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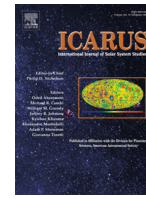

Physical conditions for Jupiter-like dynamo models

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ABSTRACT

The Juno mission will measure Jupiter's magnetic field with unprecedented precision and provide a wealth of additional data that will allow us to constrain the planet's interior structure and dynamics. Here we analyse 66 different numerical simulations in order to explore the sensitivity of the dynamo-generated magnetic field to the planets interior properties. Jupiter field models based on pre-Juno data and up-to-date interior models based on *ab initio* simulations serve as benchmarks. Our results suggest that Jupiter-like magnetic fields can be found for a number of different models. These complement the steep density gradients in the outer part of the simulated shell with an electrical conductivity profile that mimics the low conductivity in the molecular hydrogen layer and thus renders the dynamo action in this region largely unimportant. We find that whether we assume an ideal gas or use the more realistic interior model based on *ab initio* simulations makes no difference. However, two other factors are important. A low Rayleigh number leads to a too strong axial dipole contribution while the axial dipole dominance is lost altogether when the convective driving is too strong. The required intermediate range that yields Jupiter-like magnetic fields depends on the other system properties. The second important factor is the convective magnetic Reynolds number radial profile $Rm_c(r)$, basically a product of the non-axisymmetric flow velocity and electrical conductivity. We find that the depth where Rm_c exceeds about 50 is a good proxy for the top of the dynamo region. When the dynamo region sits too deep, the axial dipole is once more too dominant due to geometric reasons. Extrapolating our results to Jupiter and the result suggests that the Jovian dynamo extends to 95% of the planetary radius.

The zonal flow system in our simulations is dominated by an equatorial jet which remains largely confined to the molecular layer. Where the jet reaches down to higher electrical conductivities, however, it gives rise to a secondary $\alpha\Omega$ dynamo that modifies the dipole-dominated field produced deeper in the planet. This secondary dynamo can lead to strong magnetic field patches at lower latitudes that seem compatible with the pre-Juno field models.

1. Introduction

The interior dynamics of Jupiter has been the topic of an increasing number of studies over the last ten years (Heimpel et al., 2005; Lian and Showman, 2008; Stanley and Glatzmaier, 2010; Kaspi et al., 2009; Heimpel and Gómez-Pérez, 2011; Gastine and Wicht, 2012; Duarte et al., 2013; Gastine et al., 2014b; Jones, 2014; Heimpel et al., 2016). The growing interest is at least partially motivated by two Jovian space missions. NASA's Juno spacecraft arrived in summer 2016 and started to measure the planet's magnetic field with unprecedented precision. It will also provide important information on the inner structure and dynamics, for example via gravity data. ESA's Jupiter system mission Juice is scheduled to be launched in 2022.

Recent models for Jupiter's interior structure combine pre-Juno gravity and planetary figure measurements with refined equations of state that are based on *ab initio* calculations (French et al., 2012; Nettelmann et al., 2012). These models assume a small rocky core of uncertain size and a two layer Hydrogen and Helium envelope where the inner layer contains more heavy elements than the outer. When pressures are high enough at about 80–90% of Jupiter's radius, hydrogen undergoes a phase transition from the molecular to a metallic state (e.g. Chabrier et al., 1992; Fortney and Nettelmann, 2010; Nettelmann et al., 2012). Since this transition lies beyond the triple point (French et al., 2012) there is no sharp change in the physical properties. Using advanced *ab initio* calculations, French et al. (2012) shows that the electrical conductivity, a particularly important property for the dynamo process,

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rises steeply with depth at a super-exponential rate in the molecular layer and then more smoothly transitions into the metallic region where the gradient becomes much shallower (see Fig. 2).

Magnetic field models in the pre-Juno era rely on a few flybys and sometimes auroral information to constrain spherical harmonic surface field contributions up to degree $\ell = 4$ (Connerney et al., 1998; Grodent et al., 2008; Hess et al., 2011) or $\ell = 7$ at best (Ridley, 2012; Ridley and Holme, 2016). Due to its dedicated polar orbit, Juno is expected to constrain models up to $\ell = 15$ or higher. This exceeds the resolution available for Earth where the crustal field shields harmonics beyond $\ell \simeq 14$.

While the magnetic field offers indirect clues for the deeper processes the surface dynamics can be inferred more directly, for example by tracking cloud features. The surface winds are dominated by a system of zonal jets where a fast prograde equatorial jet is flanked by several additional jets of alternating retrograde and prograde direction. At least the equatorial jet could be a geostrophic structure that reaches through the planets and is maintained by Reynolds stresses, a statistical correlation between smaller-scale convective flow components (Christensen, 2001; Heimpel et al., 2005; Gastine and Wicht, 2012; Gastine et al., 2012). This is less clear for the flanking jets which may be much shallower thermal-wind driven structures (Kaspi et al., 2009). Constraining the depth of Jupiter's jet system is one of the main objectives of the Juno mission.

Though the *ab initio* simulations may not support a clear separation, traditional simulations of Jupiter's internal dynamics concentrated on either describing the deeper dynamo thought to operate in the metallic hydrogen layer or on the jet dynamics in the molecular envelope. While the latter are very successful in describing the observed zonal jet structure (Heimpel et al., 2005; Gastine et al., 2014a; Heimpel et al., 2016) the dynamo simulation have proven to be more problematic. Since Jupiter's magnetic field has a very Earth-like configuration is it tempting to assume that numerical geodynamo simulations capture the dynamics of the metallic layer. However, geodynamo models typically neglect compressibility and assume a constant adiabatic temperature profile in the so-called Boussinesq approximation. Moreover, the electrical conductivity is constant and rigid flow boundary conditions are often used that significantly inhibit zonal winds (Olson et al., 1999; Christensen and Wicht, 2007). These simulations show that dipolar and thus Earth-like or Jupiter-like magnetic fields can only be expected when the system is not driven too strongly, i.e. the Rayleigh number remains in a range where inertial effects are small (Christensen and Aubert, 2006).

More recent simulations have shown that it becomes increasingly complicated to maintain dipole-dominated fields when modifying the models to better represent gas planets. Using stress free rather than rigid flow boundary conditions allows strong Reynolds-stress driven zonal winds to develop, which are always highly geostrophic and thus reach through the whole gaseous envelope. The competition between these winds and strong dipolar fields plays an important role in determining whether the magnetic field becomes axial dipole-dominated or multipolar, i.e. more complex without a dominant axial dipole contribution (Grote and Busse, 2000; Busse and Simitev, 2006; Simitev and Busse, 2009; Sasaki et al., 2011; Schrinner et al., 2012; Gastine et al., 2012). Zonal flows tend to promote weaker multipolar fields while strong dipole fields can suppress the zonal flows via Lorentz forces. Dipole-dominated dynamos thus require a certain balance between flow vigour and dipole field amplitude.

A consequence of this competition is the bistability found at not too large Rayleigh numbers where dipole and multipole solutions coexist at identical parameters (Gastine et al., 2012). The multipolar branch is reached when starting a simulation with a weak field and is characterized by stronger zonal flows. Establishing a solution on the dipolar branch, on the other hand, requires to start with a strong dipole that sufficiently suppresses the zonal flows (e.g. Schrinner et al., 2012). When the Rayleigh number is increased beyond a certain point only the multipolar branch remains. However, the simple rule that describes this transition for Earth-like dynamos in terms of the relative importance of inertia (Christensen and Aubert, 2006) does mostly not apply in gas giants (Duarte et al., 2013).

Including Jupiter-like density profiles in the so-called anelastic approximation (Gilman and Glatzmaier, 1981; Glatzmaier, 1984; Braginsky and Roberts, 1995; Lantz and Fan, 1999) yields further difficulties. The density stratification leads to convective flows where the amplitude increases with radius while the length scale decreases. The zonal flow system changes less dramatically but nevertheless significantly: the equatorial jet becomes somewhat more confined and increases in amplitude while the mid to higher latitude jets slow down (Gastine and Wicht, 2012).

More successful are integrated models that include the molecular envelope and more specifically the steep decrease in electrical conductivity (Gastine et al., 2014b; Jones, 2014). This allows the strong equatorial jet to remain mostly constrained to the weakly conducting outer envelope and thus participate little in the primary dynamo action (Gastine et al., 2012; 2014b). The dipole field actually contributes to establishing itself by pushing the equatorial jet to the weakly conducting shell and by braking the remaining high to mid latitude zonal flows via Lorentz forces (Duarte et al., 2013). When the weakly conducting shell is too thick, however, the region where the Lorentz force can counteract zonal wind production via Reynolds stresses becomes too restricted and the dynamo ends up producing a multipolar field.

Another effect that can help establishing a dipole-dominated field is an increased magnetic Prandtl number $Pm = \nu/\lambda$ where ν is the kinematic viscosity and $\lambda = 1/(\sigma\mu_0)$ the magnetic diffusivity (Duarte et al., 2013; Schrinner et al., 2014; Jones, 2014; Raynaud et al., 2015). Increasing Pm is equivalent to increasing the electrical conductivity σ which leads to a more efficient dynamo and likely also stronger Lorentz forces that can more easily balance zonal flows. Several authors also report that either decreasing or increasing the Prandtl number $Pr = \nu/\kappa$ (ratio of kinematic viscosity ν to thermal diffusivity κ), from a typical value of $Pr = 1$ used in many simulations to 0.1 or 10, respectively, may also help (Jones, 2014; Yadav et al., 2015b; 2015a). Jones (2014) argues that at low Pr the convection is more evenly distributed throughout the shell which leads to a less dominant equatorial jet and stronger dipole field generated at depth, while higher Pr means reduced inertia (Yadav et al., 2015b). The effect is potentially important for Jupiter where Pr may be as low as 10^{-2} at depth (French et al., 2012).

The Ekman number E is another parameter that can influence the magnetic field configuration. E is a measure for the ratio of viscous to Coriolis forces in the flow force balance. Because of the small viscosity and fast planetary rotation, Jupiter's Ekman number is only about 10^{-18}. For the simulations, however, a much higher viscosity is assumed to damp the small scale convection that cannot be resolved numerically and E is typically of order 10^{-4} or 10^{-5}. Boussinesq dynamo simulations suggest that a lower E promotes dipolar fields because the stronger Coriolis forces help to organize large scale magnetic field generation (Christensen and Aubert, 2006; Wicht and Christensen, 2010). Since Heimpel and Gómez-Pérez (2011) and Duarte et al. (2013) suggest that a lower 10^{-5} may also help to establish dipolar dynamos in anelastic simulations it seems important to further explore this issue.

Many authors drive convection in their Jupiter models from the bottom (Gastine et al., 2012; Duarte et al., 2013; Gastine et al., 2014b) as would be more appropriate for Earth. Heat enters the modelled spherical shell through the inner and leaves it through