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.

The idea

- Surface zonal winds may extend over the whole molecular hydrogen layer [1]
- They can drive motion by viscous or electromagnetic coupling inside the electrically conducting core.
- These shearing motions are unstable and produce a drifting Rossby wave.
- The combination of shear (Ω-effect) and Rossby wave (α-effect) can produce a self-induced magnetic field.

We find that the width of the jets controls the topology of the resulting magnetic field, in good agreement with Jupiter and Neptune.

Does this also work with variable conductivity in the upper layer ?

Due to the rapid increase of electric conductivity with depth in the outer region [2] angular momentum may be transported along the magnetic field lines leading to a so-called Ferraro state [3].

We performed some axisymmetric simulations with variable conductivity to show how the picture is modified. In the case below, the zonal velocity strength is divided by 15, and the velocity profiles go from a Ferraro state (iso-rotation lines aligned with magnetic field lines) to a Proudman-Taylor state (iso-rotation lines aligned with global rotation axis).

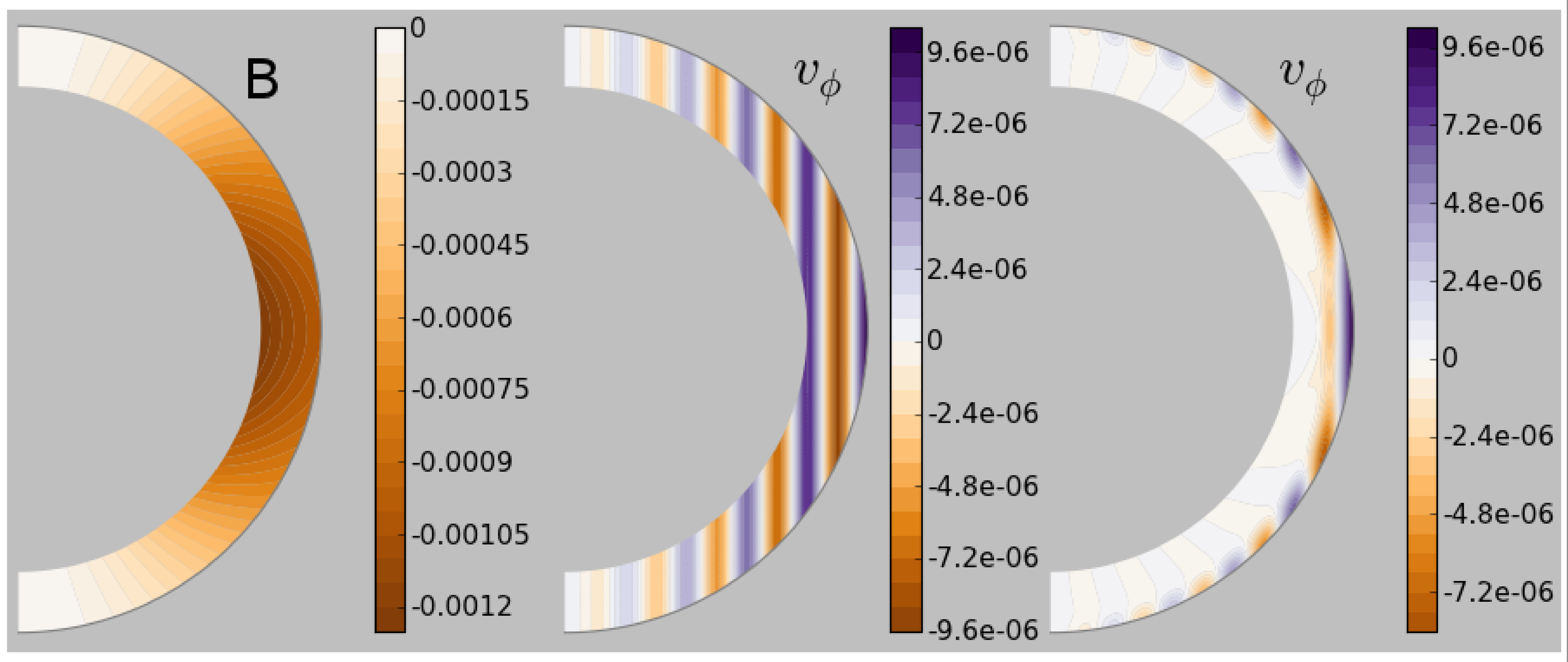

Figure: From left to right : imposed magnetic field (dipolar), velocity field produced by bulk forcing in insulator, velocity field produced by the same forcing but in a layer of conductivity exponentially decreasing with radius by a factor 10^6. At the bottom of the layer ($r = 0.8$), the following parameter were set : $Ek = 10^{-8}$, $Ro = 10^{-5}$, $\Lambda = 15$, $\lambda = 0.004$, $Pm = 0.01$, $Re = 1000$, $S = 4000$.

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.

Shear instability and Rossby waves

For strong surface forcings, shear instabilities arise (Kelvin-Helmoltz type) 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.

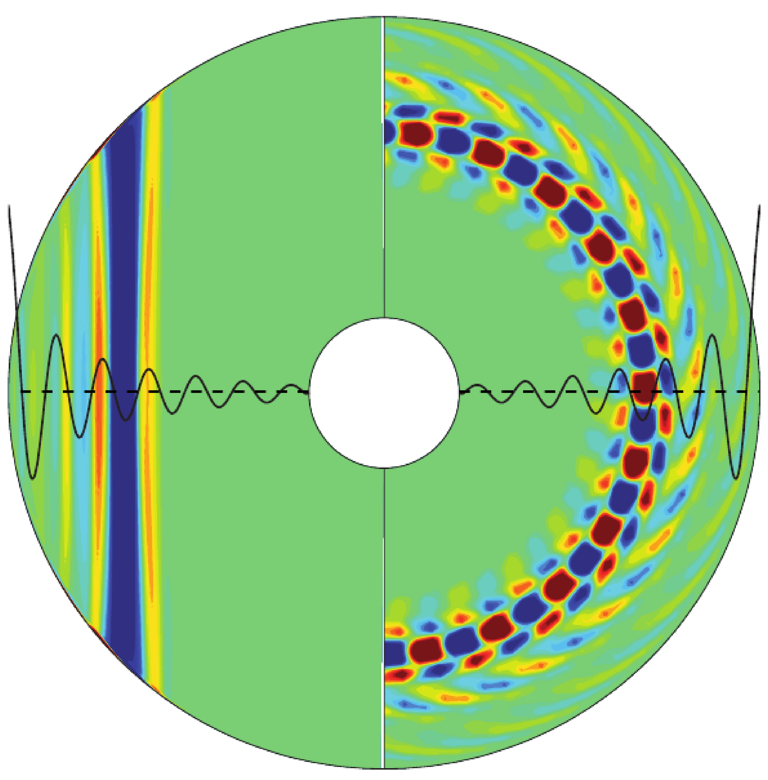

Figure: Non-zonal axial vorticity in the equatorial plane (right) and in a meridional slice (left) for the profile J at $E = 4 \times 10^{-6}$ and $Ro = 1.01 Ro_c$ (blue: negative and red: positive). The black line represents the zonal velocity in the equatorial plane.

Dynamo mechanism

The non-axisymmetry associated with the hydrodynamic shear instability is a crucial element for the dynamo process: the stable zonal flow cannot sustain a magnetic field by itself.

In addition the propagation of the wave is of prime importance too, as a snapshot of the flow does not induce a magnetic field [4, 5].

It appears that a slow small scale Rossby wave (case of Jupiter) is able to produce a dipolar magnetic field, while a fast large scale wave (case of Neptune) leads to quadrupolar field.

Numerical model

For the self-sustained dynamo numerical simulations, we use a 3D self-consistent dynamo model [6]. 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.

Dynamos for Jupiter and Saturn, driven by deep zonal motions

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 [4], 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 [2]. 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.

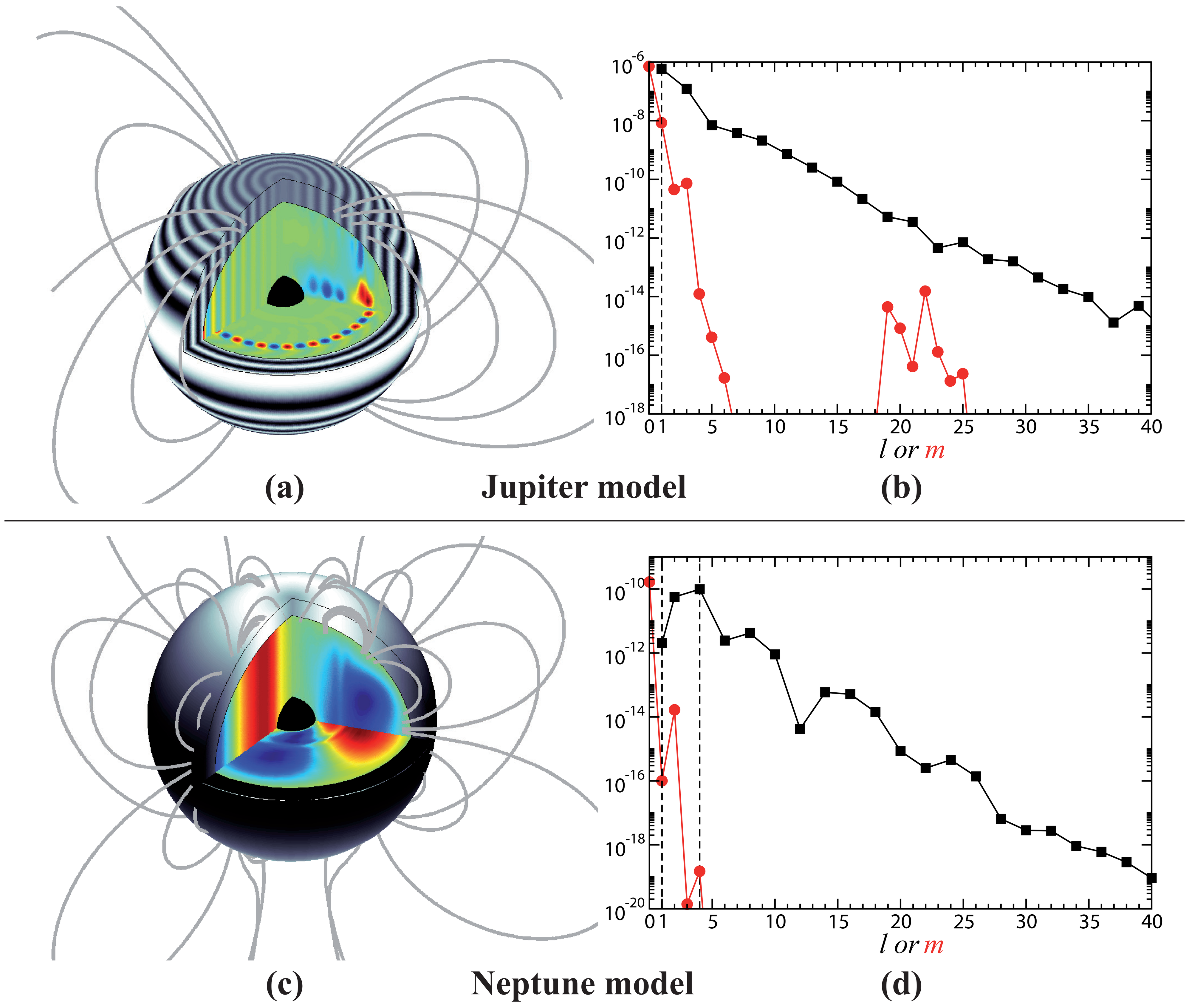

Figure: (a) and (c): In the conductiong electrically region (colored planes), we plot the zonal velocity (left meridional plane), axisymmetric azimuthal magnetic field (right meridional plane) and radial velocity (equatorial plane). The gray lines represent the magnetic field lines outside of the fully 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.

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.

References

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