

PATTERNS OF MANTLE CONVECTION ON VENUS; A.M. Leitch and D.A. Yuen, Dept Geology & Geophysics and Minnesota Supercomputer Institute, University of Minnesota, Minneapolis MN 55455

While the surface geology of Venus is being dramatically revealed by Magellan's radar images, motions in the interior remain obscured. We carried out finite-element simulations of mantle convection on Venus out to investigate some of the possibilities. Starting with Earth-like global properties, we looked at the effect of the surface boundary conditions, Rayleigh number and viscosity variation on the large scale flow. Temperature contour plots for some example results are shown in the figures.

The simulations were run on a Cray 2, using the program TWODEPEP [1] in an axisymmetric spherical geometry. 1500 to 9000 quadratic, triangular elements were used depending on the Rayleigh number, and computations ran for 10 to 65 overturn times. The equations solved were the time-dependent, anelastic-liquid compressible equations of motion [2] with Newtonian rheology and a constant distribution of internal heating. From the top of the convecting part of the mantle (TOP) to the core-mantle boundary (CMB) the density ρ increased smoothly by 40%, the thermal expansivity k increased by a factor of 2.6 and the thermal expansivity α decreased by a factor of 4.5 [3]. The viscosity η was either constant or varied with depth z and temperature T according to

$$\eta = \eta_0 \exp[-\ln 10(T - \bar{T}) + \ln 30(z_{mid} - z)]$$

Free-slip, constant temperature boundary conditions were applied at the CMB, and the TOP was at constant temperature with either a free-slip or no-slip (rigid) stress condition.

Important parameters in these simulations were the Rayleigh number $Ra = \rho g \alpha \Delta T Z^3 / \eta_0 \kappa$, where Z is the total thickness of the mantle, $\Delta T = T_{CMB} - T_{TOP}$ and κ is the thermal diffusivity; the internal heating parameter $R = \rho H Z^2 / k \Delta T$, where H is the production rate of internal heat; the dimensionless surface temperature $T_0 = T_{TOP} / \Delta T$; and the surface stress condition. Rayleigh numbers of 3×10^6 and 3×10^5 were used which assume $\eta_0 \approx 10^{22}$ and 10^{23} - that is, Earth-like and an order of magnitude greater than the Earth [4]. R was varied from 0 to 10 (\approx chondritic), and T_0 from 0.2 to 1.0, roughly corresponding to temperatures T_{TOP} of 750 K (the surface temperature of Venus) and 1500 K (the base of a rigid lithosphere).

For a viscous Venusian mantle [4] with $Ra = 3 \times 10^5$, convection is characterized by large aspect ratio cells, steady hot up-flow and unsteady down-flow of small groups of cold plumes [5]. Figure A is a plot of temperature contours showing the most stable pattern observed for an internally heated, free-slip surface. There is a rising hot sheet around the equator and cylindrical downflow at the poles. This pattern of mantle flow is favoured by some researchers based on surface features [6].

A rigid lid increases the internal temperature by several hundred degrees. This increase in temperature, combined with the steepening gradient that accompanies an increase in T_0 , can lead to the destruction of hot plumes from the CMB, as shown in Figure B. The convection pattern now consists of a number of slowly wandering cold down-flow regions and a passive return flow of hot material.

Figure C is the equivalent of Figure A, but for the higher Rayleigh number of 3×10^6 . The internal temperature is cooler, flow is more chaotic and the aspect ratio of the cells is shorter. The pattern shown in A is not stable. Figure D illustrates the effect of a rigid surface condition (though in this example T_0 is low). Large-scale flow is divided into a few cells by relatively steady hot plumes, but there are smaller recirculating regions near the surface associated with local downwellings. Velocities at the surface are zero due to the no-slip condition so that fast outflow from the hot plumes travels in a wavy line underneath the local downflow before it reaches the main downflow region near the equator.

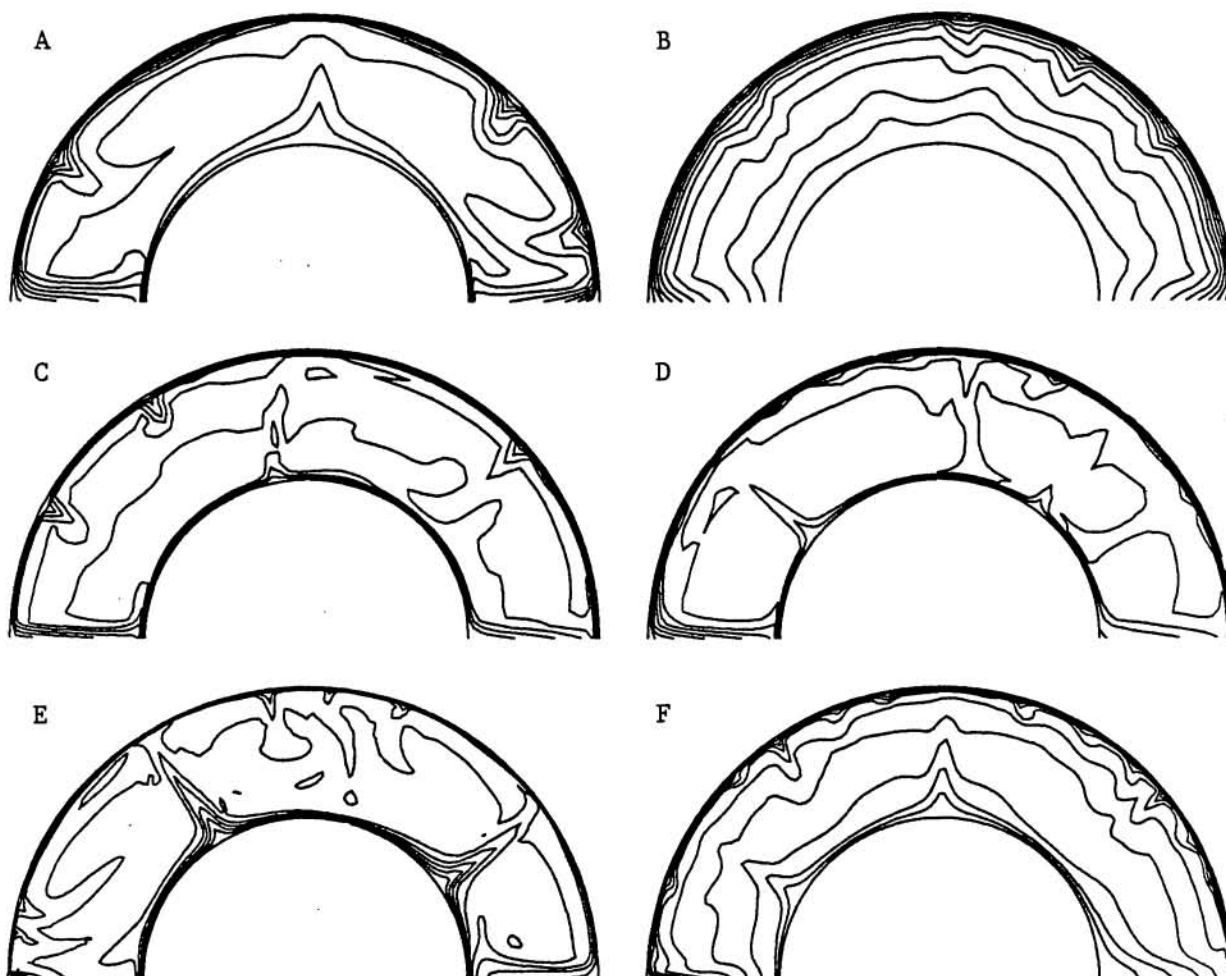
Figures E and F show convection at $Ra = 3 \times 10^6$ with viscosity varying according to the equation above. η increases about an order of magnitude with depth, there are low-viscosity regions associated with the bottom boundary layer and hot plumes and a high-viscosity region at the cold top boundary. Internal temperatures are lower than for cases C and D. Qualitatively, the convection pattern in E (free-slip surface) is similar to that of A, with upflow in single, very steady plumes and downflow in unsteady groups of plumes. For a rigid boundary (F) the hot plumes are also steady although they are not as strong and distinct because of the higher internal temperature. There are more frequent and less horizontally mobile cold downwellings.

Our results show a convection pattern with few large cells, steady upflow and unsteady downflow is

favoured for a Venus with high average viscosity or depth- and temperature-dependent viscosity. A rigid surface condition increases internal temperature and leads to smaller recirculating regions near the top boundary. For a rigid surface, chondritic quantities of heat-producing elements would produce melting of the mantle or core-heating unless viscosity is variable and the Rayleigh number is high (3×10^6).

Care must be taken in applying the exact patterns of convection found in the axisymmetric geometry to a spherical planet. Fully 3-dimensional simulations with constant viscosity [7] show upflow as always cylindrical rather than sheet-like (c.f. Fig A). However this result may change with a different rheology.

[1] Swell, G, 1985 "Analysis of a finite-element method", Springer-Verlag, New York. [2] Jarvis, G.T. and D.P. McKenzie, *J. Fluid Mech.* 96 (1980) 515-583. [3] Chopelas, A. and R. Boehler, *Geophys. Res. Lett.* 16 (1989) 1347-1350. [4] Kaula, W.M., *Geophys. Res. Lett.*, 17, 1401-1403, 1990b. [5] Leitch, A.M. and Yuen, D.A. (submitted to *J. Geophys. Res.*) [6] Head, J.W. and Crumpler, L.S., *Nature*, 346, 525-533, 1990. [7] Schubert, G., Bertovici, D. and Glatzmaier, G.A., *J. Geophys. Res.*, 95, 14105-14129, 1990.



Values of Ra , T_0 , R , $H/H_{chondritic}$ and surface stress condition for the figures are:

A: 3×10^5 , 0.2, 10, 1.2, free-slip; B: 3×10^5 , 1.0, 5, 0.3, rigid; C: 3×10^6 , 0.2, 10, 1.2, free-slip;

D: 3×10^6 , 0.2, 10, 1.2, rigid; E: 3×10^6 , 0.2, 10, 1.2, free-slip ($\eta(T, z)$); F: 3×10^6 , 0.6, 10, 0.9, rigid ($\eta(T, z)$).