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Title : Thermal History and Mantle Dynamics of Venus

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## Introduction :

One objective of this research proposal is to develop a 3-D thermal history model for Venus. The basis of our study is a finite-element computer model to simulate thermal convection of fluids with highly temperature- and pressure-dependent viscosities in a three-dimensional spherical shell. A three-dimensional model for thermal history studies is necessary for the following reasons. To study planetary thermal evolution, one needs to consider global heat budgets of a planet throughout its evolution history. Hence, three-dimensional models are necessary. This is in contrasts to studies of some local phenomena or local structures where models of lower dimensions may be sufficient. There are different approaches to treat three-dimensional thermal convection problems. Each approach has its own advantages and disadvantages. Therefore, the choice of the various approaches is subjective and dependent on the problem addressed. In our case, we are interested in the effects of viscosities that are highly temperature dependent and that their magnitudes within the computing domain can vary over many orders of magnitude. In order to resolve the rapid change of viscosities, small grid spacings are often necessary. To optimize the amount of computing, variable grids become desirable. Thus, the finite-element numerical approach is chosen for its ability to place grid elements of different sizes over the complete computational domain. For this research proposal, we did not start from scratch and develop the finite element codes from the beginning. Instead, we adopted a finite-element model developed by Baumgardner, a collaborator of this research proposal, for three-dimensional thermal convection with constant viscosity. Over the duration supported by this research proposal, a significant amount of advancements have been accomplished.

## Research Results to Date :

Governing equations for thermal convection within a fluid spherical shell with variable viscosity are much more complex than that for constant viscosities. The original computer codes from Baumgardner have been extensively re-written to accommodate the effects of variable viscosity. Finite element formulations usually result in a set of matrix equations, which in turn are solved for the final solutions. In our three-dimensional simulations, a grid system that has 16 radial grid points and 32 grid points in the azimuthal directions is used. The resultant matrix is of a rank of 522,342. Any slight refinement in grid spacing will cause the matrix rank to exceed one million. These are extremely large matrices to solve even for the current generation of supercomputers. Generally, iterative schemes are employed to solve large matrices such as ours, instead of using direct inversion techniques. Iterative schemes require the minimization of errors that arise from the differences between an approximate solution and the true solution. It has been demonstrated that short wavelength errors can be effectively removed using relaxation techniques such as Jacobi or Gauss-Seidel methods. However, long wavelength errors cannot be removed effectively using successive relaxation. Thus, a multigrid method is adopted not only to improve the accuracy of the solutions, but also to accelerate the convergence of the iterative matrix solver. The traditional multigrid method was designed for systems of scaler operators and with constant coefficients. Substantial effort has been devoted to implement the multi-grid idea to treat systems of vector operators and with variable coefficients that is more appropriate to our study because we are dealing with flow velocity fields with variable viscosities. The procedure developed is named Matrix Dependent Transfer and it is discussed in details in the PhD thesis of Woo-Sun Yang (1997).

After all the computing elements were put into place, simulations of convective dynamics were carried out. We first investigated the production of toroidal energy within a three dimensional convective system. For the Earth's surface, poloidal and toroidal energies are equally partitioned approximately. It is also known that constant viscosity convective systems are unable to generate toroidal energies. Therefore, it is important to determine how much viscosity variations are necessary to generate the observed amount of toroidal energy. According to our simulations (Hsui et. al., 1995), it appears that variable viscosity convection with a viscosity variation of less than three orders of magnitude over the complete convection regime is able to produce toroidal energy at a level of no more than 5 - 15% of the poloidal energy. It is far from the equal partition that is required for the Earth. Suggestions have been made that with rigid plates at the surface, it is possible to produce more toroidal energies. The question is whether rigid plates can be simulated within the context of variable viscosity convection. At present, it is difficult to resolve viscosity changes of one order of magnitude over a distance of only 100 km even with the fastest computer. With the current models, it appears that resolving power of a few orders of magnitude of viscosity difference over one grid element is needed to simulate rigid plates. Alternatively, a new modeling approach must be developed. Recently, we found (Yang, 1997) that if non-Newtonian rheology is incorporated to form a hybrid rheological model for our simulation, a toroidal-poloidal energy ratio as large as 35% is observed. It is encouraging to learn that substantial amount of toroidal energy can be produced using some hybrid rheological models.

From Magellan observations, there exist a number of large coronae on the surface of Venus. These coronae structures are probably the result of up-wellings within the Venusian mantle. The existence of coronae, therefore, suggests that the Venusian mantle could be dominated by poloidal energies. It follows that the viscosity of the Venusian mantle must be relatively uniform, reflecting a relatively constant thermal (or temperature) state horizontally. In other words, the Venusian mantle dynamics are probably not as rigorous as that of the Earth since thermal convection is driven by horizontal thermal gradients..

In our three dimensional simulations, we are unable to obtain solutions for viscosity variations larger than three orders of magnitude across the field of computation. It is mainly because our grid sizes are too coarse to resolve larger viscosity gradients. With

32 or 64 radial grid points, our grid spacing varies between 100 to 50 km. These grid sizes are able to resolve viscosity differences of no more than 10 over 100 km. Any gradient larger than this value will eventually lead to numerical instabilities. Nevertheless, with the present simulations we have obtained, some general conclusions can be delineated.

Generally, the interior of a convective system is under fairly uniform thermal states. For internally heated systems, dominating flows are the cold down-going plumes. These plumes are transient in nature. In our simulations, we do not see many up-welling structures. Down-going plumes are found to be narrow and well defined. They are initiated at the surface frequently and become diffused as they moved towards the bottom of the mantle. We have changed the radial viscosity structure to study the effects of radial viscosity stratifications. We confirm that kinetic energies tend to concentrate on low viscosity zones. Although concentration of high viscosity materials has significant effects on interior convective patterns, total surface heat flows do not seem to be greatly affected. This is probably due to the fact that the Rayleigh numbers used are sufficiently high and the flows are sufficiently rigorous that the internal thermal budget is self-regulating.

Through the support of this research proposal, following abstracts, articles and Ph. D. thesis are produced. Application of our convection simulations to Venusian thermal history studies remains a part of my on-going research. More articles derived from this investigation are planned. They will be submitted for publication when they become available.

List of Abstracts and Publications Derived from this Research Proposal :

Yang, W-S, A. T. Hsui and J. R. Baumgardner, On Energy Partition within a Dynamic Spherical Mantle, EOS.Trans. AGU, 73, No. 43, 575, 1992.

Yang, W-S, A. T. Hsui and J. R. Baumgardner, Flow Structure and Energy Partition within a 3-D Spherical Mantle of Variable Viscosity, EOS. Trans. AGU, 74, No. 16, 299-300, 1993.

Hsui, A. T., and J. R. Baumgardner, Surface Temperature, Mantle Convection and Thermal History of Venus, EOS. Trans. AGU, 74, No. 43, 378, 1993.

Yang, W-S, and A. T. Hsui, An Analysis of Poloidal and Toroidal Energy Partition and Its Implications to the Thermal State and Evolution of Venusian Interior, EOS. Trans. AGU, 75, No. 16, 220, 1994.

Yang, W-S, J. R. Baumgardner and A. T. Hsui, Modeling Variable Viscosity Mantle Dynamics in 3D Spherical Geometry, EOS. Trans. AGU, 76, F606, 1995.

Hsui, A. T., W-S Yang and J. R. Baumgardner, A preliminary study of the effects of some flow parameters in the generation of poloidal and toroidal energies within a 3-D spherical thermal convective system with variable viscosity, Pageoph, 145, 487-503, 1995.

Yang, W-S, Variable Viscosity Thermal Convection at Infinite Prandtl Number in a Thick Spherical Shell, PhD Thesis, Department of Geology, University of Illinois at Urbana-Champaign, Urbana, Illinois, 188 pp., 1997