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-convecting 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: 400^3

Anelastic Equations:

Entropy Equation

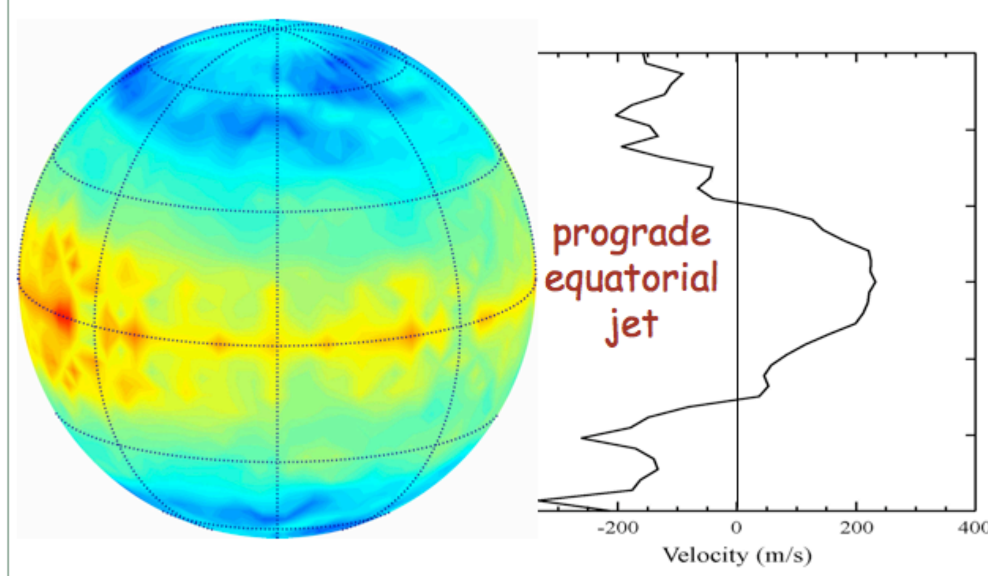
$$\frac{\partial}{\partial t}(\bar{\rho} S) = -\nabla\cdot\left(\bar{\rho} S u - \kappa_T \bar{\rho}\nabla S - \frac{C_P \kappa_R \bar{\rho}}{\bar{T}}\nabla T\right) + \frac{\bar{\rho}}{\bar{T}}\frac{d\bar{T}}{dr}\left(\kappa_T \frac{\partial S}{\partial r} + \frac{C_P \kappa_R}{\bar{T}}\frac{\partial T}{\partial r}\right) + \bar{\rho} Q_s$$

Momentum Equation

$$\frac{\partial}{\partial t}(\bar{\rho} u) = -\nabla\cdot\left[\bar{\rho} u_i u_j + P\delta_{ij} - 2\bar{\nu}\,\bar{\rho}\left(e_{ij} - \frac{1}{3}(\nabla\cdot u)\delta_{ij}\right)\right] - \rho g \hat{r} + 2\bar{\rho} u \times \Omega$$

Conservation of Momentum Flux $\nabla\cdot(\bar{\rho} u) = 0$

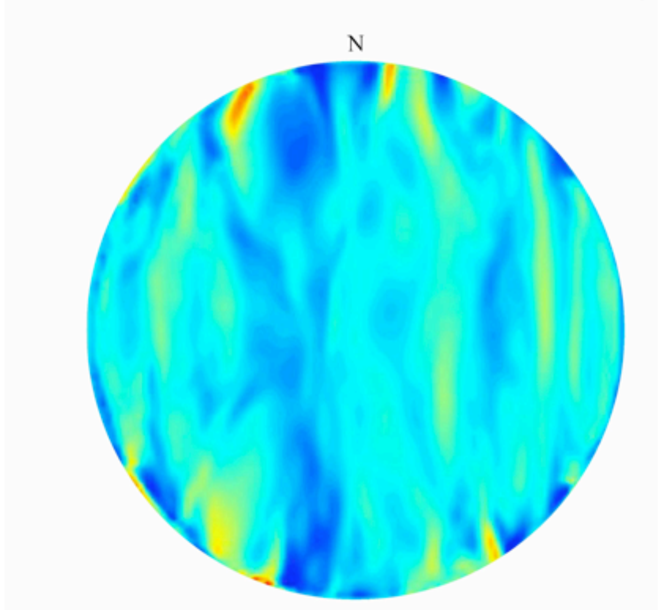
Surface Banded Flow



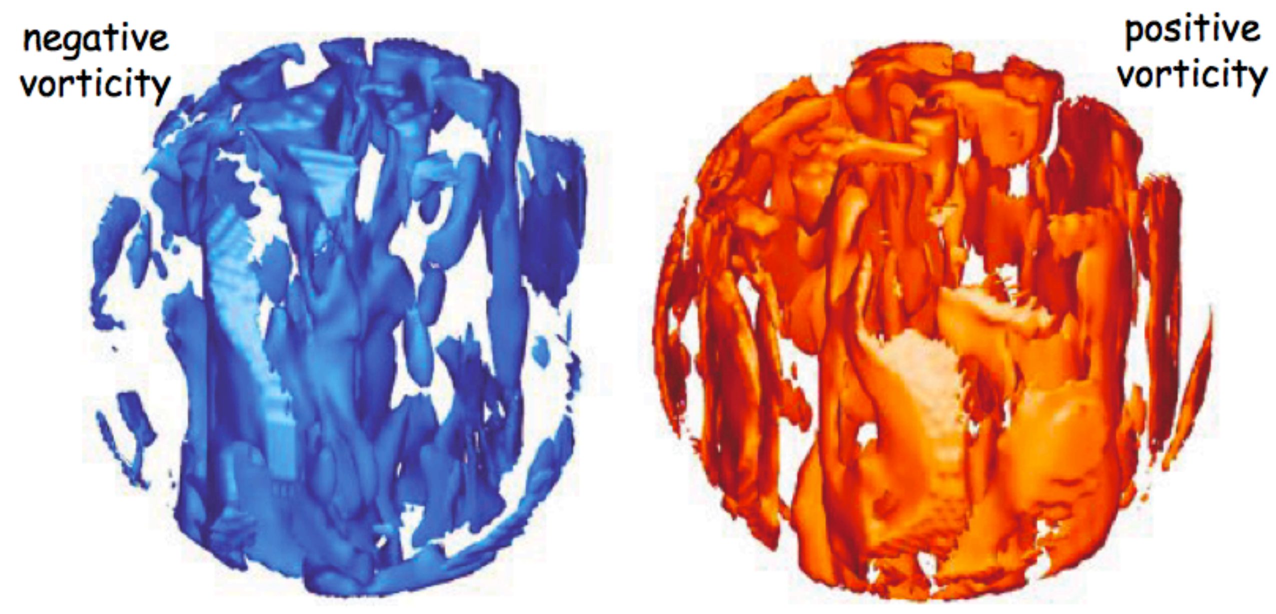
Zonal Flow: Asimulation without a core is able to maintain a multiple jet zonal flow structure even at relatively low resolution. Note: The zero in the velocity plot is chosen based on the volume-integrated angular momentum, while the zero in similar plots for Jupiter and Saturn are chosen based on the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

Vorticity Parallel to the Axis of Rotation

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.



Snapshot of meridional slice

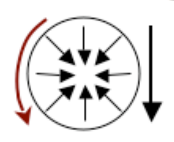


Snapshots of negative and positive vorticity isosurface contours.

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

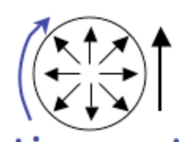
Linear Generation of Vorticity

sinking contracting material



positive vorticity

rising expanding material



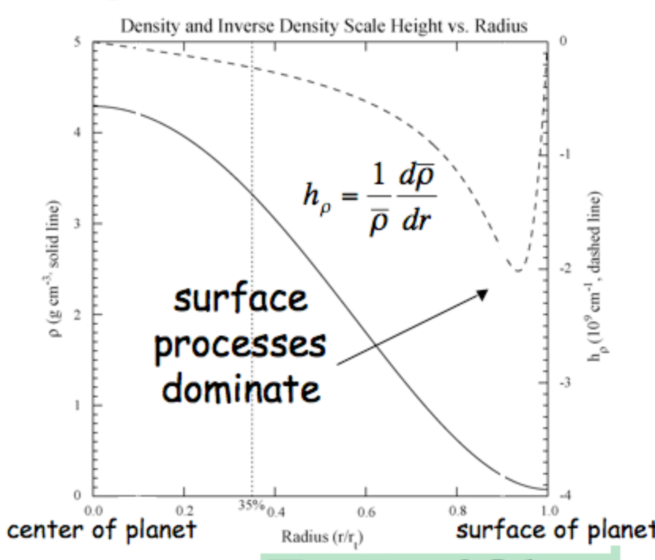
negative vorticity

⊙ rotation axis out of the page

Coriolis Force

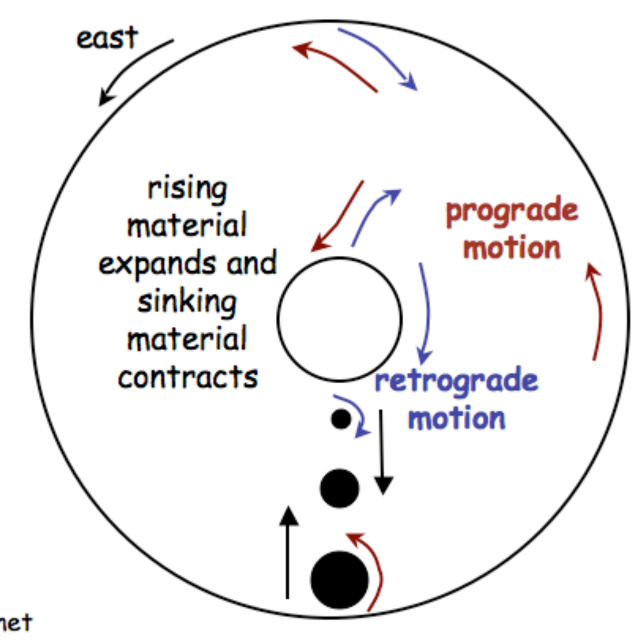
$F_c = 2u \times \Omega$

Non-Linear convergence of Angular Momentum Flux

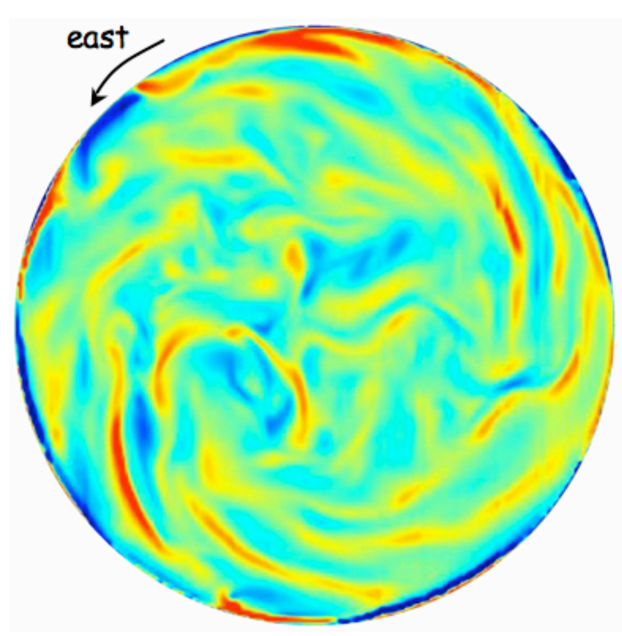


Curl of the Coriolis Force

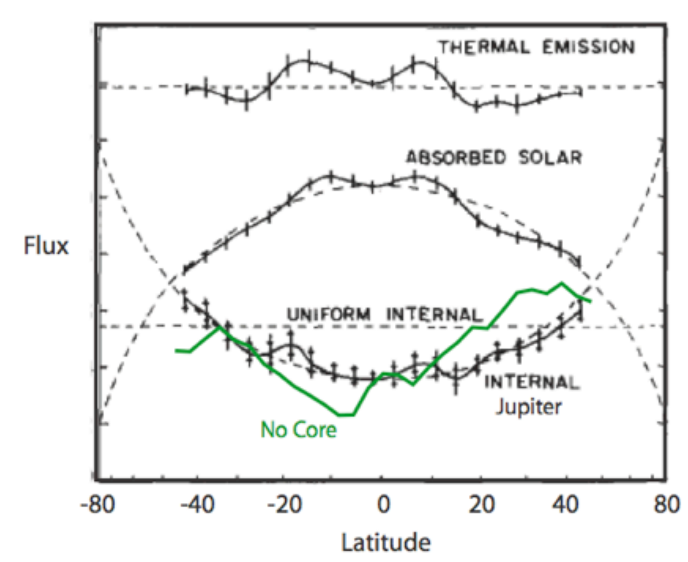
$\nabla \times F_c = 2\Omega h_\rho u_r$ (axial component in the equatorial plane)



Positive vorticity converges at outer boundary



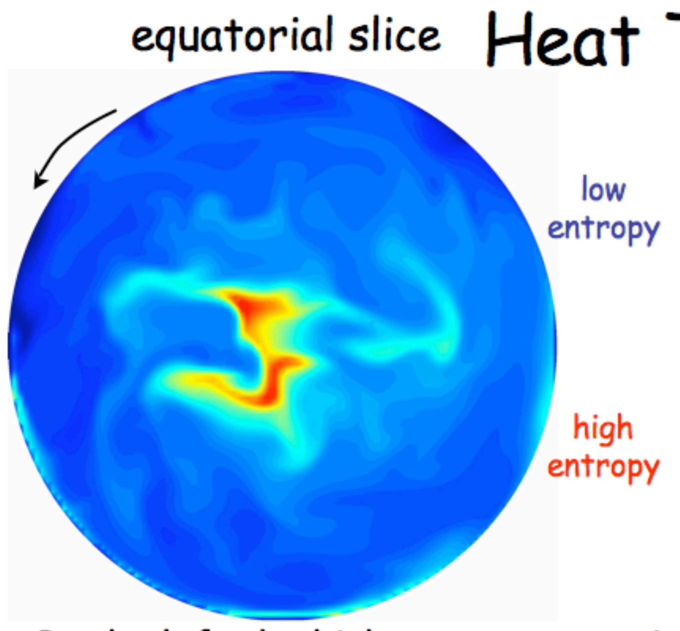
Colatitudinal vorticity in the equatorial plane viewed from Northern hemisphere



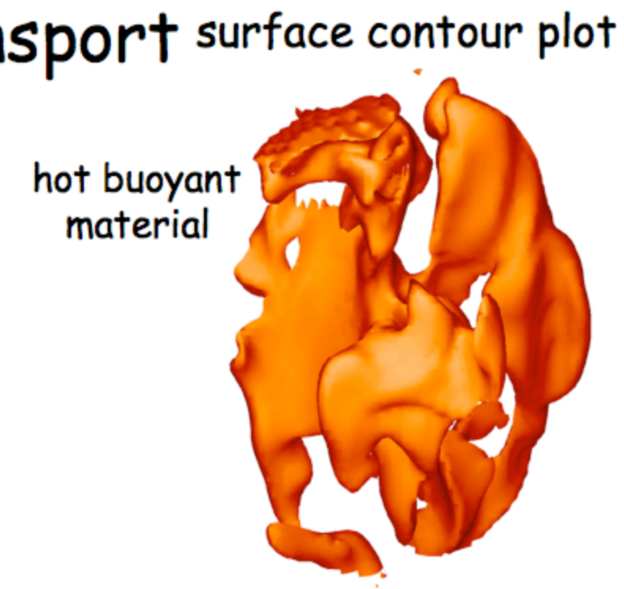
Energy Balance of Jupiter. The solid black lines are the thermal and absorbed energy, and the internal energy is calculated as the excess of the thermal over the absorbed energy (Parraglia 1984). Overlaid, as a green line, is the internal heat flux for the model simulation with no core.

Heat Transport

equatorial slice

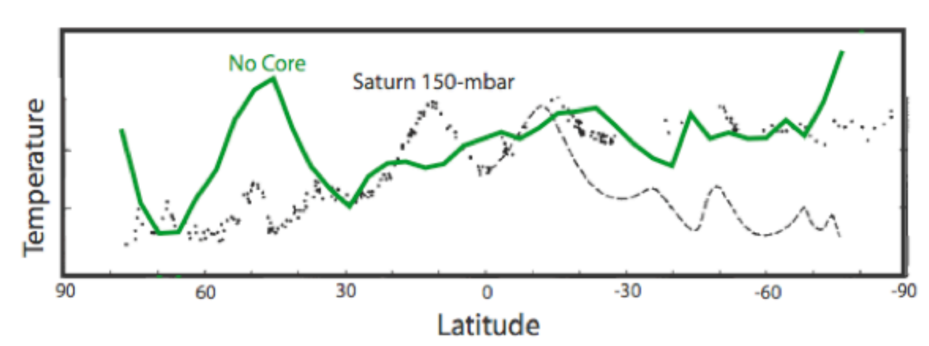


surface contour plot



On the left the high entropy material in the central equatorial regions spirals towards the surface following the pattern of the colatitudinal vorticity. On the right high entropy fluid shows preferential movement towards the surface high latitude regions as it moves along the columnar vorticity features parallel to the axis of rotation.

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.



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 folded over at the equator to compare with southern hemisphere (Conrath and Pirraglia 1983). Overlaid is a similar profile in green for the simulation with no core.

Preferential flow of high entropy along vorticity structures in fast rotating cases is important for giant planets. While fast convection is likely restricted to a thin shell due to suppression of convection in the metallic hydrogen region by the strong magnetic field, the base of this fast convection shell is likely to have non-uniform entropy and flux.

References:

Conrath, B. J., Pirraglia, J. A., 1983. Thermal structure of Saturn from Voyager infrared measurements: Implications for atmospheric dynamics. *Icarus* **53**, 286-292.

Pirraglia, J. A., 1984. Meridional energy balance of Jupiter. *Icarus* **59**, 169-176.

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