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Laboratory experiments on rain-driven convection: Implications for planetary dynamos

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ABSTRACT

Compositional convection driven by precipitating solids or immiscible liquids has been invoked as a dynamo mechanism in planets and satellites throughout the solar system, including Mercury, Ganymede, and the Earth. Here we report laboratory experiments on turbulent rain-driven convection, analogs for the flows generated by precipitation within planetary fluid interiors. We subject a two-layer fluid to a uniform intensity rainfall, in which the rain is immiscible in the upper layer and miscible in the lower layer. Rain falls through the upper layer and accumulates as a two-fluid emulsion in the interfacial region between the layers. In experiments where the rain is denser than the lower fluid, rain-injected vortices evolve into small-scale plumes that rapidly coalesce into larger structures, resulting in turbulent convection throughout the lower layer. The turbulent convective velocity in our experiments increases approximately as the cube root of the rain buoyancy flux, implying little or no dependence on viscous and chemical diffusivities. Applying diffusion-free scaling laws for magnetic field generation, we find that precipitation-driven convection can be an effective dynamo mechanism in planetary cores provided the precipitation buoyancy flux is large and the convecting region is deep and nearly adiabatic.

1. Introduction

Multi-phase flows involving liquids plus solids or several immiscible liquids have been proposed as power sources for a number of planetary dynamos, both large and small (Breuer et al., 2015). Examples include iron-snow precipitation in the iron alloy cores of Mercury (Vilim et al., 2010; Dumberry and Roldovini, 2015) and Ganymede (Hauck et al., 2006; Rückriemen et al., 2014; Christensen, 2015), in terrestrial exoplanets (Gaidos et al., 2010), precipitation of low-density constituents near the top of Earth's iron-rich core for the early geodynamo (Buffett et al., 2000; O'Rourke and Stevenson, 2016; Badro et al., 2016), and helium rain in Saturn and other hydrogen-rich giant planets (Stevenson, 1980; Fortney and Hubbard, 2004).

Although the compositions of both the precipitate and the core fluid, and the ways envisioned to generate fluid motions differ among the planets and satellites, the underlying mechanics are fundamentally similar in each case, as Fig. 1 illustrates. First, cooling of the planet leads to saturation of one or more components of the conducting fluid. Nucleation of that component produces liquid drops or solid grains, which precipitate as the equivalents of rain, sleet, graupel, or snow.

In Mercury and Ganymede, the usual assumption is that dense iron-snow precipitates downward through the upper, cooler portions of their molten iron alloy cores (Dumberry and Roldovini, 2015; Christensen, 2015). Falling into the deeper and warmer portions of the core, the iron-snow melts, increasing the density and destabilizing the fluid there. The core then consists of a two-layer system, with a precipitation-dominated region overlying a convection-dominated region, shown in Fig. 1a. More complex layering is possible, including staircase structures, particularly if the melting curve and the temperature profile are irregular (Vilim et al., 2010; Dumberry and Roldovini, 2015), or if double diffusive processes occur. In general, however, it is usually concluded that the precipitating regions are stable and that dynamo action is concentrated in the convective region (Christensen and Wicht, 2008). The process is similar to convective turbulence in Earth's troposphere, when precipitation falling from clouds as virga snow sublimates before reaching the ground, cooling and destabilizing the air below the cloud base (Kudo, 2013).

A related but somewhat different precipitation scenario has been proposed for the Earth's core in the deep past. Evidence for a geomagnetic field of similar strength as the present-day field extends to 3.4 Ga (Tarduno et al., 2010) and possibly 4.2 Ga (Tarduno et al., 2015), whereas current estimates place the age of the in-

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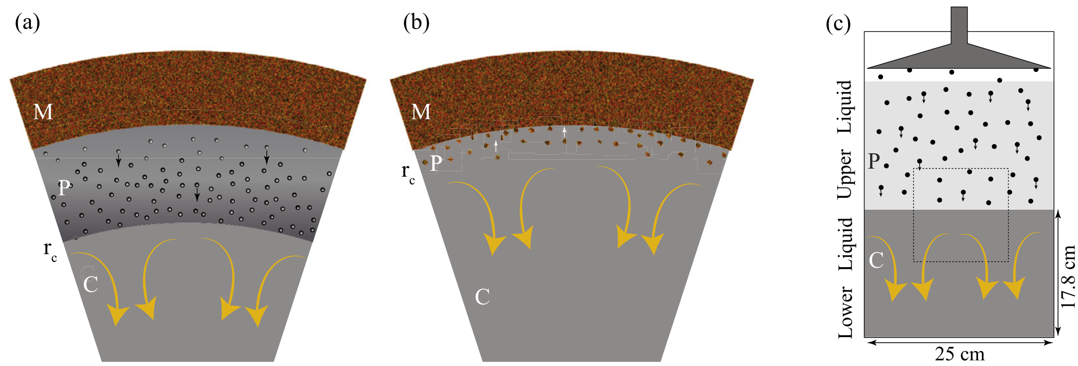

Fig. 1. Precipitation-driven convection. Schematics of precipitation-driven convection in cooling planetary cores and laboratory analog. (a) Iron-snow; (b) Magnesium precipitation; (c) Laboratory apparatus, with the dashed box indicating the region imaged in Fig. 2. M, P, C denote the mantle, the precipitation-dominated region, and the convection-dominated region, respectively. r_c denotes convective region radius. Small arrows indicate precipitation directions; large arrows denote convection.

ner core at 1 Ga or less (Olson et al., 2015), highlighting the need for geodynamo energy sources other than inner core growth. It has been hypothesized that, as the core cooled from an initially high temperature state, nucleation of weakly soluble magnesium-bearing grains or drops occurred (O'Rourke and Stevenson, 2016; Badro et al., 2016). Positively buoyant in Earth's iron-rich core, the magnesium-bearing compounds precipitated upward and accumulated at the core-mantle boundary (CMB), as shown schematically in Fig. 1b. Removal of magnesium left the residual core fluid denser and therefore unstable, enabling a compositional convective region to develop, thereby helping to maintain the early geodynamo.

Another example of precipitation-driven flow has been proposed for gas giant planets, Saturn in particular (Stevenson, 1980), but also giant exoplanets (Fortney and Hubbard, 2004). There, cooling produces supersaturated conditions for helium in the outer portion of the hydrogen-rich fluid envelope of the planet, a situation broadly similar to Fig. 1a. It is hypothesized that helium rainfall stabilizes the density profile in a precipitation-dominated layer, allowing strong horizontal shear flows to develop. It has been shown that dynamo action driven by strong shear constrains the external magnetic field to be highly axisymmetric (Stanley, 2010; Cao et al., 2012), as observed on Saturn (Cao et al., 2011).

Thermochemical evolution calculations reveal that the rate of gravitational potential energy release in the saturation–precipitation process is proportional to the cooling rate of the fluid (Rückriemen et al., 2014). For plausible planetary cooling rates, the precipitation mechanisms described above are expected to release substantial amounts of gravitational potential energy per unit time, and therefore hold potential for dynamo action. Yet, little is known about the multi-phase flows involved in precipitation-driven convection, much less their ability to produce efficient planetary dynamos. In particular, there are questions about whether the potential energy released by precipitation converts efficiently to kinetic energy of fluid motion, and whether the kinetic energy is produced at scales that are large enough for dynamo action.

Precipitation may also play an important role during late-stage planetary accretion. It has been hypothesized that late-stage giant impacts fragment core-forming metals in a deep magma ocean (Tonks and Melosh, 1993; Nakajima and Stevenson, 2015) that might extend to the core (Labrosse et al., 2007). For some impacts, complete fragmentation could produce iron rainfall from the mantle directly into the core (Ichikawa et al., 2010; Deguen et al., 2014; Kraus et al., 2015). In this scenario, high-pressure, high-temperature metal–silicate interactions predict that the metallic rain absorbs large concentrations of lighter elements from the magma (Takafuji et al., 2005; Siebert et al., 2011) and would enter the core with a large density deficit, rather than a density excess, possibly contributing to the stable layering inferred at the top of the present-day outer core (Helffrich and Kaneshima, 2010; Landeau et al., 2016).

In this study we investigate these issues using analog laboratory experiments of rain-driven convection. We exploit differences in interfacial tension to create a transition from a precipitation-dominated region to a convection-dominated region in a two-layer fluid with geometry shown in Fig. 1c. In both the laboratory and in nature, precipitation-driven convection is intrinsically non-uniform on multiple scales. On the smallest scales, it is granular in space and time because it originates from the dissolution of individual drops or particles. It is also heterogeneous at intermediate time and length scales, due to variability in the local precipitation rate, which in our experiments comes from random fluctuations in the rain production apparatus in Fig. 1c, and in natural systems comes from lateral heterogeneity in temperature, composition, and the velocity of the fluid through which the precipitation falls. A fundamental assumption is that these small and intermediate scale heterogeneities average out, so that on larger scales the precipitation induces a constant and horizontally uniform buoyancy flux, analogous to turbulent Rayleigh–Bénard convection with fixed heat flux boundary conditions (Verzicco and Sreenivasan, 2008; Johnston and Doering, 2009; Huang et al., 2015). However, because precipitation-driven convection has received so little attention, the validity of this assumption as applied to planetary dynamos is an open question.

2. Rain-driven convection experiments

Figs. 2–5 show results of laboratory experiments in which a two-layer fluid is subject to a uniform intensity rainfall of a third fluid. The rain is a dyed aqueous solution, immiscible in the upper fluid, a low-density, low-viscosity silicone oil, but miscible in the lower fluid, pure water in these experiments. The two fluids are confined in a rectangular plexiglass tank with a square 25×25 cm cross-sectional area shown in Fig. 1c, into which a 25 cm diameter circular shower head is fitted, consisting of 100 equally-spaced, 0.75 mm diameter spigots connected via a flow meter and control valve to a head tank containing the rain fluid. With this setup, the corner regions of the tank receive less direct precipitation compared to the central region. In our experiments, we concentrate on the action in the central region, where the rain is nearly uniform. Back lighting with a rectangular diode array is used to illuminate the tank.

We consider two types of rain, distinguished by their density relative to the lower fluid. In high-density rain experiments, hereafter referred to as Type 1 experiments, the rain fluid consists of a water–NaCl solution with organic dye, the salt and dye concentrations adjusted to produce the desired density excess with respect to the lower fluid. In low-density rain experiments, referred to as