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Dynamo models for Jupiter and Saturn

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Abstract

Jupiter's dynamo is modelled using the anelastic convection-driven dynamo equations. The reference state model is taken from French et al. 2012, which used density functional theory to compute the equation of state and the electrical conductivity in Jupiter's interior. Jupiter's magnetic field is approximately dipolar, but self-consistent dipolar dynamo models are rather rare when the large variation in density and the effective internal heating are taken into account. Jupiter-like dipolar magnetic fields were found here at small Prandtl number, $Pr = 0.1$. Strong differential rotation in the dynamo region tends to destroy a dominant dipolar component, but when the convection is sufficiently supercritical it generates a strong magnetic field, and the differential rotation in the electrically conducting region is suppressed by the Lorentz force. This allows a magnetic field to develop which is dominated by a steady dipolar component. This suggests that the strong zonal winds seen at Jupiter's surface cannot penetrate significantly into the dynamo region, which starts approximately 7000 km below the surface. Saturn's magnetic field presents more challenges, as the observed field is nearly axisymmetric and the ratio of the dipole to the octupole component suggests that in the magnetic core the field is concentrated near the polar regions. It seems likely that a stably stratified layer above the dynamo region is necessary for a successful Saturn dynamo model.

1. Introduction

Our model for Jupiter assumes a rocky inner core of radius 6700 km. For computational reasons the model is cut off 3000km below the surface, so the outermost regions, where the fluid is electrically non-conducting, are omitted. Our heating model assumes Jupiter releases uniform specific entropy as it cools through a succession of adiabats. The electrical conductivity is taken from French et al. 2012. The model assumes that Jupiter has no stably stratified layers. We integrate the anelastic equations for rotating MHD convection, using a code tested against the anelastic dynamo benchmark (Jones et al. 2011).

2. Results

We find that stable dipolar magnetic fields are much harder to find in compressible models than in Boussinesq models. However, at low Prandtl number (ratio of viscous diffusion to thermal diffusion small, as expected in Jupiter), stable dipolar fields resembling the Jovian field are found, see figure 1 (Jones, 2014).

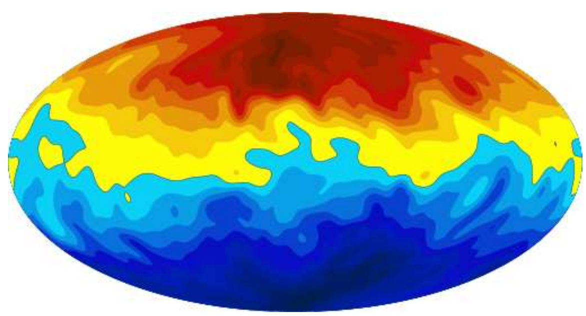

Figure 1: Simulation of the surface radial magnetic field of Jupiter.

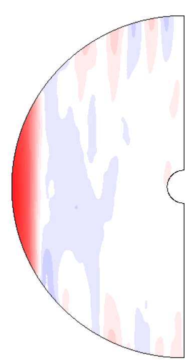

Figure 2: Meridional section of the axisymmetric component of the azimuthal flow.

To obtain a stable dipole field it is necessary that the field is strong enough to suppress the differential rotation in the electrically conducting region. If the field is weak, strong differential rotation gives rise to dynamo waves, which preclude Jupiter-like fields. A strong zonal flow which is independent of z, the coordinate parallel to the rotation axis, is found outside the tangent cylinder surrounding the electrically conducting dynamo region, in the equatorial zone: see figure 2. This zonal flow arises from the action of Reynolds' stresses arising from the nonmagnetic rotating convection in this region.

3. Conclusions

Our estimate of the convective velocity is of order 10^{-3} m/sec, consistent with the velocity required to transport the observed heat flux. A larger value would give rise to a secular variation greater than that which occurs on Jupiter. Our models suggest that the differential rotation is not much larger than the convective velocity in the electrically conducting region, at depths below 7000 km under the surface. Outside the tangent cylinder, convection can give rise to much larger zonal flows, so within latitude $\sim \pm 26^\circ$ the zonal flow could be geostrophic and therefore deep. At higher latitudes, it is not possible for a large zonal flow to be constant on cylinders whose axis is parallel to the rotation axis, because these cylinders cut the electrically conducting region where there is only weak zonal flow. The zonal flow at high latitudes must therefore be ageostrophic, and so most likely is confined to a shallow stably stratified layer.

Reference state models for Saturn based on *ab initio* calculations are not yet available, so currently we are using models scaled from Jovian values for the electrical conductivity. Work is still in progress on Saturn's dynamo, but initial results indicate that for steady, nearly axisymmetric, anelastic dynamos, we need a convectively stable layer above the dynamo region. Provided the differential rotation in this stable layer can be maintained, the non-axisymmetric field components that must be part of the full magnetic field (Cowling's theorem) can be smoothed out, leaving only the axisymmetric part visible at the surface (Stevenson, 1982).

Acknowledgements

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