth is initiated it reaches a plateau of around 20 erg/cm^{2}sec. The gravitational energy release then probably dominates the convection and the rate of core cooling decreases dramatically. This is very unlike the constant cooling rate assumed by Gubbins et al. (6), because the mantle is unable to accommodate an increase in core energy output. Without inner core growth, the Earth's core might have ceased to convect (and the magnetic field would have died away) 1 or 2 billion years ago, because F_c would have dropped below the conductive flux along an adiabat (~15 erg/cm^{2}sec) and the core would have become sub-adiabatic.

Venus. If the Earth were despun to the rotation rate of Venus, it would still be expected to have a magnetic field because the Coriolis force would still be dynamically dominant for large scale core motions. The apparent absence of an intrinsic field in Venus (7) probably needs some other explanation. Our models show that if Venus has core and mantle compositions similar to the Earth, then Venus does not yet have an inner core and hence does not have the additional energy source that insures present-day core convection in the Earth. There are two reasons for this: lower pressures (the central pressure in Venus is less than the pressure at the inner core-outer core boundary in the Earth) and slightly higher temperatures (the center of Venus "knows" that the atmosphere is hot!) In the absence of constraints such as the moment of inertia, one could also construct Venus models in which the core is nearly pure iron and almost completely frozen, but this is cosmochemically implausible (8).

Mercury. Many workers (reviewed in ref. 9) have previously noted the difficulty of insuring a partially fluid core in Mercury after 4.5×10^9 yrs. However, inclusion of a small amount of sulphur precludes complete freezing. For example, 3% sulphur by mass (one tenth of the chondritic abundance) provides a 300 km thick fluid layer for the present day. Upward migration of the sulphur drives compositional convection sufficient for a dynamo. A Mercurian dynamo may thus be possible.

Mars. Even if Mars started hot, it would not have developed an inner core yet if the sulfur content is ~15% by mass or more. Thermal convection (and a Martian dynamo) would then have ceased after only 1 - 2 billion years. Alternatively, Mars may have had a substantially non-monotonic thermal history (10) which produced a sub-adiabatic core. In either case, the absence of a large present-day field is readily explainable.

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