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Numerical modelling of planetary interiors in a 3D spherical shell using StagYY

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Abstract

The latest generation of the global 3-D spherical convection modelling code StagYY [1], which is developed from Stag3D [2] 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 [3]), chemical differentiation induced by melting, large viscosity variations, a parameterized core heat balance, and a realistic treatment of phase diagrams and material properties. Spherical geometry is handled using the so-called "yin-yang" grid [4], while in 2-D, a "spherical annulus" geometry is used [5].

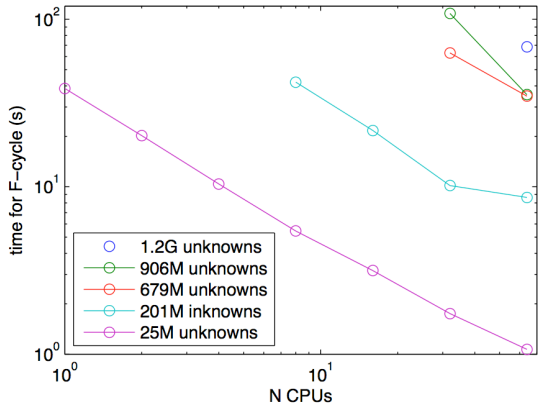

Figure 1. Speed and parallel scalability on a cluster of dual opteron nodes, from [1].

StagYY uses a multigrid solver to obtain a velocity-pressure solution at each time step, which in principle gives linear scaling of execution time with number of grid points. It is parallelised using a simple three-dimensional domain decomposition. Figure 1 shows the performance and scaling of the solver, in terms of for up to 1.2 billion unknowns on 1 to 64 opteron CPUs. 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 used here.

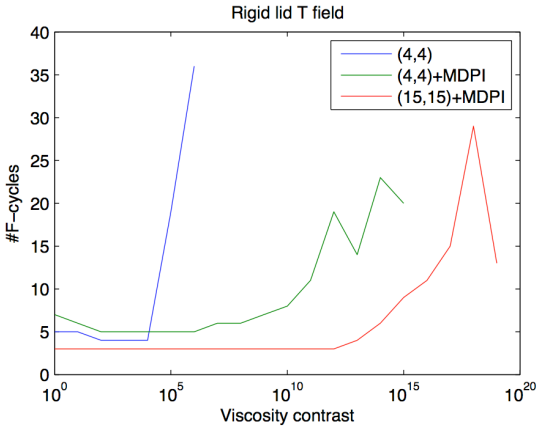

Figure 2. Number of multigrid cycles needed to obtain convergence as a function of viscosity contrast, showing the improvement made by the MDPI scheme (green compared to blue lines) and further by increasing the number of iterations at each level (red line), from [1].

Recently a major improvement was made in its ability to handle large viscosity contrasts, by using a pressure interpolation algorithm from coarse to fine grids that takes into account viscosity variations on the fine grid. The improvement given by this MDPI algorithm is illustrated in Figure 2, which shows the number of multigrid F-cycles necessary to obtain a converged solution for a test problem in which the viscosity contrast is varied. Without MDPI and with four smoothing sweeps on each grid, the viscosity contrast is limited to a factor 10^5. With MDPI, this is increased to a factor 10^{15}, and if fifteen sweeps are used at each level, a factor 10^{19} can be handled. This allows the use of "laboratory" rheological parameters in global simulations.

Recently a self-consistent treatment of mineralogy and petrology was added using free energy

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minimization to compute stable phases as a function of temperature, pressure, and composition as expressed by ratios of the five main oxides [6], and thus avoids the need for increasingly complicated and ad hoc parameterizations of phase transitions.

With modern computer clusters, the planets Mercury, Mars and Venus can be simulated in a realistic parameter range (i.e., Rayleigh number, viscosity contrast, etc.) for billions of years, although the is still computationally prohibitive for Earth. In ongoing research, this tool is being applied to understand the evolution of several planets including Earth (e.g., [6-9]), Mars [10] (Keller and Tackley, this session), Venus (Armann and Tackley, this session), Mercury, and extra-solar "super-Earths" (van Heck and Tackley, this session; Tackley et al., this session).

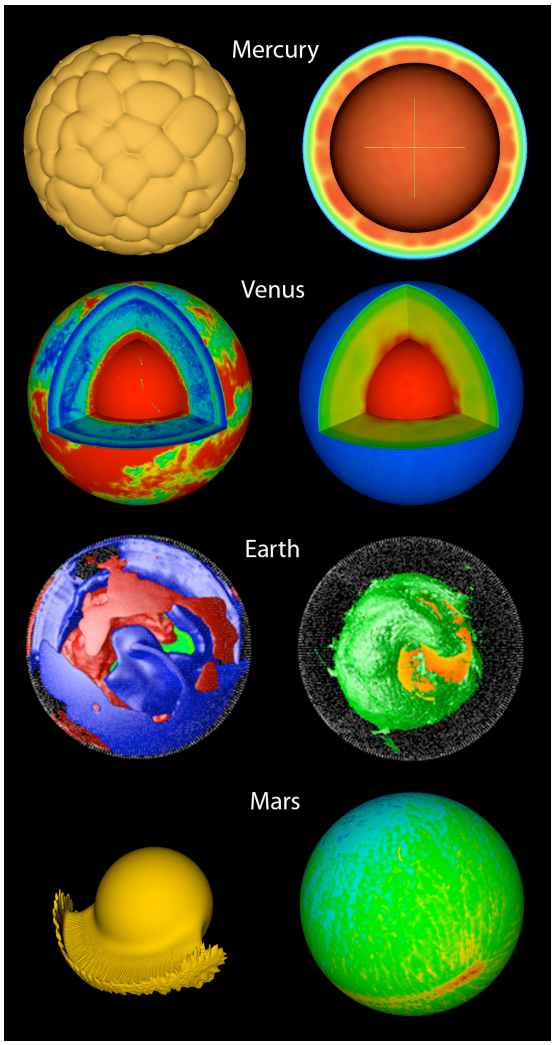

Figure 3. Example simulations using Stag3D. Further details can be found in Armann and Tackley (this session) and Keller and Tackley [10](this session).

References

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