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## A GEOPHYSICAL FLOW EXPERIMENT IN A COMPRESSIBLE CRITICAL FLUID

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### SCIENCE OBJECTIVES

The first objective of this experiment is to build an experimental system in which, in analogy to a geophysical system, a compressible fluid in a spherical annulus becomes radially stratified in density through an A.C. electric field. When this density gradient is demonstrated, the system will be augmented so that the fluid can be driven by heating and rotation and tested in preparation for a microgravity experiment. This apparatus consists of a spherical capacitor filled with critical fluid in a temperature controlled environment. To make the fluid critical, the apparatus will be operated near the critical pressure, critical density, and critical temperature of the fluid. This will result in a highly compressible fluid because of the properties of the fluid near its critical point. A high voltage A.C. source applied across the capacitor will create a spherically symmetric central force because of the dielectric properties of the fluid in an electric field gradient. This central force will induce a spherically symmetric density gradient that is analogous to a geophysical fluid system. To generate such a density gradient the system must be small ( $\approx 1$  inch diameter). This small cell will also be capable of driving the critical fluid by heating and rotation. Since a spherically symmetric density gradient can only be made in microgravity, another small cell, of the same geometry, will be built that uses incompressible fluid. The driving of the fluid by rotation and heating in these small cells will be developed. The resulting instabilities from the driving in these two systems will then be studied.

The second objective is to study the pattern forming instabilities (bifurcations) resulting from the well controlled experimental conditions in the critical fluid cell. This experiment will come close to producing conditions that are geophysically similar and will be studied as the driving parameters are changed.

### RELEVANCE OF THE SCIENCE AND POTENTIAL APPLICATIONS

Some of the most urgent problems of social concern are related to geophysical flows. Examples of these problems are the climate change from the greenhouse effect, natural disasters from violent storms, and earthquakes resulting from mantle convection. Because of the disastrous effects that these and other geophysical phenomena have, considerable scientific resources have been devoted to these problems. Aside from their social consequences, geophysical flows are interesting in and of themselves and have been an inspiration for concepts such as deterministic chaos and two dimensional turbulence. Much of the information regarding geophysical flows has come from direct planetary observations and numerical models. The former is uncontrollable with many complicated factors influencing the flow. The later is remarkable in that it comes close at all to mimicking the former. We are developing a prototype experimental system that will take full advantage of the microgravity environment to study these types of flows. The unique characteristic of this system - as compared to previous efforts - is that we will create a system where a spherically symmetric density gradient is established in a compressible fluid. This will mimic the single most striking and obvious property of any geophysical flow, the radial density gradient. The results from our prototype experimental system should establish facts and phenomenon for simulators and theoreticians to explain under simplified conditions.

To understand how our experimental system works, elements from the physics of critical phenomenon (of phase transitions), electrodynamics, and compressible fluid dynamics have to be considered. As is well known in critical phenomena, there exists in fluids a special point in the  $(p, T, \rho)$  phase diagram where the distinction between the gas phase and the liquid phase disappears ( $p$  is the pressure,  $T$  is the temperature, and  $\rho$  is the

density of the fluid). This point in the phase diagram is called the critical point ( $p_c$ ,  $T_c$ ,  $\rho_c$ ). Near the critical point many properties of a fluid, both thermodynamic and transport, diverge. The compressibility of a fluid is one of the most strongly divergent properties of a fluid[1]. Over the years many investigators in critical phenomenon have been frustrated by the difficulty that the earth's gravity makes in experiments with fluids near the critical point. In particular, the gravitational field induces a strong density gradient in the fluid that masks many interesting and exotic properties of critical fluids[1][2]. More recently, the microgravity environment now available has made more detailed investigations possible and has led to some unexpected results[3][4].

An electric field influences a dielectric fluid near the critical point. These influences include the modification of the thermodynamics of a fluid and the mechanical body force exerted on a fluid in a non uniform field[5]. Thermodynamically, the electric field must be considered another state variable. Mechanically, the electric field produces a body force on a fluid. A uniform field will exert a force on any free charge in a fluid and polarize the molecules of a fluid (i.e., induce a dipole moment in the charge distribution of a molecule and exert a torque on a polar molecule tending to align the molecules with the electric field). A non uniform field, or an electric field *gradient*, will polarize the fluid and exert a force on the fluid[5]. In spherical geometry, such as concentric spheres with dielectric fluid between them (a spherical capacitor), as shown in Figure 1, the electric field gradient produces a central body force that is similar to gravity. This effect has been used effectively in space experiments to study geophysical instabilities driven by buoyancy and rotation[6][7] in incompressible dielectric fluids. These experiments have yielded many interesting flow patterns and have shown how a dielectrophoretic force also has a buoyancy associated with it. In our experiment we will induce a spherical density gradient in a compressible critical fluid using the concentric spheres geometry and drive the system far from equilibrium by heating and rotation. The resulting instabilities and flow patterns will be studied.

## RESEARCH APPROACH

It is a well established experimental fact that the gravitational field of the earth stratifies a critical fluid in density because of its high compressibility. In a compressible dielectric fluid, the central force present in a spherical capacitor will also lead to a density gradient[5] in a manner similar to a compressible fluid in a gravitational field[8][1][2]. The density stratification from the earth's gravity, however, makes it impossible to make a spherically symmetric density gradient on earth using an electric field. Doing this experiment in microgravity is necessary. In addition, near the critical point the properties of the fluid make it highly sensitive to buoyancy from gravity. The temperature difference needed to drive convection gets very small as the average temperature approaches  $T_c$ . The high pressure of a critical fluid cell also makes it more difficult to develop the mechanical and thermal forcing mechanisms. Simplifying the development of the cell by using an incompressible fluid at room temperature and pressure in a ground-based study is desirable. Because the central force on a fluid in a spherical capacitor decreases in radius  $r$  as  $r^{-6}$ , a small incompressible fluid cell can create a large effective gravity. This makes it possible to make a second cell in parallel to the critical cell to complement and enhance the study of the critical fluid cell. In addition it enhances and expedites the development of the critical fluid cell since it can be more easily tested. The simplified cell will also help to predict phenomena that will occur in a space experiment. We are in the process of preparing an incompressible fluid cell.

The novel combination of a dielectric fluid near its critical point with a rotating inner sphere and convection, put together here for geophysical similarity, is something that has, to our knowledge, never been studied before. Because the thermodynamics and transport processes in a critical fluid are so novel and interesting, most of the previous work in critical fluids has been concerned with these properties. Very few fluid dynamics experiments have been done in a critical fluid[9], and none, that we are aware of, in the presence of an electric field. We are presently attempting to test a critical fluid cell to see if appreciable density changes can be induced through electrostriction and dielectrophoresis in a critical fluid.

Several successful electroconvection experiments have provided interesting results of geophysical significance. These previous attempts to produce spherical electroconvection experiments in incompressible fluids have shown that it is often only possible to do them in space[6][7][10][11]. The need to do the experiments in space comes partly from designing a system that can obtain high Reynolds numbers. This constraint requires that a relatively large system be built. If the system is too large, however, getting an appreciable effective gravity using an electric field below the breakdown voltage of the fluid is difficult. In a smaller system, however, getting a large effective gravity should be possible. Unfortunately such a small system compromises the possible Reynolds numbers and makes the construction of a system with a small aspect ratio  $\Gamma$  ( $\Gamma$  = ratio of the gap between the spheres to the radius of the inner sphere), such as the atmosphere or ocean, difficult. There are, however, other interesting geophysical systems, such as the earth's core, that do have a large aspect ratio and smaller Reynolds numbers. Table 1 shows estimates of various geometries and dimensionless parameters for comparison of our system to other geophysical systems. It shows that the critical fluid cell and the incompressible fluid cell could make a good analog to a planetary core. Producing cells with small aspect ratios that approach the geometrical similarity of an ocean is also possible.

The experimental system, shown in Figure 1, will have many similarities to a geophysical system. The experimental system will consist of two concentric conducting spheres with a large A.C. potential difference applied between them. Between the two spheres a dielectric fluid will be placed. The temperature of the fluid will be controlled such that the fluid is close to its critical point and as such will be highly compressible. Electrostriction and dielectrophoresis will induce a spherically symmetric density gradient in microgravity. The central sphere rotates at a controllable constant rate by attaching it to a magnet in the cell that will be magnetically coupled to another dipole magnet outside the cell (see Figure 1). These two magnets will be driven by an external motor. Convection will be induced in the cell by controlled radiative heating. Several diagnostic techniques are used, including holographic interferometry and Particle Image Velocimetry.

## SCIENCE RESULTS

We have constructed a preliminary cell and begun testing of the density gradient by applying an electric field. This cell uses a piece of cylindrical copper 3 inches long and 3 inches in diameter. A 1.5 inch diameter cylindrical hole is milled through its center along the cylinder axis. Inside of this hole is placed a small spherical electrode, as can be seen in Figure 2. Two sapphire windows are placed at each end of the copper so that light may pass through the region near the spherical electrode and to seal the SF<sub>6</sub> in the cell. The high potential is applied to this electrode and the surrounding copper is grounded. The cell is temperature controlled using a YSI thermistor and a National Instruments AT-MIO-16X DAQ board with Labview software. Figure 2 shows a holographic interferogram before the electric field has been applied. We have to date found the following preliminary results: on applying 3000 volts (RMS) to the cell when the fluid is  $\approx 20$ mK above the critical point (supercritical fluid), we have observed a fringe shift of  $\sim 1/2$  of a wavelength. This corresponds to  $\sim 0.005\%$  change in density near the electrode. This is less than we would expect in zero gravity. In 1g the presence of convection caused by buoyancy should decrease the density change.

## RESEARCH PLANS

In its currently planned final form, the critical fluid cell will include two transparent sapphire domes coated with indium tin oxide that will form the outer sphere which will be concentric with a  $\approx 0.25$  inch diameter conducting sphere at the center, as shown in Figure 1. The above mentioned incompressible fluid cell will be tested and information and techniques gained from it will be used to build this critical fluid cell. Based on the results of our tests that are currently being conducted, we anticipate the approach shown in Figure 1 will be used.

When the final critical fluid cell is developed, the diagnostic techniques will be used in an NASA KC-135 or DC-9 aircraft to test for a spherically symmetric density gradient in low gravity and for expected flow

patterns. In preparation for this, the 1g case will be explored first so that some idea of reasonable parameter values will be known in advance.

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	compressible SF <sub>6</sub>	incompress. DC-200 .65cs	outer core	ocean	atmosphere
Γ	1.5	1.5	1.5	6x10 <sup>-4</sup>	5x10 <sup>-3</sup>
R <sub>o</sub>	0-385	0-1500	21-2x10 <sup>-14</sup>	1800	1x10 <sup>6</sup>
S	∞-0.333	N/A	10 <sup>4</sup>	0.16	10 <sup>3</sup>
F <sub>r</sub>	0-0.002	0-0.002	9x10 <sup>-4</sup>	3x10 <sup>-3</sup>	3x10 <sup>-3</sup>
R <sub>a</sub>	0-∞	0-7x10 <sup>6</sup>	unknown	10 <sup>14</sup>	10 <sup>14</sup>
P <sub>r</sub>	1-∞	8	unknown	7-50	0.25

Table 1. The above table shows dimensionless parameters for comparison of the laboratory systems with other geophysical systems. These numbers are based on a flow cell with inner radius  $r_i=0.5\text{cm}$  and outer radius  $r_o=1.27\text{cm}$  using SF<sub>6</sub> in the compressible cell and Dow Corn DC-200 0.65 CS silicone oil in the incompressible flow cell. The height of the atmosphere is taken to be 30,000m which is where the average temperature begins to increase. The Reynolds Number,  $R_o$ , is  $R_o = \Omega r_i d/\nu$  where  $\nu$  is the kinematic viscosity and  $\Omega$  is the rotation of the inner sphere and  $d$  is the gap between the spheres. This parameter characterizes the mechanical driving of the system through the rotation of the sphere (note that we do not refer to the "rotating

frame" parameters, i.e., the Ekman and Rossby numbers). The thermal driving of the system though heating is characterized by the Rayleigh number  $R_a = \alpha T g d^3 / \kappa \nu$  or  $R_e = \gamma \Delta T g_e d^3 / \kappa \nu$  where  $\alpha$  is the thermal expansion coefficient,  $\gamma$  is the dielectric variability,  $\Delta T$  is the temperature difference across the gap of width  $d$ ,  $g$  or  $g_e$  is the acceleration that in our case can be due to gravity,  $g$ , or an equivalent electrostatic acceleration,  $g_e$ , and  $\kappa$  is the thermal diffusivity. We have used the turbulent eddy viscosity and not the kinematic viscosity in the Rayleigh and Reynolds numbers for the ocean and atmosphere. A material parameter important to convection in fluids is the Prandtl number  $P_r = \nu / \kappa$ . Because the properties of a critical fluid diverge,  $R_a$  also diverges for a given  $\Delta T$  near a fluids' critical point. In addition  $P_r$  also exhibits this behavior and can therefore be adjusted over many orders of magnitude by adjusting the average temperature. Another important parameter for our system is the Froude number  $F_r = \Omega^2 r / g$  or  $F_e = \Omega_e r / g_e$  that, in our case, compares the centrifugal acceleration with the central acceleration (electrostatic or gravitational). In order for the acceleration to be radial it is necessary for  $F_r$  to be small, i.e.,  $F_r \ll 1$ . One remaining important dimensionless parameter in a rotating flow with a density gradient is the stratification parameter  $S = g \Gamma \Delta \rho / 2 d \rho \Omega$ . If  $S$  is large, then density stratification is important.  $g_e$  is calculated using the formula for the dielectrophoretic force. The earth's core shows a large variation in  $R_a$  and an unknown  $R_e$  and  $P_r$ . This shows the lack of knowledge of the earth's core that exists today.

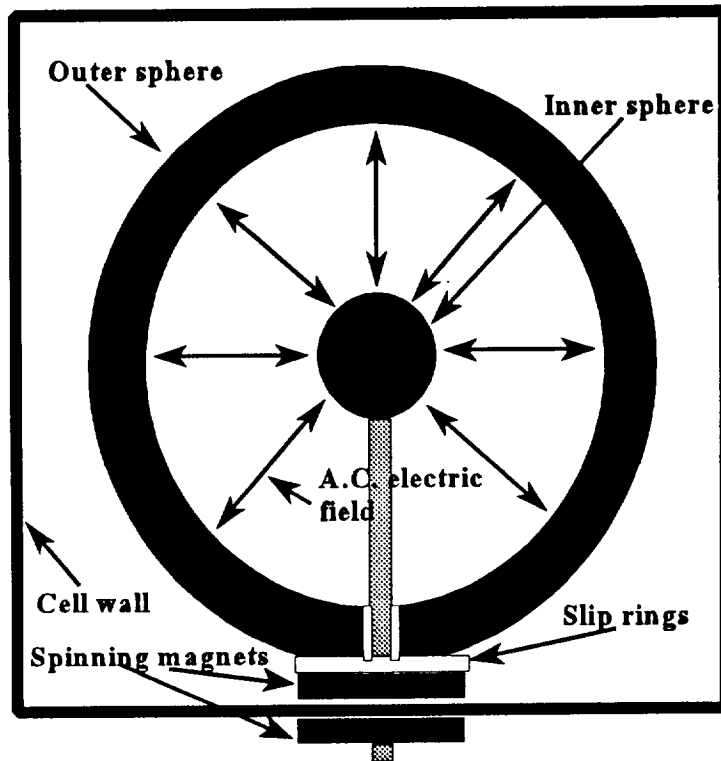


Figure 1. Above is a schematic of the compressible flow cell currently planned. Fluid near the critical point is contained inside a cell. A large A.C. potential difference applied across two conducting concentric spheres induces a spherical density gradient in the fluid between the spheres. Inside the cell will be a permanent dipole magnet attached to a conducting rod (which is attached to the inner sphere and insulated from the outer sphere). Slip rings will support the rotation of the inner sphere and allow electrical connections it. Outside the cell will be another dipole magnet connected to a step motor. The inner and outer dipole magnets will be coupled. Because the fluid in the critical fluid cell is under considerable pressure, these two magnets will allow a mechanical coupling to the outside of the cell for rotating the inner sphere. Sapphire windows in the cell will also allow infrared light from a well-calibrated source to heat the inner sphere. This heating method considerably simplifies

the cell design and maintains geophysical similarity. The density variations will be observed by using holographic interferometry where laser light is passed through the cell to produce an interference pattern



Figure 2. Shown above is a view through the preliminary cell filled with  $\text{SF}_6$  near the critical point. The dark circle in the middle is the 1/4 inch diameter spherical electrode. The dark stripes are interference fringes made using holographic interferometry. These fringes are reference fringes made by tilting an object beam mirror between holographic exposures. We have observed a fringe shift of  $\sim 1/2$  of a wavelength on applying 3000 volts (RMS) to the cell when the fluid is  $\approx 20\text{mK}$  above the critical point (supercritical fluid).