Letters to the Editor

"Physical Basis of Bird Navigation"

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IN his remarkable paper on the above subject in the Journal of Applied Physics,* Dr. Yeagley describes the astonishing experimental support to his hypothesis that navigating birds are "sensitive" to the magnetic field and Coriolis forces associated with the earth. Astonishing as this hypothesis may seem, I do not know of any fundamental law of physics which is contradicted by it, or which would rule it out, as thus stated.

However, Dr. Yeagley, in his paper, states his hypothesis in a more limited manner, and to this more limited hypothesis, it seems to me, serious objection can be made. Dr. Yeagley states that the birds are "sensitive" to the effect of motion through the earth's magnetic field (p. 1036, second column), or to the effect of flying through a magnetic field (p. 1037, second column). In both cases, I presume Dr. Yeagley means a uniform motion through the magnetic field.

The restricted principle of relativity applied to this case tells us that in a system, such as the flying bird, in uniform motion relative to the earth, electrical and magnetic phenomena will proceed in exactly the same way as if the system were at rest, that is, the bird on the ground, and the electric and magnetic field in the system changed by the following scheme:

$$E_x'=E_x, \qquad H_x'=H_x,$$

$$E_y'=\frac{E_y-\frac{v_x}{c}H_z}{\left(1-\frac{v_x^2}{c^2}\right)^{\frac{1}{2}}}, \quad H_y'=\frac{H_y+\frac{v_x}{c}E_z}{\left(1-\frac{v_x^2}{c^2}\right)^{\frac{1}{2}}}, \tag{1}$$

$$E_z'=\frac{E_z+\frac{v_x}{c}H_z}{\left(1-\frac{v_x^2}{c^2}\right)^{\frac{1}{2}}}, \quad H_z'=\frac{H_z-\frac{v_x}{c}E_y}{\left(1-\frac{v_x^2}{c^2}\right)^{\frac{1}{2}}}.$$

Here E_x, E_y, E_z, and H_x, H_y, H_z, are the components, respectively, of the earth's electric and magnetic fields, v_x, the velocity of the bird moving in the x direction, and c, the velocity of light. E_x', E_y', E_z', H_x', H_y', H_z' are the components of the electric and magnetic fields to which the bird at rest on the earth must be subjected if it is to be "sensitive" to exactly the same effects as the bird moving with velocity v_x through the fields E_x, E_y, E_z, H_x, H_y, H_z.

If we neglect v_x^2/c^2 relative to (1), and also neglect the effect of motion through the earth's electric field, that one of the above equations which is relevant to my argument becomes

$$E_y'-E_y=-\frac{v_x}{c}H_z. \tag{2}$$

Hence any "sensitivity" which the bird may have to its uniform motion, v_x, through the vertical component of the earth's magnetic field, H_z, will be indistinguishable from its "sensitivity" to a change in the horizontal component of the earth's electric field given by (2).

Unfortunately, the intensity of the earth's electric field is normally thousands of times larger than the quantity v_x/cH_z in Eq. (2). If the earth's surface were perfectly smooth and horizontal, and if there were no clouds or other disturbing charge distributions in the air, we might argue that the horizontal component of the earth's electric field, E_y, remains always zero. But with actual terrain, local winds, and clouds, E_y will always be large, and variable. Hence, we may conclude that whatever "sensitivity" the bird may have to its motion, v_x, in the field, H_z, it will be quite completely overshadowed and obliterated by the indistinguishable "sensitivity" to changes in the earth's horizontal electric field, E_y.

I have frequently had occasion in the past to use the above argument to convince inventors who aspire to measure the velocity of an airplane by observing the effects of its motion through the earth's magnetic field upon suitable electrical apparatus on the plane. No matter how ingeniously they devise their apparatus, the effect of changes in the earth's horizontal field is indistinguishable from, and overshadows, the effect they are trying to observe.

It seems to me, then, that Dr. Yeagley will need to postulate a "sensitivity" of the navigating bird to the magnetic field directly, rather than a "sensitivity" to the effect of the uniform motion of the bird through the field. He will also need to assign to the necessary observation, which the bird must have of the ground over which the bird is flying, a role more primary than that of merely cooperating with the "sensitivity" to its motion through the magnetic field (p. 1037, second column).

* Henry L. Yeagley, J. App. Phys. 18, 1035 (1947).

Remarks on: "A Preliminary Study of a Physical Basis of Bird Navigation"*

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TO support his very interesting theory of the mechanism of bird navigation, the author presents very strong experimental evidence for the conclusion that pigeons, and presumably other birds, find their way home over territory which is unfamiliar, by the aid of two senses. One is a sense of latitude, the other a sense of the strength of the vertical component of the earth's magnetic field. Since the magnetic poles of the earth are displaced from the axis of rotation, the lines of equal vertical component intersect the latitude lines, forming a grid which may be used to define a location.

The author appears to jump to unwarranted conclusions concerning the operation of these senses.

First, he postulates that the indication of the vertical component of the earth's magnetic field is provided by some organ which can measure the e.m.f. produced in a conductor cutting the lines of force of the earth's magnetic field.

The primary reason for writing this letter is that the present writer, in his student days, conceived the idea of utilizing this effect to construct a ground speed meter for airplanes, and stirred up quite a bit of interest before he discovered that the method was fundamentally fallacious. Later, Dr. D. L. Webster produced a more general refutation than that of the writer. This argument, which is based on relativity, is here outlined.

In relativity, an identity exists between an electrostatic field and a magnetic field moving relative to a frame of reference. It then follows that any attempt to shield a pick-up system from spurious electrostatic forces must shield the pick-up from the influence of the moving magnetic field. This is briefly treated by W. R. Smythe, *Static and Dynamic Electricity* (McGraw-Hill Book Company, Inc., New York, 1939), pp. 499–501. If we dispense with shielding, we are then confronted with the conductor. This reduces itself to measuring a potential difference between the conductor ends and the atmosphere, but the atmosphere is moving with respect to the magnetic field and therefore has an electrostatic field caused by its motion. Thus, if the formidable obstacle of extraneous electrostatic forces is successfully overcome, the end result is a measurement of air speed. Since pigeons cannot measure the vertical component of the earth's field by measuring the rate of cutting magnetic lines of force, the alternative appears to be that they possess an organ capable of acting as a magnetometer.

The author's second postulate is that the detection of latitude is made by measurement of the Coriolis force. This he computes for his case to be 0.0061 ft. per sec. per sec., or about 1/6000 g. In order for pigeons to locate themselves within 25 miles or so, a measurement of less than 1 percent of this would have to be made, or very roughly a measurement of 10^{-6} g. The only way the acceleration of gravity may be removed from the measurement is by a knowledge of its direction of action to about 10^{-6} radian without reference to the force of g for determining that direction. This appears to be practically impossible, even though it may be theoretically possible. It would therefore appear that as far as the evidence presented in the article is concerned, the determination of latitude by the sun is more likely than determination by Coriolis force.

The hypothesis that a bird measures latitude by the elevation of the sun should receive attention. The sun appears as a fairly large object, yet determination of its elevation to one solar diameter would give latitude within 30 miles; thus, it appears that if solar elevation is used, no great precision is required to determine latitude within the pigeon's apparent accuracy. The cited fact that pigeons are unable to navigate in thick haze or fog or complete darkness is concordant with this view.

It should be further pointed out that either mutation or chance development of an organ for another function must produce an organ capable of measuring Coriolis force sufficiently well to be of survival value before evolution can take hold to produce further refinement. This seems to be almost an impossible occurrence.

The following experiments to throw further light on the nature of the organs involved suggest themselves:

1. Attach magnets to the birds where they will be stationary with respect to the body of the bird, but will produce a change in vertical component of magnetic field.
2. Determine definitely whether pigeons can navigate under conditions of good visibility but heavy overcast. This last experiment would be conclusive if it showed pigeons could not navigate under heavy overcast, but if the result were the reverse it would not rule out an organ sensitive to extreme infra-red which could operate through considerable overcast.

* Henry L. Yeagley, J. App. Phys. **18**, 1035 (1947).

Remarks on: "The Physical Basis of Bird Navigation"

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IN a recent article[1] H. L. Yeagley describes experiments with homing pigeons which he interprets as indicating that homing ability is based on the detection of induced electromotive forces due to motion with respect to the earth's magnetic field and on the detection of the Coriolis force due to motion with respect to the rotating earth. However, even if it is assumed that a pigeon can make any required measurements with infinite accuracy, it seems conceptually impossible for it to detect either the electromotive force or the Coriolis force. A discussion of the impossibility of determining the electromotive force is given by Smythe,[2] who bases his discussion on the well established principal that the electric fields observed by virtue of motion through a uniform magnetic field are indistinguishable from uniform static fields. Since the static fields due to atmospheric electricity[3] are of the order of one volt/cm and are quite variable, it would appear impossible to detect a superposed field of 10^{-5} volt/cm due to motion. It is also impossible that these fields should produce physiological effects, as suggested by Yeagley. The situation with respect to Coriolis force is even worse. It is difficult to conceive of a device that responds to Coriolis force that does not respond equally to gravitational force, certainly no mechanical device will. Hence it is impossible to separate the Coriolis force from the force of gravity except by comparison of measurements of two observers having different velocities, and hence different Coriolis forces. It does not help the pigeon to change its speed unless it can, in effect, determine the position of the vertical when stationary on the ground and then recognize the position of this line by visual observations (or by the use of a gyroscope), to about 0.1 second of arc for comparison with the apparent vertical when flying. When flying over water or fog where the solid earth is not visible, it would seem to be impossible for the pigeon to determine either its speed or acceleration with respect to the earth, both being needed for a determination of latitude by means of the Coriolis force, and the speed being needed for a determination of the vertical component of the magnetic field from the induced electromotive force.

Even though it is impossible for the pigeon to detect the induced electromotive force produced by flying through the earth's field, and thereby determine the vertical component of the field, there is no such reason to suppose that the bird cannot measure the field directly, perhaps by means of the e.m.f.'s induced in moving blood. And there are many ways whereby latitude can be measured without measuring Coriolis force. Offhand, it would seem easier for the pigeon to observe the sun or the stars or to measure the acceleration of gravity, which depends on latitude, than to measure a force of the order of the Coriolis force. It is evident, therefore, that Yeagley can meet the above objections without an essential change in his theory merely by adopting some other mechanisms by which a pigeon measures the vertical component of the magnetic field and the latitude. It is obvious that this would not affect any of the experiments he describes.

Because it seems desirable to test such a remarkable theory in as many ways as possible in spite of the amazing experiments already reported, those of the following experiments that have not yet been tried might well be considered. To distinguish between Yeagley's assumption that pigeons are sensitive to electric fields, the assumption that they are sensitive to magnetic fields, and the assumption that they are sensitive to neither, the most direct experiment would be a maze experiment or a feeding apparatus experiment in which the essential clues that the bird would have would be appropriate fields. Similar experiments in slowly accelerating elevators or rotating houses might show whether pigeons were sensitive to small accelerations and hence that such a sensitivity could be used for the determination of latitude. It would be interesting to know the effect on homing ability of a magnet fastened to the bird's body rather than to its wings and of the effect of magnetic storms. Experiments, such as the Special Release No. 1 of Yeagley's First Nebraska Experiment, in which birds flew toward a conjugate point to which they had never been would seem to be somewhat freer of unexpected alternative explanations than experiments in which the pigeons knew their loft was at the conjugate point because they had seen it there.

[1] H. L. Yeagley, J. App. Phys. **18**, 1035 (1947).
[2] W. R. Smythe *Static and Dynamic Electricity* (McGraw-Hill Book Company, Inc., New York, 1939), §14.14.
[3] W. F. G. Swann, Int. Crit. Tab. **6**, 442.

A New Method of Measuring Diffusion Coefficient in Solids with Radioactive Tracers

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TWO experimental methods have been used up to the present time in the determination of the diffusion coefficient with the help of radioactive tracers. The older one, as described by W. A. Johnson,[1] requires the slicing of a specimen previously heated to a certain temperature for a long period of time. From the dissolved slices the average concentration of the radioactive material is determined and the concentration *versus* depth curve is constructed. From this curve, coefficient of diffusion D can readily be determined. The other method (2) dispenses of cutting, and from one reading of radioactive intensity and knowledge of the absorption coefficient for a given material the diffusion coefficient can be determined. In both methods the appropriate correction has to be made for radioactive decomposition during heating time.

The present method does not require cutting of the specimens, nor the knowledge of the absorption coefficient.

One face of a rectangular specimen a few centimeters in length is covered with a thin layer of radioactive material whose diffusion is to be measured and is then heated for a long period of time. Afterwards, the flat surface perpendicular to the activated face is etched electrolytically. The specimen is then transferred to a lead box (Fig. 1) with its etched surface up. The sliding cover is moved so that edge A is at an arbitrary distance x_1 from the radioactive layer and a reading of the radioactivity I_1 is taken. Then the sliding cover is moved to the left so that edge B will take the position x_2 such that the radioactivity reading I_2 from this portion of the specimen is equal I_1. From these two readings only, the diffusion coefficient can be calculated as follows:

$$I_1 = bL_0\alpha\pi^{-\frac{1}{2}}\int_0^{x_1/2(Dt)^{\frac{1}{2}}} e^{-z^2}dz,$$

where α is a factor expressing absorption, b the width of the specimen, and i_0 the original concentration of the radioactive material on the activated face.

$$I_2 = \frac{bL_0\alpha}{2}\left\{1 - \tfrac{1}{2}\pi^{-\frac{1}{2}}\int_0^{x_2/2(Dt)^{\frac{1}{2}}} e^{-z^2}dz\right\}.$$

From $I_1 = I_2$ denoting

$$\pi^{-\frac{1}{2}}\int_0^{x/2(Dt)^{\frac{1}{2}}} e^{-z^2}dz = \phi(y)$$

one obtains

$$\phi(y_1) + \phi(y_2) = \tfrac{1}{2},$$

where

$$y_1 = x_1/2(Dt)^{\frac{1}{2}} \quad \text{and} \quad y_2 = x_2/2(Dt)^{\frac{1}{2}}.$$

Since

$$\frac{y_2}{y_1} = \frac{x_2}{x_1}, \quad \phi(y_1) + \phi\left(\frac{x_2}{x_1}y_1\right) = \tfrac{1}{2}.$$

This equation can easily be solved by graphical methods. When y_1 is known, D is calculated from

$$D = (1/t)(x_1/2y_1)^2.$$

It can be seen that the determination of D does not depend upon knowledge of the absorption coefficient and original concentration of the radioactive material on the activated face.

This method is expected to produce results under the following conditions: 1. The radioactive layer should be thin. 2. The surface from which the readings are taken should be deeply and uniformly etched to remove all