Vorticity Generation and Heat Transport in 3D Anelastic Simulations of the Internal Dynamics of Giant Planets without Cores

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Abstract
Differential rotation, similar to that seen on our gas giants, is manifested at the surface of three-dimensional (3D) computer simulations of thermal convection in density-stratified rotating planets without solid cores. Below the surface, the flow forms short axially-aligned vortices, generated by fluid expanding as it rises and contracting as it sinks. The convergence of the nonlinear Reynolds stresses resulting from the vorticity generated by fluid flowing through the density stratification maintains the surface banded zonal flow without the classical vortex stretching of Taylor columns. These preliminary simulations demonstrate that large non-convection cores are not required to obtain multiple zonal jets at the surface, and show greater convective heat flux towards the poles relative to that seen at the equator. This result could help explain the nearly uniform with latitude thermal emission observed at the surface of Jupiter.

Model Setup
- 3D finite volume code
- Impermeable outer boundaries
- Internal heating inner 35% of planet
- 10 hour rotation rate
- No magnetic fields
- No core
- Five density scale heights
- Resolution: 400¹

Anelastic Equations:
- Entropy Equation
  \[ \frac{\partial}{\partial t} \left( \hat{\rho} S \right) = \nabla \cdot \left( \hat{\rho} \bar{u} - \hat{S} \nabla \right) \frac{C_s \hat{S}}{T} \frac{\partial T}{\partial t} \]
- Momentum Equation
  \[ \frac{\partial}{\partial t} \left( \hat{\rho} u \right) = \nabla \cdot \left( \hat{\rho} \bar{u} u + P \delta + 2
\rho \nu \left( \nabla \cdot \delta \right) - \frac{1}{2} \left( \nabla \cdot \bar{u} \right) \delta \right) + \hat{\rho} \nu \Omega \]
- Conservation of Momentum Flux
  \[ \nabla \cdot \left( \hat{\rho} u \right) = 0 \]

Surface Banded Flow
- Snapshots of meridional slice
- Snapshots of negative and positive vorticity contours

Zonal Flow: A simulation without a core is able to maintain a multiple jet zonal flow structure even at relatively low resolution. Note: The zero in the velocity plot is chosen based on the volume-integrated angular momentum, while the zero in similar plots for Jupiter and Saturn are chosen based on the rotation rates of the surface magnetic fields as the interior profiles of angular momentum for these planets are unknown.

Convergence of Reynolds Stresses: local generation due to density stratification (Anelastic)

Linear Generation of Vorticity Non-Linear convergence of Angular Momentum Flux

Heat Transport surface contour plot

References:

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In 3D simulations without a core, while we see axially aligned vorticity features, we see no evidence for Busse columns which would consist of coherent columns spanning the convection zone from pole to pole.

Vorticity Parallel to the Axis of Rotation
- Negative vorticity
- Positive vorticity

Simulation results show to first order lower flux in the equatorial regions. The absolute amplitudes of the flux for Jupiter and the simulation are not shown as the simulation is driven much harder than Jupiter to compensate for the necessarily larger diffusivities used in the simulation. Also to first order we see asymmetrical distributions of the heat at the surface of the planet with an overall trend towards higher temperatures in the southern hemisphere similar to the trend seen at the 150-mbar level in Saturn’s atmosphere. These results are time dependent and the simulation is not specific to either planet.

Energy Balance of Jupiter. The solid black lines are the thermal and absorbed energy, and the internal energy is calculated as the excess of the thermal over the absorbed energy (Pirraglia 1984). Overlaid, as a green line, is the internal heat flux for the model simulation with no core.

Temperatures retrieved by inversion of Voyager infrared spectral measurements. The broken curve is a fit to the northern hemisphere 150-mbar temperatures which has been fielded ever at the equator to compare with southern hemisphere (Goel and Pirraglia 1983). Overlaid is a similar profile in green for the simulation with no core.