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Review

Laboratory Experiments on the Dynamics of the Core ☆

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A B S T R A C T

Many innovative laboratory experiments have been used to investigate the fluid dynamics of the Earth's core. Experiments with liquid metals and non-metals range from turbulence and waves in the outer core to creeping flow in the inner core, and include the effects of rotation (steady and variable), thermal and chemical convection, spherical geometry, magnetic fields, melting and solidification. In this review, the strengths and limitations of laboratory fluid experiments are analyzed by comparing their dynamical similarity with the corresponding geophysical processes in the core. Recent advances in several areas are highlighted, including variable rotation dynamics, convection in liquid metals, the effects of magnetic fields on fluid motions, experimental dynamos, flow in the solid inner core, and metal–silicate interactions during core formation.

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1. Introduction

Physical processes that govern fluid and solid dynamics in the Earth's core span many orders of magnitude in their spatial and

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temporal scales, are governed by interactions between many forces, including buoyancy, viscous, electromagnetic, and interfacial, and are subject to multiple forms of accelerations, including inertia, centrifugal, Coriolis, and transverse. Laboratory fluid dynamics experiments have played an important role in quantifying these interactions, as well as uncovering the new structures and the new effects they produce. Because laboratory fluid dynamics experiments have practical restrictions, the range of fluid properties and the huge differences in length and time scales between experiments and Earth's core being the most obvious ones, it is appropriate to ask: what are the payoffs from modeling core dynamics in the lab?

There are at least three compelling reasons why laboratory fluid experiments offer unique perspectives on core dynamics. First, there is similarity to core properties, especially the transport properties. Critical physical properties of the iron-rich metals that comprise the core, particularly their viscous, thermal, magnetic, and chemical diffusivities, are well represented in laboratory experiments, as is turbulence. In contrast, these properties are typically very far from realistic in numerical models of the core (see Glatzmaier and Roberts, 1996; Takahashi et al., 2005; Miyagoshi et al., 2010, for examples of state-of-the art numerical geodynamo models). Second, lab experiments lead to new discoveries. The often unexpected results of laboratory experiments provide fresh interpretations of existing geophysical observations of the core, and motivate new ones. Third, laboratory experiments can be projected to core conditions. Systematic laboratory experiments often provide data over wide enough parameter ranges to establish asymptotic scaling laws, that can be extrapolated to the core and can also serve as benchmarks for numerical modeling.

It is important to emphasize that no single experiment can reproduce the full structural and dynamical complexity of the core. Therefore, experiments are usually designed to isolate one or at most a few of the basic processes that affect the geodynamo, the evolution of the outer and inner cores, and their interaction with the mantle. This strategy is necessary for several reasons. First, the volume of the working fluids is limited, as mentioned above. The linear dimensions in fluid experiments range from centimeters to a few meters at most, at least six orders of magnitude smaller than the linear dimensions of the core. Although the dimensions of lab experiments are much smaller than the core, it is nevertheless possible in some cases to get close to similarity in terms of some of the dynamical parameters by using much larger flow velocities in the experiments than in the core. Second, a limited set of working fluids are available. Aqueous solutions are generally the preferred fluids for non-magnetic experiments, whereas liquid gallium and sodium are used in experiments where magnetic fields and electric currents are required. Both of these liquid metals have viscous, thermal, and magnetic diffusivities that are reasonably close the core values. Two important physical attributes that distinguish experiments on the core from experiments on the Earth's mantle, for example, are the Earth's solid-body rotation and the magnetic field, which are critical in the core but are unimportant in the solid and poorly conducting silicate portions of the Earth. Very high rotation rates can be achieved in laboratory experiments, up to several thousand rpm. Likewise, the intensity of applied magnetic field can also be quite large, up to nearly 1 T.

A major advantage that laboratory experiments offer is that they self-consistently incorporate non-linear effects, instabilities, and multi-scale processes such as turbulence. A major disadvantage is the difficulty of obtaining full global measurements of dynamical variables such as velocity and temperature. As a rule, fluid dynamics experiments have to be interpreted on the basis of images, which may yield qualitative information only, plus a small number of localized measurements. Accordingly, it is sometimes difficult to get a full understanding of an experiment,

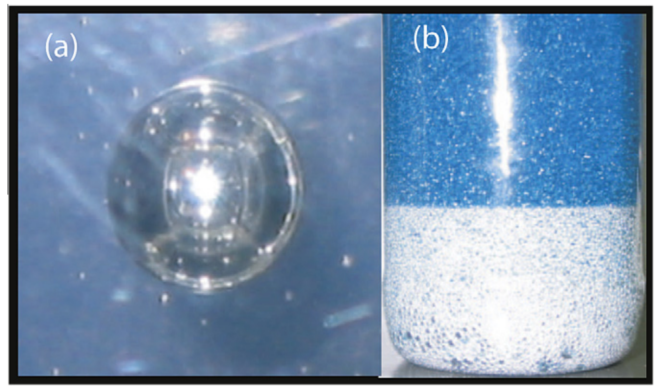

Fig. 1. (a) liquid gallium drop in sucrose solution at 5 °C below its freezing point. (b) Development of a settling interface in a gallium–sucrose solution mixture with a viscosity ratio 10^2 and a nominal Bond number $Bo \simeq 0.1$ undergoing gravitational phase separation and compaction.

particularly in situations where no theory exists to help out. Finally, although asymptotic behavior is a desirable goal, it is sometimes impractical to vary the dimensionless parameters widely enough in a given apparatus to resolve asymptotic trends. Because of this limitation, it is often necessary to repeat even the most successful experiments, using different fluids and a range of apparatus sizes and geometries.

The next section summarizes the properties of the fluids commonly used for modeling core dynamics. The important dimensionless numbers for core dynamics are then defined, and their values in the core are compared to typical values in laboratory experiments, in order to assess their dynamical similarity. Subsequent sections review experiments on rotating convection with and without magnetic field effects, experiments on instabilities produced by variable rotation including precession, tides, and libration. We then review the ongoing efforts to produce self-sustaining laboratory fluid dynamos. The final sections deal with newly emerging subjects for laboratory experimenters – inner core dynamics, and core–mantle interactions during Earth's differentiation.

2. Experimental fluids

Gallium (Ga) and its alloys are commonly used experimental fluids for modeling both liquid and solid dynamics in planetary cores. Liquid gallium has a density of approximately $\rho = 6.09\ \mathrm{Mg\,m^{-3}}$, electrical and thermal conductivities of $\sigma = 3.9 \times 10^6\ \mathrm{S\,m^{-1}}$ and $k = 40\ \mathrm{W\,m^{-1}\,K^{-1}}$, respectively, and a dynamic viscosity of approximately $\mu = 1.9 \times 10^{-3}\ \mathrm{Pa-s}$ just above its 29.8° melting point. The magnetic diffusivity of liquid gallium in this temperature range is $\eta = 1\mu_0\sigma \simeq\ 0.2\ \mathrm{m^2\,s^{-1}}$, its thermal diffusivity is $\kappa = 1.3 \times 10^{-5}\ \mathrm{m^2\,s^{-1}}$, and its thermal expansion coefficient is $\alpha =\ 1.3 \times\ 10^{-5}\ \mathrm{K^{-1}}$. Although gallium has the greatest liquid temperature range of any element, it retains anisotropic properties well above its melting temperature. Gallium alloys such as Ga–Sn–In show eutectic behavior, with melting points as low as 15°C (Sheka et al., 1966). Pure gallium is nevertheless a convenient liquid metal for experimentation at room temperatures because its kinetics strongly inhibit freezing while in contact with other liquids such as oils and corn syrups (see Fig. 1a). By virtue of its low vapor pressure and low volatility, gallium does not pose the same health hazards as other liquid metals such as Hg or Na. Liquid gallium quickly dissolves aluminum, however, and it plates both copper and glass. Gallium reacts slowly with air and also with dissolved oxygen to form various oxides, particularly Ga_2O_3, although these reactions can be largely suppressed for the duration of an