HYDROMAGNETIC EFFECTS UNDER CONDITIONS OF LOCALIZED THERMAL INSTABILITY

W. C. LEVENGOOD
Ball Brothers Research Corporation, Muncie, Indiana

Received October 21, 1958; revised November 17, 1958

ABSTRACT

Thermal convection experiments were conducted in an attempt to explain previously observed hydromagnetic effects in silver patterns deposited on glass. Convective regions were produced in alcohol and alcohol-powder mixtures by locally heating with the poles of permanent magnets. Optical and weight-difference techniques were developed to compare observed differences in the convection process over the pole regions of the magnet. These phenomena suggested electric charge effects within the liquid, and the results were found to agree with the basic electrodynamics of charges moving in a magnetic field. These force effects on charged particles also provided an explanation for the observed differences in the silver-deposit patterns. The earth's magnetic field was found to have an effect on the localized convection process. The difference over the pole regions was most pronounced when the magnet poles were aligned in the same position as the geomagnetic poles of the earth.

I. INTRODUCTION

Kinetic studies of electrical conducting liquids in a magnetic field have presented significant clues regarding hydromagnetic processes in stars and galactic systems. Alfvén (1950) was the first to demonstrate experimentally a magnetic viscosity effect which was produced by rotating mercury in a magnetic field. Lehnert (1955), using this same general technique, photographically demonstrated a magnetic rigidity effect in mercury.

A thorough discussion of these laboratory experiments has been presented by Cowling (1957). The studies have not been extensive. One possible explanation for this may be the fact that the mechanisms are very subtle and difficult to observe. Even though the situation becomes even more complex to analyze mathematically, these hydromagnetic experiments are of particular interest to the astronomer when carried out under conditions of thermal instability. This interest is due in part to the fact that thermal convective processes are believed to occur in the sun's photosphere and may be noticeably affected by magnetic fields in sunspot regions.

Using mercury as the test liquid, Nakagawa (1955) demonstrated the inhibition effect of a magnetic field on the onset of thermal convection. The writer (1956) also reported differences in silver patterns chemically deposited on glass under conditions of thermal convection. During the silvering process the glass plate was heated from below by the poles of a magnet. Subtle and consistent differences occurred in the patterns of silver particles deposited in the regions heated by contact with the poles of the magnet. At the time this work was published the explanation for this effect was not known. The theories pertaining to thermal instability in the presence of a magnetic field are complicated and do not appear to suggest any possible mechanism which could account for differences in convection over regions of opposite magnetic polarity.

Because of the importance of thermal instability effects, it was decided to carry out additional studies. The experimental results reported here demonstrate that it is now possible to explain qualitatively differences in the hydromagnetic processes over the pole regions. The earth's magnetic field was also found to have an influence on the convective processes. The techniques used in these experiments may be utilized in studies of subtle magnetic effects in liquids.

II. EXPERIMENTAL RESULTS

Solutions used to silver glass are chemically complex and temperature-sensitive. It was found that convection patterns very similar to those produced in the silvering experiments could be formed in methyl alcohol at room temperature. Convection cells were made visible by mixing fine aluminum powder with the alcohol. At about 25° C. the particles flow laterally at a rate of approximately 1 cm/sec, which agrees with the value reported by Muller (1955), using aluminum particles in acetone. The velocity of the aluminum particles was very difficult to determine precisely because of their complex motion in the convection cells. Absolute methyl alchol was used, and the aluminum powder was made by Fisher Chemical (labeled "finest powder").

a) Qualitative Observations

Convection cell patterns were studied qualitatively by using shallow, flat-bottomed containers with horseshoe magnets positioned with their pole faces in contact with the bottom surface of the container. A water film was placed between the magnet poles and the bottom of the dish to insure good thermal contact. The plan area of the pole pieces was 1.5×1.5 cm with a separation of 1.0 cm. The field strength at the center of the poles was about 1000 gauss. The poles of the magnet (at room temperature) acted as heat sources, and the surface cooling of the liquid by evaporation was sufficient to produce convection effects without any additional supply of heat from below.

Using a dish 17.2 cm in diameter, $\frac{1}{2}$ gm of the aluminum powder was mixed with 70 cc methanol, giving a liquid depth of about 3 mm. The convection patterns were broken up into flow lines in the pole regions. At the north pole the flow lines were observed to stream toward a central focal point, whereas at the south pole they were more haphazard and disclosed more curvature. This is in agreement with the effects found with the silvering experiments.

b) Surface Distortion with Pure Alcohol

When pure alcohol was used, the structure of the convection cells could not be seen in detail. It was necessary to use a somewhat different method of examination. In this case a grid pattern was reflected from the surface of the liquid, as shown in Figure 1. The low angle of incidence ($\sim 16°$) was used to prevent secondary reflections from the bottom of the dish.

The use of the lens is optional. With the lens in position, black regions appeared in the reflected grid patterns because of light scattered from the distorted regions of the liquid surface. Without the lens, the surface distortion showed up as curved lines in the grid reflection.

Reflection patterns with and without the lens in position are shown in Figure 2. It may be seen that in both cases the greatest distortion occurred over the south pole region. The pole region distortions became less pronounced with increasing depth of liquid. It was observed that the distortion over both pole regions was actually caused by depressions in the surface of the liquid. This depression effect was also seen in all the subsequent experiments.

The distortion patterns shown in Figure 2 were photographed with the magnet aligned with the geomagnetic poles of the earth. The effect of reversing the magnet with respect to the earth's field is shown in Figure 3, using methanol in the dish. In Figure 3, *A*, the magnet was aligned with the geomagnetic poles of the earth, and the greater distortion over the south pole region is apparent. The effect with the magnet opposite the geomagnetic poles is shown in Figure 3, *B*. In this case the distortion effect is less pronounced, and the difference between the regions is much less apparent.

When aluminum powder was added to the alcohol, a difference was again observed in the distortions over the pole regions, although not so pronounced as with alcohol alone. Also in these experiments the greater depression occurred over the north pole region (magnet aligned with geomagnetic poles), which is the reverse of the effect with pure alcohol.

c) Quantitative Studies of Flow Effects

The reversal of the depression effect with the addition of the aluminum powder suggested the possibility of charged particles or molecular groups within the liquid. One should therefore be able to vary the effect by adding fine powders with different net electrical charges. The literature (1954) indicates that sols of metals carry a net minus (−) charge, whereas oxides and hydroxides carry a plus (+) charge. This was confirmed by subjecting the alcohol and aluminum powder mixture to a 1600-volt d.c. electric field. There was a very pronounced migration to the positive electrode, indicating negative-charged particles. Particles of opposite charge were produced by mixing extremely fine silica powder (0.5–3 μ) with the methanol. This powder did not, however, produce visible convection cells, as did the aluminum powder.

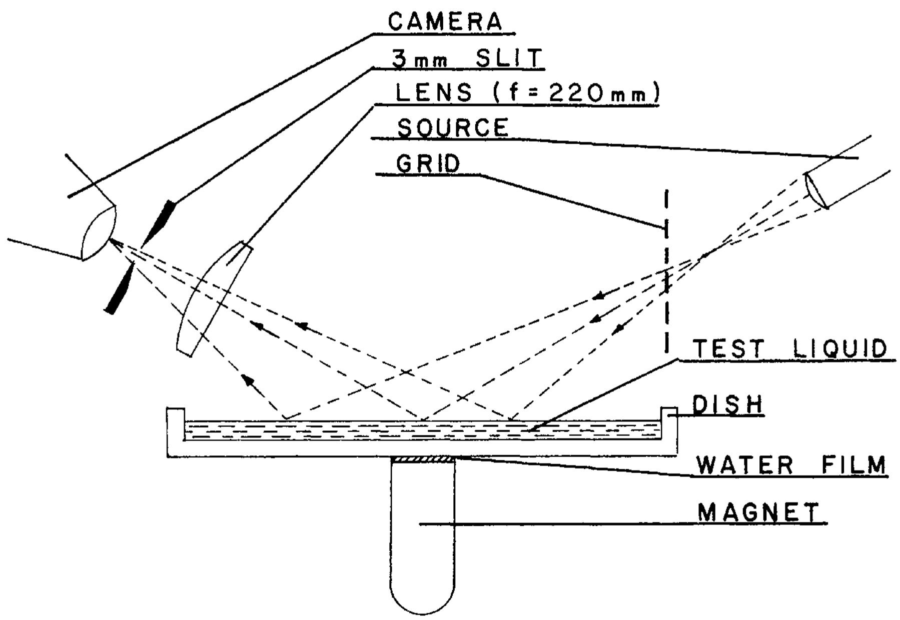


FIG. 1.—Schematic diagram of experimental apparatus

It was discovered, however, that when these alcohol mixtures were placed in the dishes and the alcohol allowed to evaporate, heavy deposits of powder were formed over the pole regions. These deposits of powder were very sharply outlined. The "pumping action" over the pole regions appears to be pronounced, and material flows into this area and deposits heavily.

A series of comparative experiments was made by allowing the dishes to stand for about 16 hours, then collecting the deposits over the pole regions and weighing them. The circular convection dishes were about 4 cm high and 10 cm in diameter, with flat sheet-glass bottoms. A total of 20 mg of the test powder was mixed with 12 cc methanol, giving a layer about 1.5 mm deep in the dish. The dish was centered on the magnet, as shown in Figure 1 (grid and lens removed). The apparatus and test liquid were at room temperature. The material, deposited only in the areas covered by the poles of the magnet, was collected in vials and weighed on a Fisher "Gram-atic" analytical balance with an accuracy of 0.1 mg. A total of thirty-four individual experiments was made for each given set of conditions.

The average weights of the pole region deposits using aluminum and silica powder are given in Table 1. It was determined that there was a significant difference between the means ($\bar{S}$ and $\bar{N}$) of the pole deposit weights. This conclusion was reached as the result of an analysis of the pairs of pole deposit weights. A ratio $\bar{S} - \bar{N}/\sigma_{\bar{d}}$ was compared with the "critical value" from the Student-*t* distribution table (1952). The value $\sigma_{\bar{d}}$ is the standard deviation of the mean of the paired differences (weight differences of individual tests). A ratio greater than the critical value of 2.576 indicates a significant difference at the 99 per cent confidence level. These ratios shown in Table 1 were in every case greater than this value.

It may be seen that the heaviest deposit in the aluminum powder tests occurred over the north pole regions. The grid reflection experiments also disclosed a greater distortion over the north pole in the aluminum powder mixtures, indicating a more pronounced flow effect. The tests with the silica powder show the opposite effect, or a heavier deposit over the south pole region.

TABLE 1

WEIGHT COMPARISONS (IN MG) OF POLE REGION DEPOSITS

(Averages of 34 Tests)

Sol Particles in Methanol	S (Av.)	N (Av.)	($\bar{S}-\bar{N}$)	Ratio ($\bar{S}-\bar{N}$)/$\sigma_{\bar{d}}$
Aluminum......	0.641	0.791	−0.150	13.7
Silica...........	2.644	2.332	0.312	7.3

TABLE 2

POLE REGION DEPOSITS (IN MG) WITH MAGNET POLES OPPOSITE GEOMAGNETIC POLES

(Averages of 34 Tests)

Sol Particles in Methanol	S (Av.)	N (Av.)	($\bar{S}-\bar{N}$)	Ratio ($\bar{S}-\bar{N}$)/$\sigma_{\bar{d}}$
Silica...........	2.360	2.228	0.132	5.8

Deposit experiments were also made with the magnet rotated 180° and using the silica powder. These results are shown in Table 2. It may be seen that the south pole region again shows the greater deposit; however, there is less difference between the average values. This again demonstrates the effect of the earth's field on the convection processes.

III. DISCUSSION OF RESULTS

According to Spitzer (1956), a charged particle which moves laterally in a magnetic field (parallel to the Z-axis and changing strength along the X-axis) gyrates with a helix motion. The direction of this helix, that is, whether toward or away from the magnetic dipole, depends on the charge of the particle and the direction of the magnetic field. The component of lateral force experienced by the charged particle is given by Richtmyer and Kennard (1947) as

$$F \cos \theta = \frac{e v \mathfrak{M}}{r^3} \cos \theta , \tag{1}$$

where e is the charge on the particle, v its velocity, M the magnetic moment of the dipole, and r the radial distance from the dipole. The angle θ is formed by the radius drawn from the instantaneous position of the particle to the dipole and the tangent to its path drawn in the direction of motion. To an observer looking down onto the north pole of a magnet, the lateral force on a negatively charged particle is such that the motion would be toward the magnetic pole and away from the pole for a positively charged particle. At the south pole of the magnet, the situation would be the opposite of this.

We can now compare this force relationship with what was observed experimentally with the aluminum and silica particles in the alcohol. The result will be qualitative because neither the net electric charge nor the absolute velocity effect of the magnetic field is known in the case of the particles. The velocity of a given charged particle in the alcohol is a combination of the momentum effect produced by the thermal convection process and the lateral force of the magnetic field. A rigorous treatment of this interrelationship appears to be a difficult theoretical exercise.

In the case of the negatively charged aluminum particles in the alcohol, the greater deposit was formed over the north pole region. The magnetic force over the north pole (given by eq. [1]) would be in the same general direction as the convection process, which also causes the particles to flow into the region heated by the poles of the magnet. Over the south pole of the magnet, the magnetic force would oppose the convection force on the aluminum particles. The more pronounced "pumping action" would therefore occur over the north pole, and this probably accounts for the greater deposit of material in this region. This same argument would apply with the positively charged silica particles, and in this case the forces would be additive over the south pole region, and this again agrees with the experimental observations.

The unexpected effect of the earth's magnetic field indicates that the flow processes are extremely sensitive to minute force effects. The silica particles disclosed less difference in the average pole deposits when the position of the magnet was opposite the geomagnetic poles. By keeping in mind that the geomagnetic north pole may be considered a south pole of a magnet and the geomagnetic south pole a north pole of a magnet, the same kind of reasoning may be used to show that when the magnet is reversed in position, the force effects are also reversed. Since the magnetic field of the earth is about 2×10^{-4} times the strength of the magnet used in these experiments, it is very surprising that its effect may be detected. This may possibly be due to the fact that the force of the magnet varies inversely as the cube of the radial distance of the particle from the magnet, whereas the earth's field is constant over the convection region, even though of less magnitude.

The experiments with pure alcohol indicate that there are groups or particles within the liquid with a net positive electric charge. The charge effect in alcohol may explain why the difference in the pole deposit averages is less in the case of the aluminum powder than with the silica particles (Table 1). The positive particle effect in the alcohol tends partially to cancel the force effect on the minus-charged aluminum particles and add to the effect with the silica particles.

The force effects described by equation (1) may also be applied to the negatively charged silver particles in the earlier reported experiments. Here also a more definite or localized pumping action was observed over the north pole of the magnets.

IV. CONCLUSIONS

A series of thermal convection experiments was made with pure alcohol and mixtures of alcohol and fine powders in an attempt to explain peculiar magnetic effects previously found in silver patterns deposited on glass. Localized thermal convection effects were produced by using shallow flat-bottomed containers resting on the poles of horseshoe-type permanent magnets.

By mixing fine aluminum powder with methyl alcohol, convection patterns were produced in the pole regions of the magnets which were analogous to effects found in previously reported silvering experiments. These alcohol experiments suggested the possibility that the particles possessed a net electric charge which affected their flow characteristics in the magnetic field.

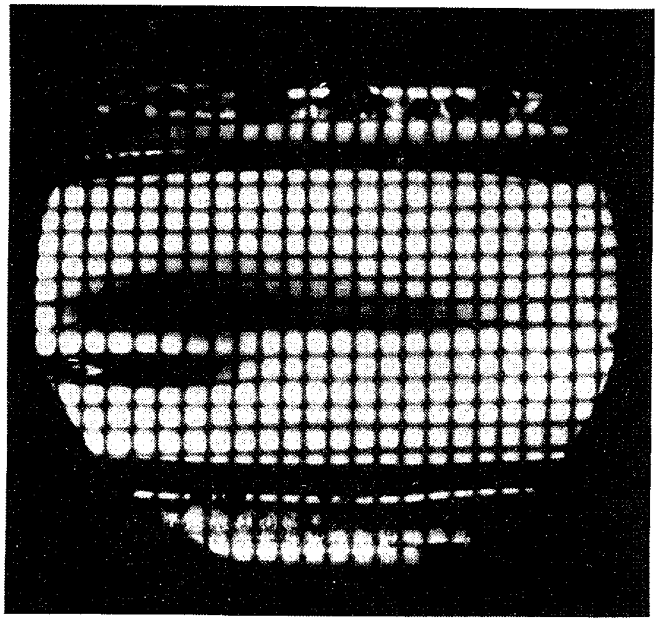
When the alcohol was allowed to evaporate in the dishes, heavy deposits of powder collected over the pole regions of the magnet. Aluminum powder with a negative charge disclosed heavier deposits over the north pole region, and silica powder with a net positive charge collected in greater quantities over the south pole region. These results agree with the electrodynamics of charges moving in a magnetic field.

Grid reflection studies were made of thermal convection processes in pure alcohol, and these results indicate that methyl alcohol possesses positively charged groups within the liquid. The differences in the localized convection effects were most pronounced when the magnet was aligned with the geomagnetic poles of the earth. When placed opposite the geomagnetic poles, the convection was reduced, and the differences in the structure at the pole regions were much less evident. This effect of the earth's field was observed with pure alcohol and with alcohol-powder mixtures.

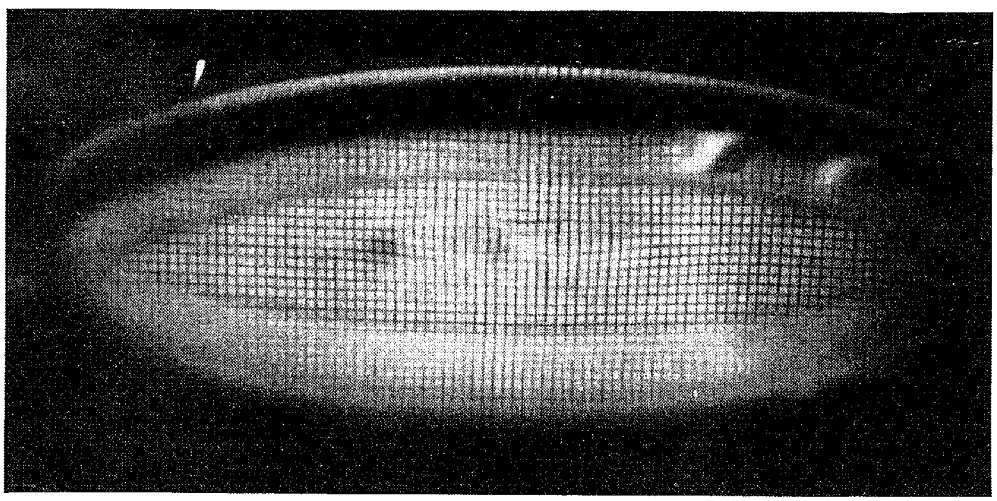
The author would like to express his appreciation to Dr. John Strong, director, Laboratory of Astrophysics and Physical Meteorology, Johns Hopkins University, for his personal encouragement and helpful suggestions during the course of this work; also to Mr. R. W. Garrett, of our organization, for consultation regarding the statistical methods of treating the data.

REFERENCES

Alfvén, H. 1950, *Cosmical Electrodynamics* (Oxford: Oxford University Press).
Cowling, T. G. 1957, *Magnetohydrodynamics* (New York: Interscience Publishers, Inc.).
Encyclopedia of Chemical Technology (New York: Interscience Encyclopedia, Inc., 1954), **4,** 229.
Freund, J. E. 1952, *Modern Elementary Statistics* (New York: Prentice-Hall, Inc.), p. 390.
Lehnert, B. 1955, *Proc. R. Soc. London, A*, **233,** 301.
Levengood, W. C. 1956, *Nature*, **177,** 631.
Muller, J. H. 1955, *Am. J. Phys.*, **23,** 198.
Nakagawa, Y. 1955, *Nature*, **175,** 118.
Richtmyer, F. K., and Kennard, E. H. 1947, *Introduction to Modern Physics* (New York: McGraw-Hill Book Co., Inc.).
Spitzer, L., Jr. 1956, *Physics of Fully Ionized Gases* (New York: Interscience Publishers, Inc.).

S  N

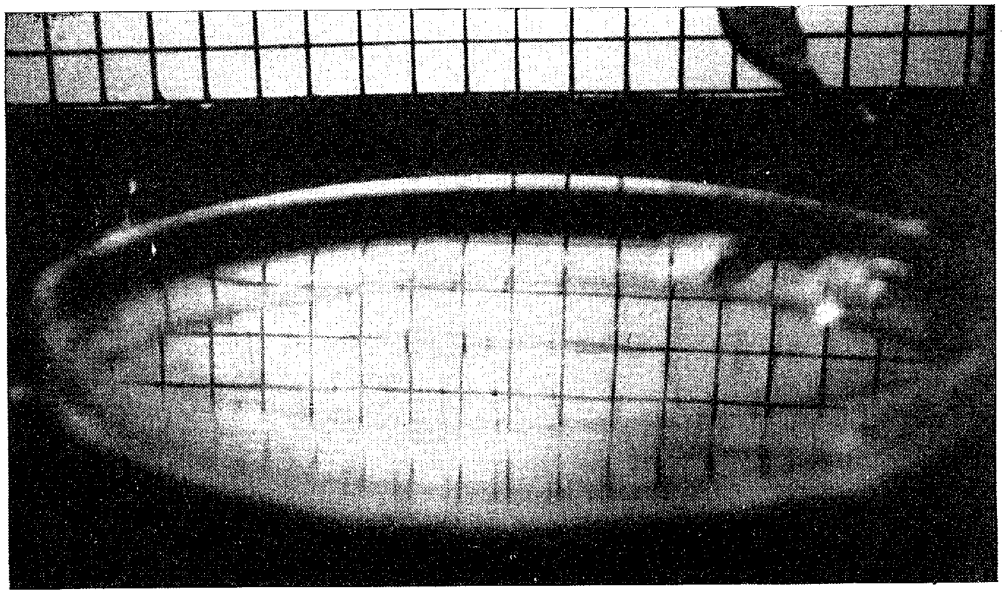
(A)

S  N

(B)

FIG. 2.—Convection in methanol heated by magnet poles (dish diameter, 17.2 cm; liquid depth, 1.8 mm; $\frac{1}{10}$-inch grid spacing). (A) with lens in system; (B) with lens removed.

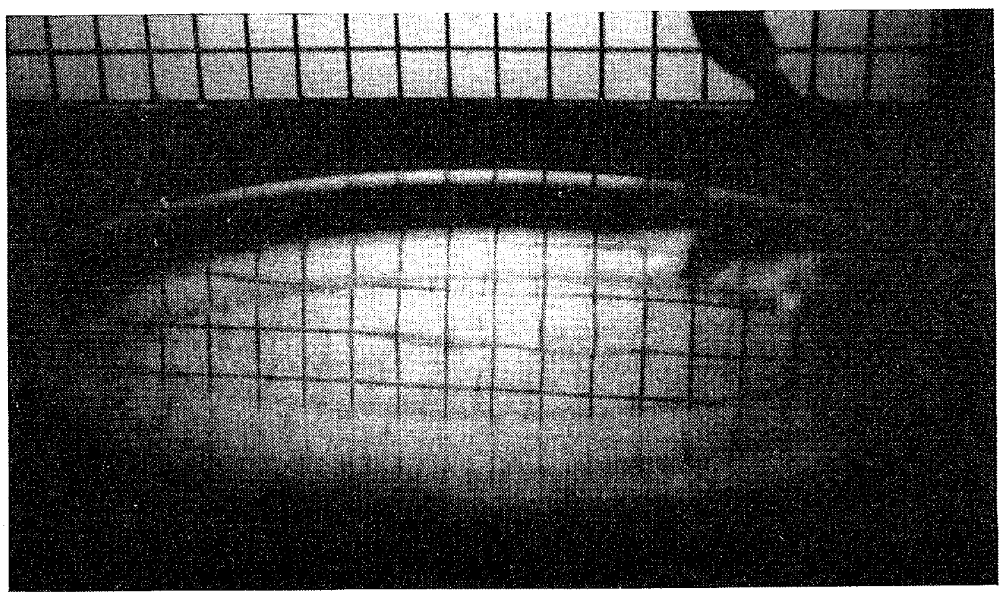
S



N

(A)

N



S

(B)

FIG. 3.—Effect of magnet position on thermal convection in methanol (liquid depth, 1.5 mm; $\frac{1}{2}$-inch grid spacing). (*A*) magnet aligned with geomagnetic poles; (*B*) magnet poles opposite geomagnetic poles.