CORE FORMATION DYNAMICS AND PRIMORDIAL PLANETARY DYNAMOS. D.J. STEVENSON, Dept. Earth & Space Sci., UCLA, Los Angeles, CA 90024.

The energetics of core formation in a homogeneously accreted terrestrial planet are quite well understood (1) but the kinetics and dynamics remain obscure. In particular, the core formation timescale is not known, although geochemical constraints exist (2). The large energy release of core formation in large terrestrial planets (Earth, Venus) does not insure a rapid formation if the deep interior of the accreting planet is cold and "rigid" since there is no efficient mechanism for the downward transport of heat. Both of the commonly invoked mechanisms--Elsasser droplets (3) and "sinking layer" (4)--are shown below to work much less rapidly than is commonly believed. Core formation may nevertheless be rapid--even contemporaneous with accretion--because of the finite strength (i.e. the non-Newtonian rheology) of the cold interior. A magnetic field will be generated by the dynamo mechanism almost immediately, and might be large enough to modify accretion dynamics and redistribute angular momentum. In the Moon, core formation would be much slower and dynamo generation in a thin, sinking fluid layer might explain the controversial lunar paleomagnetism, without invoking superheavy elements. The asymmetry of the lunar crust might also be explained.

Fundamental to the analysis presented here is the assumption of approximately homogeneous accretion, with the temperature within the forming planet being determined by the infall energy of planetesimals, as in the models of Kaula (5,6). In these models, the maximum temperature occurs near but below the planetary surface.

Initial iron segregation. Accretional energy is sufficient to melt the iron. In the Earth and Venus, this melting may already begin when the forming planet is only about the size of Mars. Latent heat is unimportant and the iron (assumed to be initially in particulate form) can readily percolate after melting to form a fluid layer, the bottom of which is necessarily at the freezing point. Below this layer is the primordial, cold mixture. The iron layer is well stirred and adiabatic. The mantle above is iron depleted and well stirred by thermal convection and Rayleigh-Taylor instabilities initiated by incoming iron-rich planetesimals.

Why the "Elsasser drop" mode is ineffective. Consider an inviscid, fluid layer of density $\rho+\Delta\rho$ overlying an infinite layer of density ρ and viscosity $\nu_o \exp(Z/L)$ where Z is measured downwards and $Z = 0$ at the interface. The fastest growing modes of the resulting Rayleigh-Taylor instability are found to have a growthrate $\simeq 0.25(\Delta\rho/\rho)$. gL/ν_o and a characteristic lengthscale $\simeq L$, where g is the gravitational acceleration. However, L is very small because of the strong temperature inversion and the very strong dependence of viscosity on temperature (typically $d\ell n\nu/d\ell nT \sim -25$ for mantle rock). Large drops are not possible and small drops ($\sim$ few kilometers in radius) sink slowly because of the need to warm the region ahead of them. The timescale of core formation by this process is several hundred million years, despite the exothermic nature of the process. This may be reduced

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somewhat by invoking "channelling" of the iron rather than the Stokes flow of individual droplets, but it takes a long time to get any iron to the planetary center by the Elsasser mode. The fundamental reason for the difficulty is that thermal diffusion is slow, yet is essential for "softening" the path ahead of downgoing iron drops.

Why the "Sinking layer" mode is inefficient. In this model (4), the iron layer grows by directly melting the iron present in the primordial core below it, with the released silicate grains then floating up to merge with the mantle above. The problem with this mode is again the slow thermal diffusion: heat must be conducted into the interface from above to supply the latent heat of fusion L. Detailed models (which include the fluid dynamics of the iron layer and the stirring by the silicate grains) show that the velocity at which the iron layer sinks is less than $K\Delta\rho g/L \sim 10^{-9}$cm/sec and the time of core formation $\sim 10^9$ years.

What really happens? The fastest instability is the "catastrophic asymmetry": the upward, rigid displacement of the less dense, primordial core relative to the more dense liquid iron layer. (The timescale for this is of the order of hours). This creates a pear-shaped planet; however, the resulting non-hydrostatic stresses are sufficient to fragment the primordial core. The deep interior of the planet then turns itself inside-out: the result is a liquid iron core upon which float "rockbergs" (the cold, undifferentiated fragments of the primordial core) overlaid in turn by the hot, well-stirred (but solid) mantle. The stirring and rotational energy loss associated with this process are ample to prevent pressure-induced freezing of the iron--the core is adiabatic and entirely fluid. At least in the Earth and Venus, the above processes will be contemporaneous with accretion.

Primordial dynamos. The stirring of the liquid iron in these early stages is much more vigorous than it is in the present day outer core of the earth (the magnetic Reynolds number for which is believed to be ~ 100 for large scale motions). Application of mixing length theory or variants thereof (7), including allowance for gravitational stirring, suggest convective velocities of 1-10cm/sec. For a magnetic diffusivity of $\sim 10^4$cm^2/sec (appropriate to iron) a fluid layer of a few kilometers should suffice for dynamo generation! Thus, a dynamo might be generated even in the thin iron layer that would form below the lunar magma ocean. Gravitational stirring provides enough energy for a field ~ 1 Gauss. The difficulties described by Runcorn for a thermally driven lunar dynamo (8) do not exist in this case. The inferred decay of the dynamo is here reinterpreted as being due to the gradually increasing distance between the lunar surface and the field source, as the iron layer sinks. Dynamo generation would cease when the iron reaches the center of the Moon. Furthermore, the "catastrophic asymmetry" described above might explain the inferred crustal asymmetry of the present Moon.

In the Earth, the surface field might have been of order 10 Gauss, if the field scales as the square root of the heat flux (a result suggested by equating the Ohmic dissipation to the available energy). Application of Hoyle's model for the transfer of angular momentum from the primordial Sun by hydromagnetic

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torques (9) shows that a transfer of ∿1% of the Earth's mass (i.e. the Moon) from the Earth's surface to beyond the Roche limit is achievable in principle, but consideration of the details of this process suggests that there are difficulties in using this to create the Moon by binary fission.

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