EXPERIMENTAL STUDIES OF PLANETARY CORE CONVECTION AND DYNAMO PROCESSES

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Summary Here we will present a basic review of planetary core processes and then discuss experimental means for studying core convection dynamics and dynamo processes, focussing on the rotating magnetoconvection experiment presently being set up at UCLA.

INTRODUCTION

Planetary magnetic fields are generated by convectively driven dynamo processes occurring within the electrically conductive fluid regions of deep planetary interiors. In the terrestrial planets, dynamo generation occurs within the planet's iron-rich molten core [1]. In the giant planets, dynamo generation occurs either below the depth where pressure-induced metallization of hydrogen occurs on Jupiter and Saturn or in the interior region of relatively high ionic conductivity on Uranus and Neptune [1]. Because dynamo generation occurs in deep planetary interiors, the effects of these processes can only be detected via remote techniques, such as satellite magnetometry. Thus, workers use theoretical, numerical and experimental studies to determine the possible dynamo mechanisms that can explain the planetary magnetic field observations.

The fluid motions in planetary cores are affected at first order by buoyancy, Coriolis and Lorentz forces. Linear stability analysis predicts that the onset of thermal convection is facilitated in the regime where Lorentz and Coriolis forces are comparable [2,3], i.e., in the regime where the Elsasser number Λ = (Lorentz force/Coriolis force) ~ 1. Thus, the interaction of strong magnetic fields and strong rotation allows convection to occur more easily, whereas, if these forces were to each act alone, convection would be strongly suppressed. This has lead to the idea that convection-driven dynamos will naturally function most efficiently in the regime where the convection itself is most efficient, again, in the $\Lambda \sim 1$ regime. However, this scaling concept for dynamo field saturation has not been clearly and quantitatively substantiated.

Experimental and numerical studies provide excellent means by which to test this $\Lambda \sim 1$ scaling concept. These methods each have their strengths and weaknesses. A difficulty facing numerical dynamo approaches is that they are presently unable to be carried out using realistic fluid properties [4]. On the other hand, numerical simulations are able to generate dynamo action precisely because they are able to use highly artificial fluid properties that lead to strong magnetic induction (i.e., large magnetic Reynolds numbers, $\boldsymbol{Re_m}$) in weakly driven, nearly laminar convective flows (i.e., at relatively low values of the Rayleigh number, $\boldsymbol{Ra}$).

In the laboratory, it is possible to use liquid metals, such as liquid sodium and gallium, which have physical properties similar to core fluids [5]. Experimental groups are taking two different approaches for improving our understanding of the geodynamo: mechanically-driven dynamo experiments and thermally-driven rotating magnetoconvection experiments. These approaches are complementary ways of studying convectively-driven dynamo generation, which cannot presently be achieved in the laboratory; each type of experiment isolates a different part of the dynamo process. The mechanically-driven experiments impose a velocity field in hopes of producing dynamo-generated magnetic fields. In contrast, the thermally-driven experiments impose a magnetic field and study how the convective velocity field is altered.

Mechanically-driven laboratory dynamo experiments are presently being designed and built by the groups at the University of Maryland, College Park; University of Wisconsin, Madison; CNRS, Cadarache, France; Universite Joseph Fourier and CNRS, Grenoble, France; and at the New Mexico Institute of Mining and Technology, Socorro. These devices will study magnetic induction processes at $\boldsymbol{Re_m} \sim 10^2$. In order to reach such high $\boldsymbol{Re_m}$ in the laboratory, these devices use large mechanical motors to drive electrically-conducting fluids to high velocities where dynamo generation may occur. These mechanically-forced flows are not realistic analogs to flows in planetary cores. Yet should dynamo generation come about, their experimental results will provide an excellent opportunity to determine how dynamo-generated fields equilibrate and whether this nonlinear saturation process occurs in the $\Lambda \sim O(1)$ regime.

Alternatively, in rotating magnetoconvection experiments, the flows are thermally-driven and, in addition to the rotation, the magnetic field is imposed. This forces the convection to occur in the externally imposed $\Lambda \sim 1$ regime. Diagnostic measurements can then determine how the convection varies with Λ. These convective flows are far less energetic than mechanically-driven flows. Thus, the convection-driven induction processes are weak ($\boldsymbol{Re_m} < 1$), and dynamo action cannot be achieved in such devices. The strength of these experiments is that the thermally-driven convection is geophysically realistic and the dynamics, controlled by Λ, are similar to those of the Earth's core.

THE UCLA ROTATING MAGNETOCONVECTION EXPERIMENT

We are presently setting up a large volume rotating magnetoconvection experiment at UCLA. No large volume, plane layer rotating magnetoconvection experiments have been carried out since those made nearly 50 years ago by Nakagawa [6,7]. Smaller volume experiments were recently carried out by Aurnou and Olson [8]. Their experiments, which were made using liquid gallium as the working fluid, agreed with Chandrasekhar's basic predictions for relatively weak Coriolis and Lorentz forces. Thus, their experiments act as a small-scale feasibility study for the large volume device that is now being fabricated.

Figure 1 shows design drawings of the rotating magnetoconvection device presently being set up at UCLA. In order to study the ~ 1 regime, it is necessary that the experimental geometry requires strong Lorentz and Coriolis forces to simultaneously affect the convective motions. Thus, we have chosen a horizontal plane layer geometry, which satisfies this criterion by having the gravity vector, the magnetic field vector and the rotation axis all aligned in the vertical. The design consists of three major sections: 1) the convection tank, 2) the rotary table and 3) the solenoidal magnet coil. Figure 1a shows the cylindrical convection tank and rotary table. Figure 1b also includes the solenoidal electromagnet, shown in its lowered position in which it surrounds the convection tank. The working fluid for these experiments will be gallium-indium-tin eutectic alloy, which has a melting temperature of 10.7^{o}C. The alloy will be heated from below by a non-inductively wound heat pad, allowing us to reach $\boldsymbol{Ra} \sim 5\text{x}10^{7}$ in non-rotating, non-magnetic, Rayleigh-Benard convection experiments. Rotation rates up to 2 rad/s (i.e., 60 rpm) will allow us to reach Taylor numbers of $\boldsymbol{Ta} \sim 10^{12}$ without strongly deflecting the gravitational equipotential surfaces within the fluid layer. The magnetic field will be uniform to 0.5% over the entire volume of the fluid layer and will attain a maximum intensity of 1300 gauss. This will allow us to reach Chandrasekhar numbers of $\boldsymbol{Q} \sim 10^{5}$. Our inability to produce a much stronger, uniform magnetic field is the limiting factor in this experimental design.

This rotating magnetoconvection device will greatly benefit from an acoustic Doppler velocimetry system that will provide non-invasive measurements of convective velocities in the opaque liquid gallium alloy [8]. These measurements, as well as temperature and magnetic field measurements, will allow us to test the linear predictions for rotating magnetoconvection in the ~ 1 regime and, for the first time, to study strongly nonlinear, turbulent rotating magnetoconvection in order to determine whether the linear results are also valid for fully-developed convective flows. Our experimental findings will be relevant to those studying core convection processes and to the broader fluid mechanics community as well.

References

[1] Stevenson, D.J.: Planetary magnetic fields. *Earth Planet. Sci. Lett,* **208**:1-11, 2003.

[2] Chandrasekhar, S.: Hydrodynamic and Hydromagnetic Stability. Oxford University Press, Oxford, 1961.

[3] Eltayeb, I. A., Roberts, P.H.: On the hydromagnetics of rotating fluids, *Astrophys. J.*, **162**: 699-701, 1970.

[4] Glatzmaier, G.A.: Geodynamo simulations: How realistic are they? *Annu. Rev. Earth Planet. Sci.,* **30**:237-257, 2002.

[5] Poirier, J.P.: Introduction to the Physics of the Earth's Interior, 2nd Ed., Cambridge University Press, Cambridge, 2000.

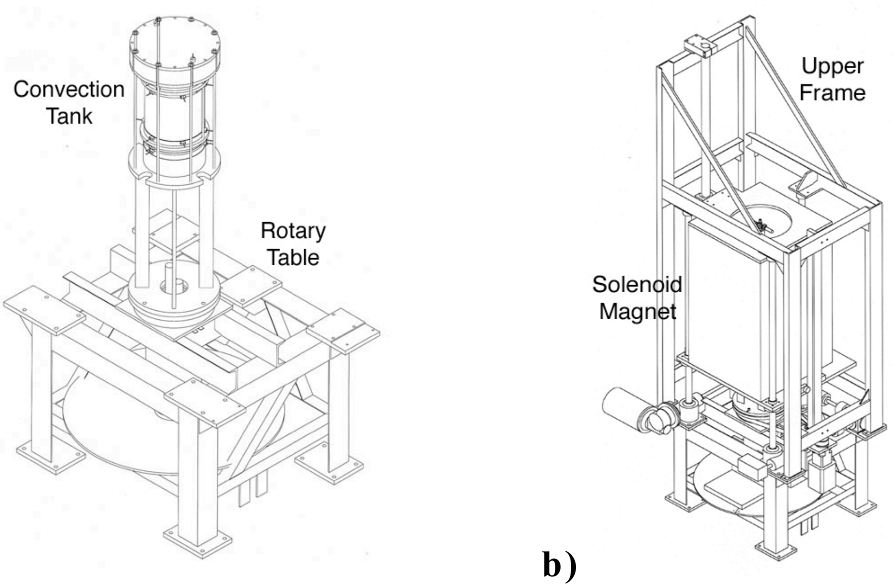
[6] Nakagawa, Y.: Experiments on the instability of a layer of mercury heated from below and subject to the simultaneous action of a magnetic field and rotation, *Proc. R. Soc. Lond. A,* **242**:81-88, 1957.

[7] Nakagawa, Y.: Experiments on the instability of a layer of mercury heated from below and subject to the simultaneous action of a magnetic field and rotation. II., *Proc. R. Soc. Lond. A,* **249**:138-145, 1958.

[8] Aurnou, J.M., Olson, P.L.: Experiments on Rayleigh-Benard convection, magnetoconvection and rotating magnetoconvection in liquid gallium, *J. Fluid Mech.,* **430**:283-307, 2001.

[9] Brito, D., et al.: Ultrasonic Doppler velocimetry in liquid gallium, *Expts. Fluids,* **31**:653-663, 2001.

Figure 1: **a)** Close-up of the convection tank, rotary table and lower structural frame. **b)** The entire apparatus including the magnet and its upper structural frame. The total height of the experimental structure is 330 cm.



a) **b)**