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Anelastic dynamo models with variable electrical conductivity: An application to gas giants

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A B S T R A C T

The observed surface dynamics of Jupiter and Saturn *are* dominated by a banded system of fierce zonal winds. The depth of these winds remains unclear but they are thought to be confined to the very outer envelopes where hydrogen remains molecular and the electrical conductivity is small. The dynamo maintaining the dipole-dominated magnetic fields of both gas giants, on the other hand, likely operates in the deeper interior where hydrogen assumes a metallic state.

Here, we present numerical simulations that attempt to model both the zonal winds and the interior dynamo action in an integrated approach. Using the anelastic version of the MHD code MagIC, we explore the effects of density stratification and radial electrical conductivity variations. The electrical conductivity is mostly assumed to remain constant in the thicker inner metallic region and it decays exponentially towards the outer boundary throughout the molecular envelope.

Our results show that the combination of a stronger density stratification and a weaker conducting outer layer is essential for reconciling dipole dominated dynamo action and a fierce equatorial zonal jet. Previous simulations with homogeneous electrical conductivity show that both are *mutually* exclusive, with solutions either having strong zonal winds and multipolar magnetic fields or weak zonal winds and dipole-dominated magnetic fields. All jets tend to be geostrophic and therefore reach right through the convective shell in our simulations.

The particular setup explored here allows a strong equatorial jet to remain confined to the weaker conducting outer region where it does not interfere with the deeper seated dynamo action. The flanking mid to high latitude jets, on the other hand, have to remain faint to yield a strongly dipolar magnetic field. The fiercer jets on Jupiter and Saturn only seem compatible with the observed dipolar fields when they remain confined to a weaker conducting outer layer.

1. Introduction

The gas giants, Jupiter and Saturn, mainly consist of a hydrogen-helium mixture. Due to the large pressures and temperatures reached inside these planets, hydrogen acquires metallic properties (Chabrier et al., 1992; Fortney and Nettelmann, 2010). The transition happens at 85–90% of Jupiter's and 65% of Saturn's radii. A classical view is that the lower metallic layer likely hosts the dynamo of these planets, while the upper molecular envelope accommodates the observed fierce zonal jets. Higher densities, Lorentz forces and Ohmic diffusion would lead to a more sluggish dynamics in the metallic layer and confine the zonal winds to the upper region. Traditional dynamical models therefore treat the two layers separately with dynamo simulations modelling only the metallic layer and jet simulations concentrating on the molecular envelope.

The zonal jets have been investigated since the 70s by tracking cloud features (see, for example, Ingersoll et al. (1979) for Jupiter and SanchezLavega (1982) for Saturn). Their driving forces and depth are still debated. Some authors argue that they are a shallow weather phenomenon (Williams, 1978; Cho and Polvani, 1996) while others promote deeper-rooted jets that extend through the whole molecular envelope (Heimpel et al., 2005; Jones and Kuzanyan, 2009; Gastine and Wicht, 2012). Both gas giants emit roughly twice as much energy as they receive from the sun which implies vigorous interior convection. In the rotationally-dominated dynamics ruling planetary atmospheres, interior convection naturally drives zonal winds via Reynolds stresses (i.e. a statistical correlation between the convective flow components; Christensen, 2002; Heimpel et al., 2005). These winds follow a geostrophic structure, minimizing variations in the direction of the rotation axis, and therefore reach through the whole fluid atmosphere. Lian

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and Showman (2008) show that even when the forcing is restricted to a shallow weather layer the jets may reach much deeper into the planet. Kaspi et al. (2009), on the other hand, present an anelastic deep convection model where the equatorial *zonal flow* is geostrophic and the higher latitude jets are confined to the outer few percent in radius.

Saturn's magnetic field is very axisymmetric and strongly concentrated at higher latitudes (Cao et al., 2012) which is incompatible with the results of a classical Earth-like dynamo model. A stably stratified layer at the top of the dynamo region (Christensen and Wicht, 2008; Stanley, 2010) or a completely different dynamo driven by differential rotation (Cao et al., 2012) are two proposed alternatives for the special situation encountered at Saturn.

Here we concentrate on Jupiter whose field is very similar to the geomagnetic field so that the well-explored geodynamo models also seem to apply at first sight. These models typically adopt the Boussinesq approximation where the mild 30% density stratification of Earth's core is simply ignored. In Jupiter, however, the density increases by more than a factor of 5000 below the 1 bar level. While the stratification is mostly concentrated in the outer molecular envelope, the density still rises by about one order of magnitude across the metallic layer (Fig. 1 of French et al., 2012). Some newer numerical models therefore use the anelastic approximation which allows to incorporate the effects of the background density stratification while filtering out fast sound waves (Gilman and Glatzmaier, 1981; Stanley and Glatzmaier, 2010; Jones and Kuzanyan, 2009).

In an extensive parameter study, Gastine et al. (2012) (hereafter referred to as GDW12) show that dipole-dominated dynamos are rather rare when stronger stratifications are assumed. GDW12 quantify the stratification in their anelastic models in terms of the number of density scale heights $N_\rho = \ln(\rho_i/\rho_o)$, where ρ_i and ρ_o are the densities at the inner and outer boundaries of the simulated shell, respectively. For the larger density stratifications $N_\rho > 2$, a value that corresponds to an increase by a factor 7.4, no dipole-dominated solutions were found. This is attributed to the fact that the focus of convective action moves progressively outward in cylindrical radius when the stratification is intensified. Once the convective columns are mainly confined to a relatively thin outer shell, a non-axisymmetric dynamo mode is preferred that has previously only been observed in mean field dynamo simulations (Rüdiger et al., 2003; Jiang and Wang, 2006). We will refer to this as the thin-shell dynamo model in the following.

For the smaller to intermediate stratifications $N_\rho \leqslant 2$, GDW12 find dipole dominated magnetic fields when the local Rossby number remains smaller than a critical value of $Ro_{\ell c} \approx 0.1$. This is consistent with the findings of Christensen and Aubert (2006) who introduced Ro_ℓ as a measure for the relative importance of inertia in their Boussinesq models (see Eq. (21)). Multipolar solutions with weaker magnetic fields on the other hand exist for all Ro_ℓ values which means that both types of solutions coexist below $Ro_{\ell c}$ for identical model parameters, forming two distinct branches. This so-called bistability can be attributed to the fact that free-slip boundary conditions were employed (Simitev and Busse, 2009; Schrinner et al., 2012; Gastine et al., 2012). These conditions allow strong zonal winds to develop that compete with large scale magnetic fields. On the dipolar branch, zonal winds are weak, on the multipolar branch they are stronger. When no-slip conditions are used zonal flows generally remain weaker and only the dipolar branch is found for $Ro_\ell < Ro_{\ell c}$ (Christensen and Aubert, 2006).

Ab initio calculations suggest that there is actually no clear phase transition between the regions of molecular and metallic hydrogen states (Lorenzen et al., 2011; French et al., 2012). In the dynamo context, the electrical conductivity profile is of particular importance. Due to the increasing degree of hydrogen ionization, the conductivity rises super-exponentially with depth and matches the conductivity of the metallic region at the transition radius without any pronounced jump. The classical separation of the dynamics for the two envelopes thus becomes questionable. Liu et al. (2008) argue that this has important consequences for the depth of the zonal winds which should remain confined to a shallow outer layer where the conductivity remains negligible. The strong shear associated with the zonal winds would otherwise create strong azimuthal magnetic field and lead to Ohmic heating incompatible with the observed luminosity (see however Glatzmaier, 2008).

Stanley and Glatzmaier (2010) present an anelastic simulation of a relatively thin shell with exponentially decaying electrical conductivity to model the very outer part of the shell. The model uses extreme parameters (i.e. low Ekman and Prandtl number and high Rayleigh number) and a dipole-dominated magnetic field develops in the presence of strong geostrophic zonal winds. However, since a detailed discussion and a systematic parameter study are missing, it remains impossible to disentangle the effects of density stratification, varying conductivity, and the particular parameter choice. Gómez-Pérez et al. (2010) and Heimpel and Gómez-Pérez (2011) also include a radial conductivity profile in their deep shell Boussinesq models, with a constant conductivity in the deeper interior and an exponential decay in the outer part. These models also demonstrate that well-pronounced deep-rooted zonal winds can be compatible with dipole-dominated dynamo action.

The present paper extends the work of GDW12 by adding an electrical conductivity profile loosely based on the *ab initio* calculations by French et al. (2012). Following Gómez-Pérez et al. (2010) and Heimpel and Gómez-Pérez (2011), the electrical conductivity profile assumes a constant value in the metallic region and an exponential decay in the molecular region. The aim is to systematically explore under which circumstances dipole-dominated dynamo action and strong zonal surface winds can coexist in anelastic dynamo models.

We describe our model in Section 2 with special attention to the anelastic formulation and the electrical conductivity profile. The numerical results are presented in Section 3, first concentrating on the question of dipole-dominance and then on the dynamo mechanism. Section 4 summarizes our main results and discusses their implications for the gas giants.

2. Model

2.1. Anelastic approximation

The fluid and convective interior of the planet is modelled by solving the MHD equations in a rapidly-rotating spherical shell. Previous models typically used the Boussinesq approximation, which neglects the background density and temperature variations. This is questionable in gas planets and, following Gilman and Glatzmaier (1981), Braginsky and Roberts (1995) and Lantz and Fan (1999), we therefore adopt the anelastic approximation. This allows to include background variations while ruling out sound waves by neglecting fast local density variations.

We solve the equations in a dimensionless form (e.g. Christensen and Aubert, 2006), using the shell thickness $d = r_o - r_i$ as a length scale and the viscous diffusion time $\tau_\nu = d^2/\nu$ as a timescale. Here, r_o and r_i are the outer and inner radii, respectively, and ν is the kinematic viscosity. Temperature and density are both nondimensionalized by their values at the outer boundary, T_o and ρ_o. We employ constant entropy boundary conditions and use the imposed contrast Δs across the shell as the entropy scale. There are no internal heat sources and all the heating coming into the shell via the inner boundary leaves it through the outer. While this is not the most realistic heating mode for gas giants, it has been cho-