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Experimental approach of planetary magnetism

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Abstract

The DTS experiment in Grenoble is the only experiment designed to explore the 'magnetostrophic' dynamic regime of planetary cores. We report on the latest results and on the prospect for data assimilation.

1. Introduction

Most planets produce a magnetic field by dynamo action. Because planets spin, their dynamo operates in the so-called 'magnetostrophic' regime, in which the dominant forces are the Coriolis and Lorentz forces. We have been exploring this particular regime with the DTS experiment. We now have a good description and understanding of both the average axisymmetric velocity and magnetic fields and of their fluctuations.

2. Experimental set-up

The central part of the DTS set-up is shown in figure 1. Fifty liters of liquid sodium fill the shell between a copper inner sphere and a stainless steel outer shell. The inner sphere contains a strong permanent magnet that enables us to span a large range of Elsasser numbers (a measure of the Lorentz to Coriolis ratio), when we impose a differential rotation between the two spheres. The removable ports of the outer stainless steel shell can receive ultrasound transducers (as shown) or a sleeve that penetrates all the way to the inner sphere and enables us to measure the induced magnetic field inside the liquid sodium flow.

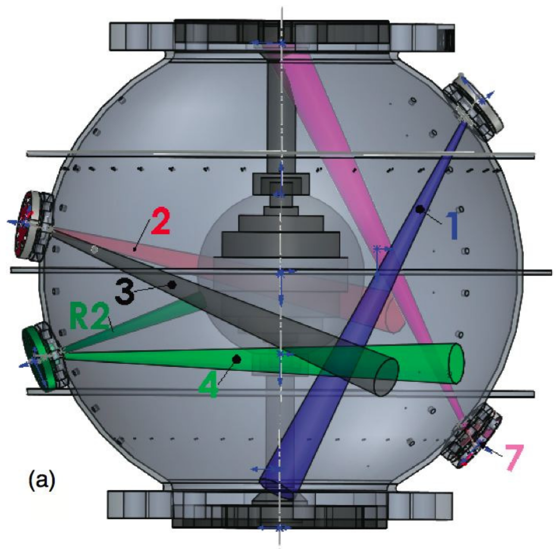

Figure 1: Sketch of the magnetized spherical Couette DTS set-up. Both inner and outer spheres can rotate around the same vertical axis. Layers of permanent magnets are visible inside the inner copper sphere. The outer stainless steel shell has a number of tiny blind holes, which are used for electric potential measurements. It is also equipped with 6 removable ports, in which ultrasound transducers can be installed. Examples of the resulting ultrasound beams are shown in various colors: they provide a rich collection of velocity profiles inside liquid sodium.

3. Zonal shear and super-rotation

Using ultrasound Doppler velocimetry, we could retrieve the mean axisymmetric flow field. Figure 2 shows the obtained map of angular velocity when the inner sphere spins at 3 Hz, while the outer shell is at rest (see [1] for a full account).

The map exhibits a region with strong super-rotation near the inner sphere, obeying Ferraro law of isorotation. Further away toward the outer shell, inertial forces dominate and impose geostrophy, even when the outer shell is at rest. The transition between these two regimes takes place where the local Elsasser number is about 1. The map also exhibits unexpected deviations from Ferraro law in the polar regions.

The magnetized spherical Couette geometry is well adapted for numerical modeling, and we can adequately reproduce the observations if we impose the same Elsasser number as in the experiments, even though the Reynolds number is several orders of magnitude higher in the experiments.

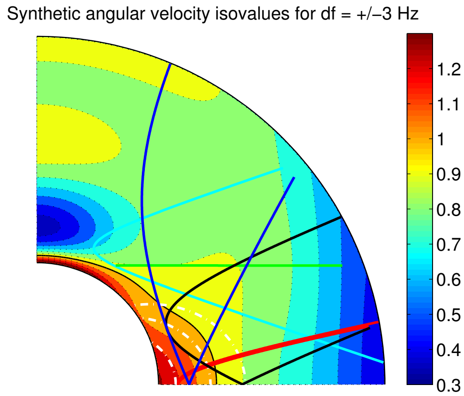

Figure 2: Meridional map of isolines of the angular velocity in the liquid sodium shell, reconstructed from a collection of Doppler velocity profiles. The color lines give the projection in this plane of the ultrasound beams shown in figure 1. Angular velocities are adimensionalized by that of the inner sphere (spinning at 3 Hz, while the outer sphere is at rest). The orange and red region near the inner sphere exhibits super-rotation.

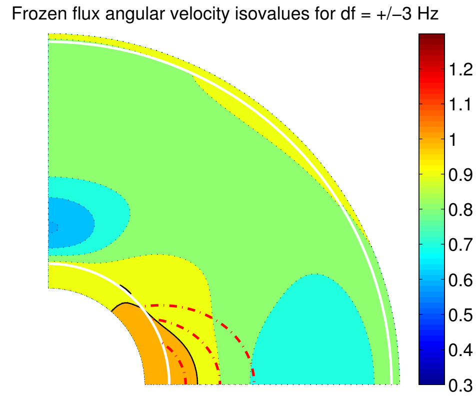

Figure 3: Meridional map of isolines of the angular velocity recovered under the frozen flux approximation from the electric field created by the flow of figure 2. The red dash-dot lines are field lines of the imposed dipolar magnetic field. The thick white lines are the frontiers between the liquid sodium and the solid copper (inner) and stainless steel (outer) shells.

4. Frozen flux approximation

We have computed the induced azimuthal field, the electric currents and the electric field produced by the flow of figure 2. The frozen flux approximation, used in most inversions of observational data, assumes that electric currents are negligible. If we make this assumption and derive the velocity field from our estimated electric field through the current-free Ohm law $\mathbf{E} = -\mathbf{u} \times \mathbf{B}$, we obtain the angular velocity map shown in figure 3. We observe that the velocity variations are strongly underestimated, and that the frozen approximation fails in the outer region, where inertial forces dominate.

5. Towards data assimilation

The DTS experiment provides us with a nice case study of data assimilation. Indeed, the strong constraints brought by the Coriolis and Lorentz forces produce a well-behaved dominant mean flow, but fluctuations are well present. In addition, we have a dense coverage of diverse measurements (velocity profiles, induced magnetic field, electric potentials, global torque), which all constrain the flow and its interplay with the magnetic field. We have therefore developed modeling tools to extract as much information as possible on the dynamics controlling the flow, and we will present our current efforts toward the construction of a truly dynamical model constrained by data assimilation.

6. Summary and Conclusions

The DTS experiment shows how the Coriolis and Lorentz forces control the flow in the 'magnetostrophic' regime expected for planetary cores. The rich collection of experimental data and the simple geometry of the boundary conditions enable us to get a good understanding of the dynamics, by combining experimental data and numerical simulation. This opens the way for implementing a scheme of experimental data assimilation.

References

[1] Brito, D., Alboussière, T., Cardin, P., Gagnière, N., Jault, D., La Rizza, P., Masson, J-P., Nataf, H-C. and Schmitt, D.: Zonal shear and super-rotation in a magnetized spherical Couette flow experiment, *Physical Review E*, in press, 2011.