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A dynamo driven by zonal jets at the upper surface in the giant planets

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Abstract

A dynamo mechanism explains the dipolar magnetic field of Jupiter and the multipolar magnetic field of Neptune in terms of the width of the zonal jet streams observed at their surfaces.

1 Introduction

The multiple zonal (i.e. axisymmetric and azimuthal) winds observed at the surface of the giant planets can be explained by the non-linear interaction of convective motions within a thick outer molecular hydrogen layer [3]. In these deep non-magnetic models, zonal motions extend geostrophically, i.e. aligned with the rotation axis, throughout the planet's interior despite the increase of density with depth yielding ageostrophic convective motions [4]. However, due to the rapid increase of electric conductivity with depth in the outer region [5] angular momentum may be transported along the magnetic field lines leading to a so-called "Ferraro state" [1]. Both scenarios, either geostrophic zonal balance or Ferraro state, suggest the presence of multiple zonal jets of significant amplitude at the top of the fully electrically conducting region beneath, within which a dynamo mechanism generates the strong magnetic fields observed at the surface of the giant planets. We argue that, by viscous or electromagnetic coupling, these jets drive deep zonal motions in the bulk of this envelope that may contribute to the dynamo mechanism.

2 Numerical model

In order to study the plausibility of a dynamo driven by this coupling we carried out numerical simulations using a 3D self-consistent dynamo model (described in [2]). A latitudinally dependent zonal velocity profile imposed at the surface of a rapidly rotating spherical shell drives geostrophic zonal motions of a conducting, incompressible and isothermal fluid. For strong surface forcings, shear instabilities arise in the strongest shear bands. They take form of Rossby waves, azimuthal necklaces of cyclonic and anticyclonic vortices elongated along the axis of rotation, that propagate eastward due to the spherical geometry. The wavenumber is determined by the width of the unstable zonal jet. A dynamo magnetic field is sustained by a classical $\alpha-\omega$ mechanism: the strong zonal shear generates a strong internal axisymmetric toroidal field (ω-effect), while the vortical motions of the Rossby waves generate a poloidal field (macroscopic α-effect) that extends out of the conducting region. The non-axisymmetry of the wave and its propagation are both key ingredients in the dynamo mechanism.

3 Results

A narrow Jupiter-like jet profile is unstable to shear instabilities of azimuthal wavenumber $m = 22$ for a critical equatorial zonal forcing velocity of 10m/s, about 10 times slower than Jupiter's surface wind. If the dynamo threshold (that is the critical magnetic Reynolds number) is independent of the Ekman number [6], then this Rossby wave dynamo mechanism is sustainable for an electric conductivity greater than 100S/m in the jovian metallic region, which is likely the case [5]. Interactions between the small scale ($m = 22$) velocity and induced magnetic fields produce a dominant axisymmetric outer dipolar magnetic field (corresponding to $l = 1$ on the magnetic energy spectrum).

A broad Neptune-like jet profile is unstable for a forcing 4 times slower than the observed surface wind. The instability takes the form of a $m = 2$ Rossby wave that propagates too rapidly compared to the magnetic diffusion rate at the vortex scale to produce a large scale dipolar magnetic field. The field is mainly axisymmetric multipolar ($l = 2, 4$ on the magnetic energy spectrum) with significant contributions from the $m = 2$ structures.

4 Discussion

Our results suggest that the differences in the magnetic fields and the surface zonal winds of the Gas Giant and Ice Giant planets are related through a dynamo mechanism arising from the transport of angular momentum between the surface and the deep conducting region. In the presence of convection, and even for a convectively-driven dynamo, the mechanism described here may still impose a similar relationship between the magnetic field morphology and the zonal wind profile. The following predictions of our model can be tested against the magnetic measurements of the forthcoming Juno mission : (i) the presence of a peak at small azimuthal scale in the magnetic field spectrum that is correlated with the width of the hydrodynamically unstable zonal jets; and (ii) a correlation between the secular variations of zonal jets and the external magnetic field.

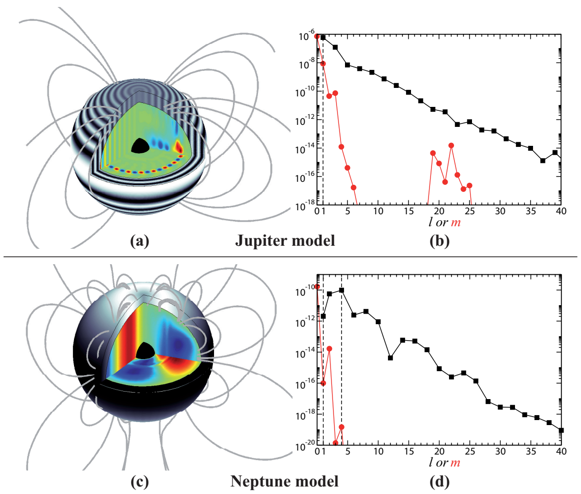

Figure 1: (a) and (c): In the conductiong electrically region (colored planes), we plot the zonal velocity (left meridional plane), axisymmetric azimuthal magnetic field (right meridional plane) and radial velocity (equatorial plane). The gray lines represent the magnetic field lines outside of the fully conducting region. Zonal winds in the molecular hydrogen layer (assumed geostrophic for simplicity) are shown in black (westward) and white (eastward); (b) and (d): Magnetic energy spectra at the surface of the planet for each latitudinal mode l (black squares) and azimuthal mode m (red circles) given in units of $\rho\mu_0 r_o \Omega U_0$ with ρ the density, μ_0 the vacuum magnetic permeability, r_o the radius of the conducting layer, Ω the rotation rate and U_0 the equatorial zonal velocity imposed at the top of the model.

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