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Modelling the thermo-chemical evolution of the interiors of Venus, Mars and Mercury

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The latest generation of the global 3-D spherical convection model StagYY [Tackley, PEPI 2008] allows the direct computation of a planet's thermo-chemical evolution, including self-consistent lithospheric behavior (e.g., rigid lid, plate tectonics, or episodic plate tectonics [van Heck and Tackley, GRL 2008]), chemical differentiation induced by melting, large viscosity variations, a parameterized core heat balance, and a realistic treatment of phase diagrams and material properties. The latter has recently been added using free energy minimization to compute stable phases as a function of temperature, pressure, and composition as expressed by ratios of the five main oxides, and thus avoids the need for increasingly complicated and ad hoc parameterizations of phase transitions. Global models allow the computation of planetary secular cooling including prediction of how the core heat flux varies with time hence the evolution of the geodynamo, and possible transitions in plate tectonic mode. Modern supercomputers and clusters allow increasingly higher resolution, with up to 1.2 billion unknowns possible on only 32 dual-processor nodes of an opteron cluster. In ongoing research, this tool is being applied to understand the evolution of Earth, Mars, Venus, and Mercury.

Our Mars models [T. Keller and P.J. Tackley, submitted] show that with an appropriate viscosity profile, convection rapidly develops a 'one ridge' planform consisting of a single ridge-like upwelling and small-scale downwellings below a stagnant lid, and that this produces a dichotomous crustal distribution that bears a striking first-order resemblance to the crustal distribution on Mars. The actual boundary of the crustal dichotomy on Mars is not hemispherical but rather like the seam on a tennis ball, and this is reproduced by our models, with the highland region being located above the upwelling. Furthermore, the elevation difference between the highland and lowland regions is very similar to that on Mars, although the average crustal thickness is higher than thought to be appropriate for Mars. In some calculations, the location of the upwelling subsequently migrates to the edge of the highland region, providing an explanation for Tharsis. Melting is found to have a dramatic influence on thermal evolution particularly during the early stages.

With our Venus models we are studing the modes of heat loss, the origin of the inferred surface age and understanding the admittance (gravity/topography) ratio. Of particular interest is whether a smooth evolution can satisfy the various observational constraints, or whether episodic or catastrophic behaviour is needed, as has been hypothesised by some authors. Simulations in which the lithosphere remains stagnant over the entire history indicate that over time, the crust becomes at least as thick as the mechanical lithosphere, and delamination occurs from its base. The dominant heat transport mechanism is magmatic. A thick crust is a quite robust feature of these calculations. Higher mantle viscosity results in larger topographic variations, thicker crust and lithosphere and higher admittance ratios; to match those of Venus, the upper mantle reference viscosity is about 1020 Pa s and internal convection is quite vigorous. The most successful results in matching observations are those in which the evolution is episodic, being in stagnant lid mode for most of the evolution but with 2-3 bursts of activity caused by lithospheric overturn. If the last burst of activity occurs Ĩ Ga before present, then the present day tends to display low magmatic rates and mostly conductive heat transport, consistent with observations. In ongoing work we are examining the effect of crustal rheology and a more accurate melting treatment.

Due to the absence of an atmosphere and proximity to the Sun, Mercury's surface temperature varies laterally by several 100s K, even when averaged over long time periods. The dominant variation in time-averaged

surface T occurs from pole to equator (2̃25 K). Here we demonstrate, using models of mantle convection in a 3-D spherical shell, that this stationary lateral variation in surface temperature has a small but significant influence on mantle convection and on the lateral variation of heat flux across the core-mantle boundary (CMB). We evaluate the possible observational signature of this laterally-varying convection in terms of boundary topography, stress distribution, gravity and moment of inertia tensor. In future we plan to test whether the lateral variation in CMB flux is capable of driving a thermal wind dynamo, i.e., weak dynamo action with no internally-driven core convective motions.