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SECTION II.—GENERAL METEOROLOGY.

SOME PROBLEMS OF ATMOSPHERIC ELECTRICITY.

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The problems of atmospheric electricity with which we are about to deal must be solved by means of the laws which govern the behavior of electricity in gases, and I therefore propose, before discussing the actual conditions, to sketch in a few words the main principles involved.

The earth is a solid body which for all purposes of atmospheric electricity may be considered to be a perfect conductor. Its dimensions are so large, and therefore its electrical capacity so great, that no amounts of electricity which we can extract or add at any place can alter its electrical potential. As the potential of the earth does not change, it is convenient to take its potential as our standard and refer all other potentials to it. We therefore describe the earth as being at zero potential and the potentials of all other bodies as plus or minus the difference between the potential of the body and the earth.

Let us suppose that the earth has no atmosphere, and we give to it a charge of electricity which, in order to fix our attention, we will assume to be negative, then by the laws of electrostatics the charge would distribute itself all over the surface. If the surface were a perfect sphere, the surface distribution would be everywhere the same; but as there are irregularities, every hill would have an excess of electricity and every valley a defect. The value of the surface density at any point could easily be measured. An ideal, although not a practical, method to do this would be to take a unit charge of positive electricity and hold it at a certain distance from the earth. The negative charge on the earth would then attract our positive charge, and if we moved the latter away from the earth's surface we should have to do work. If we moved the charge from the ground to a meter above the ground, we should do against the electrical forces an amount of work equivalent to the electrical potential energy of the charge at 1 meter above the ground. More work would have to be done to convey the charge to 2 meters, and still more to 3 meters. At every position, then, above the surface our unit charge would have a different potential. From this experiment we could calculate the change in potential of our unit charge at every position above the surface, and it would be a simple matter, by the laws of electrostatics, to calculate from this change of potential, or, as it is called, the potential gradient, the amount of charge on the earth's surface. It is important to realize that when we measure the potential gradient immediately above the earth's surface we are only finding the force due to the electricity spread over the ground.

Now, let us imagine that an atmosphere is given to the earth, and see what consequences we might expect. For long it was supposed that air was a perfect nonconductor of electricity, and we will for a short time retain this false impression. A nonconducting atmosphere at rest would not affect the electrical state of the surface and we should still be able to measure the amount of charge by measuring the potential gradient. If, however, the air moves and we get winds, the electrical state of the surface may be greatly affected. I have explained how the whole charge on the earth is situated on the upper surface of the ground; hence every particle of dust, every blade of grass, and every leaf of a tree has a charge of electricity upon its surface. If, therefore, the wind raises the dust (we are to neglect any frictional electricity produced by the process) or whirls away the leaves of a tree, a certain amount of electricity is separated from the earth and raised into the air. But so long as the air is nonconducting the charge remains fixed onto the dust and onto the leaves, so that when the wind stops and they fall to the ground again the charge is returned to the surface of the earth. With a nonconducting atmosphere the charge on the earth can not be permanently separated, and after any length of time we should still find the same quantity of electricity from our measurements of the potential gradient.

But recent research has shown that air is not a perfect nonconductor; it conducts electricity slowly, but as surely as copper conducts it. Electrically a conducting atmosphere becomes a part of a conducting earth, and just as before there was an atmosphere electrostatic forces drove all the electricity up to its surface, the same forces will drive it through the air until it reaches the surface of the conducting sphere which is now the confines of the conducting atmosphere. All our electricity then will ultimately spread itself in a uniform layer over the outside of the atmosphere. Now, it is well known that there is no electrical force within a conductor no matter how much electricity there may be on the surface. Therefore no experiments that we can make at the surface of the earth would reveal the charge spread over the upper atmosphere. It is important to realize that there may be a charge of untold amount in the upper atmosphere of which we are entirely ignorant because of this property of a conducting body to exhibit no electrical force within itself.

It therefore appears that it would be impossible for a charge to remain on the surface of the earth while the air is ever present to conduct it away into the upper atmosphere. Yet we find that the whole surface of the earth is charged and remains charged with an undiminishing quantity of electricity. This is a paradox about which I shall have a great deal to say later, but before discussing it, it will be necessary to go more fully into the causes of the conductivity of the air.

The conductivity of the air is a very variable quantity, its average value is near to 3×10^{-4} electrostatic units, which means that its resistivity is 3×10^{7} ohms or twenty thousand million (2×10^{10}) times that of copper. The mechanism of the conductivity in copper and air are, however, very different. The air conducts only when its molecules are ionized; that is, split up into positive and negative ions which move under the influence of the electrical field. Thus, when a current of electricity passes through conducting air there is an actual transferrence of matter, while in copper the electricity moves independently of the mass of the copper.

1. RADIOACTIVE SUBSTANCES AND ATMOSPHERIC IONIZATION.

Observations in all parts of the world have shown that the atmosphere everywhere is ionized and it is generally held that the radioactive substances in the earth and air are the cause of this ionization. The first question which I wish to discuss is whether this radioactive theory of the ionization of the air is alone capable of explaining the facts.

To do this we will first consider the ionization actually found by experiment over the land and over the sea, then the number of ions formed by the known radioactive matter over the land and over the sea, and lastly whether these values agree.

The ionization, over the land particularly, is greatly affected by the meteorological conditions, the chief factor being the temperature. We shall therefore in the following only consider the ionization with temperatures between 10° and 20°C. Very many measurements of the ionization have been made and these show that within the limits of temperature we are considering, there are on the average over the land 1,000 ions of each sign in each cubic centimeter of air.

The measurements over the sea are much less numerous, but when on a voyage from England to New Zealand Wright and I [1] made a number of determinations of the ions present over the ocean far from land, and the mean value of sixteen observations with the temperature between 10° and 20° C. was 800 ions per cubic centimeter.

We therefore have over land 1,000 and over the ocean far from land 800 ions per cubic centimeter.

We will now turn our attention to the radioactive matter which is supposed to be capable of producing this ionization.

It is now definitely known that the rocks of the earth's crust contain appreciable amounts of radium and thorium, and numerous measurements of the radioactive contents of the rocks have shown that this radioactive matter is present in nearly all kinds of rocks and fairly uniformly distributed throughout all soils. The radioactive matter in the ground produces α, β, and γ rays, but the two former do not escape into the atmosphere, except in a negligibly small proportion from the actual surface, and therefore cannot effect ionization there. On the other hand, owing to their greater penetrating power, a certain proportion of the γ rays do pass out of the ground into the air and ionize it. These rays are absorbed in the air and therefore the ionization due to them decreases as we ascend but giving our attention to the air near the surface, say, within 6 feet, a simple calculation [2] shows that the average amount of radium in the soil gives out sufficient γ radiation to produce 0.8 ion per cubic centimeter per second. The amount of thorium is not known with such accuracy, but it is generally supposed that the ionizing power of the thorium in the soil is about equal to that of the radium. Hence the thorium and radium in the soil combined produce by means of their γ radiation something like 1.6 ions per cubic centimeter per second in the air just above the ground.

The radium and thorium in the soil are constantly giving off their respective emanations. These emanations fill the interstices of the soil, from which they escape into the atmosphere by ordinary diffusion and in consequence of any fall of barometric pressure. Thus the air over the land receives emanations from the ground which behaves very much like one of the ordinary gases of the atmosphere except that it is constantly decaying owing to radioactive change.

This emanation or radioactive gas is constantly emitting α, β, and γ radiations and in consequence ionizing the air. In this case all three kinds of radiation are in a position to ionize the air and we are able to form some idea of the magnitude of the effect. The calculations of Eve [2] show that the actual radiation from each of the emanations in the air produces the ions given in Table 1.

TABLE 1.—*Ions per cubic centimeter per second produced in the atmosphere by the different emanations in the air.*

Rays.	Radium.	Thorium.	Total.
	Ions/cc., sec.	*Ions/cc., sec.*	*Ions/cc., sec.*
α	1.63	1.00	2.63
β	0.035	0.025	0.06
γ	0.035	0.025	0.06
Total	1.70	1.05	2.75

It will be seen that the ionization due to the emanation in the air is mainly caused by the α rays.

We can now state how many ions are produced each second in a cubic centimeter of the air near the ground by the radium and thorium in the earth and air.

TABLE 2.—*Ions per cubic centimeter per second produced in the air near the ground by the radium and thorium in both earth and atmosphere.*

Sources of rays.	Radium.	Thorium.	Total.
	Ions/cc., sec.	*Ions/cc., sec.*	*Ions/cc., sec.*
Air	1.70	1.05	2.75
Earth	0.80	0.80	1.60
Total	2.50	1.85	4.35

Thus the best estimates show that in each cubic centimeter of air over the land there are 4.35 ions of each sign generated every second.

Similar considerations can be applied to find the number of ions generated by radioactive matter over the ocean. We have the radioactive matter in the sea and the emanation in the air. The radioactive matter in the sea itself is so small that it can not produce by means of its γ rays more than 0.01 ion per cubic centimeter per second in the air over the sea. Also the emanation given out from the sea is so minute that it can be neglected, therefore if there is any emanation in the air over the sea it must have been brought from the land by the winds. This makes it impossible for there to be any appreciable thorium emanation over the oceans, for thorium emanation reduces to half value in less than a minute and it would therefore have entirely disappeared before the wind could have carried it far from the land.

We are, therefore, left with radium emanation only in the air over the sea. Naturally the amount of radium emanation over the sea has not been determined to anything like the same extent as it has over the land. But we know that it is very much less. At Hammerfest, in Norway, I found [3] that when the wind blew from the west, i. e., from the Atlantic Ocean, the radium it contained was only a little more than a twentieth part of the amount brought from inland by southerly winds.

[1] Simpson & Wright *in* Proc. Roy. soc., London, 1911, 85A: 175.
[2] Eve *in* Phil. mag., London, 1911, 21:26.
[3] Simpson *in* Phil. trans., Royal soc., 1905, 205A: 61.

During the voyage already referred to Wright and I measured the radioactivity of the air over the Atlantic and southern Indian Oceans far from land. When we arrived at South Africa the apparatus we had used on the ship was taken 200 miles inland. It was found that the radium collected inland was twenty times that collected over the ocean.

These experiments indicate, then, that over the ocean there is only 5 per cent of the radium emanation found over the land, but as other observers have found slightly higher values we will assume that there is 10 per cent. Thus, the radium in the air over the ocean can produce at the most only a tenth of the ions produced by the radium over the land.

We therefore are justified in constructing for the ocean the following table to compare with Table 2 for the land.

TABLE 3.—*Ions per cubic centimeter per second produced in the air near the surface of the sea by the radium and thorium in both air and sea.*

Source of rays.	Radium.	Thorium.	Total.
	Ions/c. c., sec.	*Ions/c. c., sec.*	*Ions/c. c., sec.*
Air	0.17	0	0.17
Sea	0.01	0	0.01
Total	0.18	0	0.18

Thus, using the most liberal estimate, all the known radioactive matter over the sea is able to produce only 0.18 ion per cubic centimeter per second.

Collecting our results, we have Table 4.

TABLE 4.—*Total numbers of ions per cubic centimeter present and being generated per second.*

Locality.	Number of ions per cubic centimeter. (n)	Number of ions generated per cubic centimeter per second by radioactive matter. (q)
Over land	1,000	4.35
Over ocean	800	0.18

We must now examine whether the number of ions generated in each case is capable of maintaining the number of ions actually found.

If every ion formed in the atmosphere remained an ion we should have an ever increasing number; but we know that when a positive and a negative ion meet they recombine to form a neutral molecule. It is obvious that the more ions there are in a given volume the more rapidly they will join together, and it is easily shown that for the steady state we have the folowing relationship:

$$q - \alpha n^2 = 0$$

in which q is the number of ions of each sign formed each second, n the number of ions of each sign present and α the coefficient of recombination. This equation simply means that for the steady state the number of ions formed in a second, q, is equal to the number of ions which recombine in a second.

If we can determine α for the land and the sea we shall be able to decide whether the values of n and q given in Table 4 are consistent. The rate of recombination of ions has been determined by several observers. The method used has been to ionise air by some outside ioniser, X rays or Becquerel rays, then to remove the ioniser and determine the decrease in ions due to recombination after definite intervals of time.

Before discussing the results of these measurements, we must say something about the factors on which the rate of recombination depends. If an ion comes near to matter, say the wall of the vessel containing the air, it induces a charge on the wall and the electrical force so produced causes the ion to attach itself to the wall and it is lost. In the same way ions attach themselves to any dust floating in the air and in consequence lose their property of moving freely in an electric field; again these are lost to measurement. It is found that water vapor tends to attach itself to ions and in consequence the ions lose their mobility in a damp atmosphere. Thus, dust and damp in the air have the apparent effect of increasing the rate of recombination of ions, hence we should expect the rate of recombination to be least in dry, dust-free air, greater in damp air, and greatest in damp and dusty air.

Experiments have confirmed this conclusion, and the values of α found have been—

(a) in dust-free dry air, 1.5×10^{-6} (Townsend[4]).

(b) in the air in the outskirts of Vienna, 3×10^{-6} (Mache & Rimmer[5]).

(c) in the dusty and damp winter air of Manchester, 4×10^{-6} (Schuster[6]).

In order to arrive at a definite conclusion, we ought to have made our determinations of n, q, and α simultaneously. As, however, this is impossible, we must choose from the above values of α the most probable value for the conditions under discussion.

We can say at once that α both over the sea and land must be greater than the value found for dry dust-free air. As the values of n for the land given above were determined in pure country air, we can say equally definitely that α must be less than the value found during winter in Manchester. Also, it is probable that α is greater over the land than over the sea.

It therefore seems reasonable to take α over the land as 3×10^{-6} and α over the sea as 2×10^{-6}.

With these values of α and the rates of generation of ions given in Table 4, we find from the equation

$$n = \sqrt{\frac{q}{\alpha}}$$

that if the whole ionisation were due to the radioactive matter known to be present, the air over the land should contain 1,200 ions per cubic centimeter, and the air over the sea only 300 ions per cubic centimeter.

Comparing these numbers with those given in the second column of Table 4, we see that the radioactive matter over the land is quite sufficient to account for the ionisation found there; but this is far from being the case over the ocean, where there are nearly three times as many ions as can be accounted for by the radioactive matter present.

It therefore appears that over the ocean at least the radioactive theory of the ionisation of the air is not satisfactory. This, then, is the first unsolved problem that I wish to bring forward for discussion.

[4] Townsend *in* Phil. trans., Royal Society, 1899, A193: 157.
[5] Mache & Rimmer *in* Physik. Ztschr., 1906, 7: 617.
[6] Schuster *in* Mem., Manchester litt. and Phil. soc., 1904, 48, Mem. 12.

2. EARTH'S PENETRATING RADIATION.

My second problem is generally described as the problem of the earth's penetrating radiation.[7]

If a closed metal box of suitable dimensions is cleaned with the greatest care so as to remove all radioactive matter from the inside, and if it is filled with air from which all radioactive matter has been removed by passing it through liquid air, it is found that the air within still has a residual ionization.

This in itself would not be very surprising, for it might be due to some small radioactivity of an impurity in the walls of the box, or even to some general radioactive property of all matter. What is surprising is that even when the box is kept at a constant temperature and hermetically sealed, the ionization within undergoes large changes both when the box is moved from place to place and also when it is kept in one place without being disturbed.

It is obvious that such changes must be due to a radiation entering the box from the outside, and as the walls are always too thick to allow either α or β radiation to enter, the radiation must be of the γ type.

We know of only two sources of γ radiation: The radioactive matter in the ground and the radioactive emanation in the atmosphere. The latter, however, can be ruled out at once for, as we see from Table 1, it can produce at the most only 0.06 ion per cubic centimeter per second, which is a quantity far too small to measure.

On the other hand the known radium and thorium in the ground are able by their γ rays to produce 1.6 ions per cubic centimeter per second, which amount may be largely exceeded in places where the ground is unusually rich in radioactive matter.

Neglecting, then, the ionization which is characteristic of the instrument and can not vary, we know of only one source of radiation which enters the instrument from the outside and can vary from place to place and time to time. This source is the radioactive matter in the rocks and soil.

The γ radiation from the rocks and soil although relatively very penetrating has an appreciable absorption coefficient. It is entirely cut off by less than 1 meter of water and is rapidly absorbed by the air. Eve [8] has calculated that at an elevation of 100 meters the radiation from the ground should be diminished by 36 per cent and it should have disappeared entirely at an elevation of 1,000 meters.

One would conclude from this, therefore, that if we measure the ionization within our vessel over the land, then remove it to a place far removed from rocks and soil, as, for example, to a place over deep water or to a place 1,000 meters in the air, the ionization within the box would decrease by the amount due to the radiation from the earth. Also as the remaining ionization would then be due to the instrument itself, one would conclude that it could not be decreased further.

Such experiments have been made by many observers, but not with this expected result.

When the apparatus has been removed from the land over deep radium-free water a decrease in the ionization has been found, the average decrease being about 3 ions per cubic centimeter per second which is of the order we should expect. If the apparatus is now sunk into the water, a further unexpected decrease takes place, the new decrease (2 ions per cubic centimeter per second) being only slightly less than the previous one.[9] It appears then that by sinking the apparatus into the water we are cutting off another radiation which can only come from above, and is nearly as strong as that due to the radioactive matter in the soil.

Similar experiments have been made on land by building screens of lead about the apparatus, and these have also shown that some radiation apparently comes from above as well as from the ground.[10]

The results attained by taking the apparatus up into the air are also important. As has been already pointed out, if the penetrating radiation came only from the ground it would be rapidly cut off by the air and at 100 meters it would be reduced by 36 per cent.

Many observations have been made on towers and all have shown that the decrease of ionization within the apparatus is much less than the theory requires. A typical example is a set of observations made by Wulf [11] at 300 meters on the Eiffel Tower. The ionization was only reduced by 40 per cent, while according to Eve's calculations it should have been reduced by more than 90 per cent.

Such observations are, however, not satisfactory, as the towers may possibly have a considerable deposit of radioactive matter upon them which might be the cause of some increase of ionization.

Observations in free balloons, however, are free from this objection, and quite a number of these have been made.[12] They all agree in showing a much smaller decrease in the penetrating radiation with ascent than would be given by radiation from the ground only.

The balloon observations, however, go much further; they show that after about 2,000 meters the decrease with ascent ceases and the radiation commences to increase. At first the increase is slow and at 3,000 meters the ionization has returned to the value found on the ground. This increase with the height above sea level has also been found by Gockel [13] to occur when observations are made on glaciers in the Alps. There can, therefore, be little doubt as to the reality of the effect. As one ascends still higher a strange phenomenon is observed: The rate of increase of the radiation goes up by leaps and bounds. At 4,000 meters there are produced each second 9 ions more than on the ground; at 5,000 meters 19, and at 6,000 meters 30.[14] It appears from all these observations that in addition to the γ radiation from the earth there is another radiation coming from the sky. Sinking the apparatus in water shows that at sea level the sky radiation can produce 2 ions per cubic centimeter per second and is therefore nearly equal to that from the rocks and soil. Further, the balloon observations show that this radiation increases with height. At first, however, as one ascends over the land the total ionization within the box decreases owing to the cutting off of the radiation from the ground, so that at 2,000 meters the ionization is somewhat less than on the ground; above this the radiation increases rapidly and at 6,000 meters it is

[7] A good résumé of this subject, up to 1912, is given by *Chauveau* in Annuaire, Soc. météorol. de France, Paris, oct.-nov., 1912.
[8] Eve *in* Phil. mag., London, 1911, 21: 26.
[9] Gockel *in* Physikal. Ztschr., 1915, 16: 345.
[10] Cooke *in* Phil. mag., London, 1903, 6: 403.
[11] Wulf *in* Physikal. Ztschr., 1910, 11: 811. Also see last paragraph of Eve in Phil. mag., loc. cit.
[12] Hess *in* Wien. Ber., 1912, 121: 2001.
Kolhörster *in* Physikal. Ztschr., 1913, 14: 1066, 1153.
[13] Gockel *in* Physikal. Ztschr., 1915, 16: 345.
[14] I see, from a reference in a recent paper by Gockel, that 80 ions per second have been observed at 9,000 meters; but I have not yet been able to see the original communication.—*G. C. S.* [Cf. Abstract of Kolhörster's paper, MONTHLY WEATHER REVIEW, Dec. 1915, 43: 596.—ED.]

more than ten times as much as that due to the radioactive matter in the ground, and still greater values are found at greater heights.

What can be the source of this radiation? Two suggestions have been made. *First*, that there is an unknown radioactive gas in the air which is mainly confined to the upper atmosphere. *Second*, that a true penetrating radiation enters the atmosphere from cosmical space.

It would take me too long to discuss all the pros and cons of these suggestions. It is sufficient to say that both are highly improbable on our present knowledge, although perhaps not impossible.

Here is a field for research which holds out great possibilities; but I am afraid that it is one which will not be investigated further at present. Germany up to the present has been practically the only country which has made atmospheric-electricity observations from balloons, for in recent years ballooning has been a popular sport in that country. This sport was no doubt fostered by its military associations, and it is very unlikely that it will survive the great war. Ballooning is an expensive pastime and it is unlikely that after the war any European nation will have money to spare for the purpose. India is unsuitable for ballooning, so we have practically only America to look to for the investigation of this interesting question. Let us hope that observation will soon be made in that country.

This, then, is our second problem: What is the origin of the penetrating radiation which produces 2 ions per cubic centimeter per second within a closed box at sea level, and very many more as one ascends into the upper atmosphere?

3. THE ORIGIN AND MAINTENANCE OF THE EARTH'S CHARGE.

We must now leave the subject of the ionization of the air, its magnitude and cause, which has given us two important unsolved problems and return to our consideration of the charge on the earth which was the starting point of our discussion.

The problem that I intend to consider next is the origin of the charge on the ground and how it is maintained.

It has already been stated that the charge on the earth is measured by the potential gradient that it produces, and observations of the potential gradient have shown that during fine weather every part of the earth's surface, sea, land, plain, and mountain, from north polar regions to south polar regions, has a negative charge which is fairly constant except where the shape of the land causes local excesses or defects.

The potential gradient has also been measured in the upper atmosphere,[15] and it has been found that it decreases rapidly, so that at about 3,000 meters the field is only a tenth of what it is near the ground. This change in the field in a vertical direction can only be due to the air containing free positive electricity, which counterbalances the negative charge on the ground. The potential gradient continues to decrease slightly to the highest altitudes reached, and if, as is generally assumed, it disappears entirely at great altitudes this can only mean that the whole of the positive charge corresponding to the negative charge on the surface is contained in the air. The natural inference is that the electrical field in the atmosphere is due to some process which has separated the negative electricity on the surface from the positive in the air.

It is not sufficient for this process to have caused the separation once for all, for on account of the air being a conductor a current of electricity is set up between the charge on the earth and the charge in the air which tends to neutralize the charges and to cause the field due to them to disappear. That this current actually exists can be shown by insulating a portion of the earth's surface and measuring the actual amount of electricity which leaves it each second.[16] It is then found that the loss from the surface is exactly the amount which is calculated for the current caused by the potential gradient and conductivity of the air.

The loss which thus constantly takes place on account of the conductivity of the atmosphere must be constantly replaced, and as long as we hold that the positive charge in the air and the charge on the ground are complementary the process which maintains the charges and field must be sought mainly in the lower atmosphere, where the large proportion of the separated charge exists.

Numerous suggestions have been made to explain the maintenance of the field in spite of the constant neutralizing current, and they can all be divided into two classes:

(*a*) Suggestions which suppose the electricity to be separated in the air and the negative electricity to be carried by some mechanical means to the ground, leaving the positive charge in the air; and

(*b*) Suggestions which suppose the separation to take place at the earth's surface, which retains the negative charge while the positive charge is carried to the upper atmosphere in ascending air currents.

I think it is worth while to give an example from each of these classes.

The first and most important theory is generally called the Wilson-Gerdien theory.[17] According to this theory negative ions are nuclei, on which water vapor is readily deposited; hence when it rains the negative ions are carried to the ground with the rain drops. Thus every rain shower has been looked upon as carrying negative electricity from the air to the ground, and so maintaining the electrical field in the atmosphere.

This theory received a fatal blow when it was found that rain in all parts of the world carries down more positive than negative electricity.

Ebert's theory is a good example of the second class,[18] and deserves to be specially mentioned as it is still seriously maintained by a large proportion of German physicists. Experiment shows that when ionized air is passed through conducting tubes, the air under certain conditions emerges with more positive than negative ions. Applying this to the earth, Ebert says that the interstices in the soil are all full of radium emanation; hence the air in the soil must be highly ionized. When the barometer falls, this highly ionized gas streams into the atmosphere through all the channels and cracks in the soil, which are equivalent to the tubes used in the laboratory. Hence the air will emerge with a charge of positive electricity which is rapidly disseminated throughout the atmosphere by ascending air currents.

The fallacy of this reasoning has been pointed out,[19] but it does not appear to have convinced Ebert's disciples.

[15] Linke *in* Abhandl. d. königl. Gesellsch. d. Wissensch. zu Göttingen, 1904, III, No. 5.

[16] Wilson, C. T. R., *in* Proc., Royal soc., 1908, 80A: 537.
Simpson, George C., *in* Phil. mag., London, 1910, 19: 715.

[17] Gerdien *in* Physikal. Ztschr., 1905, 6: 847.
Simpson *in* Phil. mag., London, 1909, 17: 619.

[18] Ebert *in* Physikal. Ztschr., 1904, 5: 135: Meteorol. Ztschr., 1904, 21: 201.

[19] Simpson *in* Physikal. Ztschr., 1904, 5: 325, 734.
Gerdien *in* Physikal. Ztschr., 1905, 6: 654.
Ebert *in* Physikal. Ztschr., 1904, 5: 499; 1905, 6: 825, 828.

The interstices in the soil are so very small that in spite of the emanation there can be no high ionization, for the ions are absorbed by the walls at once. Also the rate of flow through the channels and cracks due to a falling barometer is so small that the air emerges with neither positive nor negative ions, for the laboratory experiments show that the ionized air must travel relatively rapidly through the tubes if the air is not to be robbed of all its charge in the passage.

This is not the place to go into details of what has proved to be a long and unsatisfactory controversy. I shall therefore content myself by stating that no process has been suggested to account for the separation of the charge in the air from the charge on the ground.

I now propose to show that the charge in the air is not the charge which has been separated from the electricity on the surface, and therefore it is useless to look for a process which constantly effects such a separation.

I have already stated that the loss from the surface is in accordance with the current which can be calculated from a knowledge of the potential gradient and the conductivity of the air just above the surface. Measurements have been made of both these factors by Gerdien [20] to a height of 6,000 feet (1,828.8 meters), and it is found that in all heights of the atmosphere the potential gradient multiplied by the conductivity is a constant. In other words the same vertical current is present throughout the atmosphere up to the greatest height reached by balloons carrying measuring instruments.

Now, as the same vertical current is present in 6,000 meters as on the ground, this means that none of the negative charge which left the ground has combined with the positive electricity in the air. This leads to the important conclusion that the negative charge on the surface and the positive charge in the air are not complementary in the sense that one has been extracted from the other. The relationship between these two charges will now be explained.

Let us imagine that by some means the earth is receiving a constant supply of negative electricity. We need not consider how this is effected; we are only concerned with the supposition that negative electricity is set free at a constant rate on the earth. This charge immediately spreads uniformly over the whole surface and sets up in the atmosphere a vertical electrostatic field. In this field the ions of the atmosphere move and so conduct a certain amount of the charge received by the earth into the upper atmosphere. In other words, under the laws of electrostatics the charge passes on to the outside of the conducting sphere which is the atmosphere. As long as the charge which passes away into the atmosphere in a given time is less than the charge received by the earth there must be an accumulation of electricity on the surface which increases the field and so the current. After a certain time the accumulated charge on the earth has risen until it has set up, in the atmosphere, a field sufficiently great to carry away the charge as rapidly as it is received. This is a final steady state which continues so long as the earth receives its constant supply of electricity. When this state has been reached throughout there must be equal quantities of electricity passing upward in all parts of the atmosphere. If the conductivity of the air were the same throughout the atmosphere it would need the same force to drive the same current through all layers. But the air does not have the same conductivity throughout, the conductivity increases with height and therefore the force necessary to drive the current decreases with height; in other words, the potential gradient decreases with height. This adjustment of the force to the conductivity so that a constant current can flow, can only be effected by the accumulation of a volume charge of electricity.

The following is a statement of the process by which the steady state is reached. The charge on the earth itself increases until it produces such a field in the air immediately above the ground that the electricity is conducted from the surface at the rate at which it is received. Now, in another layer some distance above the ground the conductivity is greater, hence if the field due to the charge on the earth extended so high it would produce too large a current through the layer; in other words, the layer would lose electricity faster than it received it from below. The consequence would be that uncompensated positive electricity would appear in the layer. This would counteract some of the field due to the negative charge on the ground and the field in the layer would decrease. Finally the field in the layer owing to the positive charge so induced, would be cut down until a steady state was reached in which the current from the ground would just be conducted through it and no more. This process would go on throughout the atmosphere; in every layer sufficient free positive charge would appear to reduce the field to the value required to conduct the constant current through it.

Thus the two independent variables are, *a*, the rate at which the earth receives its charge and, *b*, the conductivity of the atmosphere. Given these the potential gradient and the volume charge adjust themselves until the same quantity of electricity passes through every layer of the atmosphere.

But these are exactly the conditions which we find in the earth's atmosphere; the charge on the earth, the volume charge in the air and the potential gradient are so adjusted that the existing conductivity is just sufficient to carry a constant vertical current through all layers of the atmosphere. We must therefore conclude that the prime cause of the electrical field in the atmosphere is that the earth receives a constant charge of negative electricity which must be conducted away as rapidly as it is received.

We can go further and say that as observations have shown that the same current passes the 6,000-meters layer as leaves the ground, the supply of electricity to the ground can not be obtained from the atmosphere below this height.

We now see why all attempts to solve the problem of the earth's negative charge by considering processes which are completed within the lower atmosphere have led to failure.

To solve our problem then we have to discover some means by which the earth may receive a constant supply of negative electricity without the corresponding positive charge being set free within the earth itself or the lower atmosphere.

This is a much more difficult problem and one which, it may be stated at once, baffles all known physical processes.

When long and serious attempts have been made to solve a problem along recognized lines without result, it appears to me that it is justifiable to draw on one's imagination and to state what kind of process, probable or not, would satisfy the conditions. I therefore propose to describe two processes which would explain the phenom-

[20] Gerdien in Nachr. d. k. Gesellsch. d. Wissens. zu Göttingen, 1905, Heft 5.

enon although both of them are against the recognized principles of physics. My only justification is that these may suggest parallel lines of thought and so be more profitable than a mere statement that we have reached a cul-de-sac.

The *first process* which I can imagine, is that the earth and its atmosphere are constantly being bombarded by particles of negative electricity which have such a great penetrating power that they can pierce the atmosphere in order to be absorbed in the great mass of the earth itself.

This explanation, simple as it is, can not be accepted by physicists for it necessitates a penetrating power of the charged particles quite impossible according to our present knowledge. How great the penetrating power would have to be can be realized from the fact that the absorbing power of the atmosphere is equivalent to a layer of mercury 30 inches deep. The most penetrating electrical particles of which we have knowledge are the β rays from radioactive substances, and none of these can pass even half an inch of mercury. Still, because we know of no electrical particles which can pierce the atmosphere, it can not be said that they are impossible; they can at least be conceived. The measurements of the ionization within closed vessels described above indicate that there is a radiation in the atmosphere far surpassing in penetrating power that from any known radioactive substance, and although I do not go so far as to suggest that this radiation and the one necessary to supply the earth's negative charge are the same, yet it does indicate that our knowledge of radiation is far from complete.

I am now going to make *another suggestion* which at first sight will appear much more improbable than the last one, but I hope to be able to show that it is not entirely ridiculous.

This is nothing less than the idea that there is a spontaneous production of negative electricity within the mass of the earth.

This is against all our ideas of the nature and the methods of production of electricity. It has become an axiom of physics that no electricity can be produced without the production at the same time of an equivalent amount of electricity of the opposite kind. Hence the constant production of negative electricity alone in the earth seems an impossibility.

But our ideas of the axioms of physics are at present in such a state of flux that it would be difficult to state exactly what they are. Twenty years ago it would have been rank heresy to state that the mass of a body was not constant; now the majority of physicists believe that mass, charged or uncharged with electricity, is a function of velocity. This is based upon the experimentally verified facts that the ratio $\frac{m}{e}$ varies with the velocity of the moving body. As it is generally held that the electric charge can not vary, the variation of the ratio has been ascribed to the variation of the mass.

Now, in 1911 Prof. More[21] discussed in the Philosophical Magazine the justification for this assumption and came to the conclusion that a much more satisfactory hypothesis is to "consider m to be the mass of a particle of matter in the Newtonian sense, of constant and small value, and e, the electrical charge, to be a force attribute of matter which varies with the velocity of the particle."

[21] More, *in* Phil. mag., London, 1911, 21: 196.

In other words, the ratio $\frac{m}{e}$ does not change because m changes but because e changes.

The difference is fundamental, but which hypothesis is correct, can not be investigated at present in our laboratories. The change in the ratio $\frac{m}{e}$ although it occurs in all velocities only becomes appreciable when the velocity of the particle approaches the velocity of light, but the only particles which can attain this velocity are the electrons from radioactive bodies, and their masses are so small that we can not determine them directly.

What is required to make the determination is to be able to alter the velocity of a large moving mass, then if the change produces electricity, as More sugggests, it might be possible to detect it, for our means of electrical measurement are much more delicate than our means of mass measurement.

Now, the earth is a very large, moving, insulated mass, and apparently it is producing a constant quantity of electricity, hence it does not seem altogether unreasonable to make the suggestion that the velocity of the earth relative to the center of gravity of the universe, is changing and the charge which appears on its surface is the consequence of this change. What values of the rate of production of electricity are possible can not be stated, for as far as I know the change of $\frac{m}{e}$ for a neutral molecule has not been calculated. The apparent rate of production of electricity by the earth, as judged by the current from the earth into the air, is between 1 and 2 electrons per ton per second. The smallest possible number of electrons associated with a given mass of matter is found from a consideration of the electrochemical equivalent according to which a metric ton of iron (of which we may consider the earth to be composed) has associated with it at least 3.4×10^{28} electrons, hence the change in the number of electrons in a year is only about 10^{-22} of the number present; which shows how small is the quantity of electricity appearing on the earth compared with that associated with the matter of which the earth is composed.

Again I must insist that these two suggestions are not put forward as solutions of our problem; they are only made in order to show along what lines a solution is conceivable, and if they cause one to think they have served their purpose.

4. NATURE AND CAUSE OF BALL LIGHTNING.

During the last few years considerable progress has been made toward solving the problems of the thunderstorm, but many interesting and important questions still remain unanswered. Of these I have only time to refer to one, not probably the most important, but one which to me at least is exceedingly interesting. This is the nature and cause of ball lightning.

From the mass of evidence, which might almost be called chaotic, three characteristics of ball lightning appear to stand out with such prominence that they can not be longer doubted:

(*a*) The body or ball itself, which is able to retain its individuality as it moves through the air, appears to be composed of gas or matter in some novel luminous condition.

(*b*) The balls appear to exist independently of any large electrical intensity, for they have been observed within closed rooms where large electrical fields are impossible, and have also been observed to pass in and out of parallel telegraph wires.

(*c*) They appear to be associated directly or indirectly with large quantities of energy, for they have been observed to explode with violence and have also been seen to fuse the overhead wire of an electric tramway.

There have been, of course, many attempts to explain this phenomenon with an entire want of success. In most explanations the seat of the glow is supposed to be associated with intense electrical force so that the glow itself is of the nature of a brush discharge; this, however, is almost certainly not the case with ball lightning. Until recently we had no knowledge of glowing gas except when associated with an existing electrical discharge or a flame. Prof. Strutt [22] has, however, shown that by means of an electrical discharge a mass of nitrogen can be put into a state in which it continues to glow for some time after it has been removed from the field. I can not help believing that the body of the ball lightning is some gas made to glow in this way by the intense discharge of a lightning flash. Prof. Strutt has pointed out to me serious difficulties of this explanation and I can see others, but future work may remove them. In any case active nitrogen is the nearest physical phenomenon to ball lightning yet produced in our laboratories. I feel that this subject has not received the attention it deserves by experimental physicists, and experiments made to solve this problem might well lead to most important results.

5. NATURE AND ORIGIN OF THE AURORA.

I now come to the last and probably the most interesting of the problems which I propose to discuss.

Many years ago Birkeland [23] suggested that the aurora is due to electrified particles shot off from the sun, and as was only natural, he considered these to be of the same nature as the negative electrons with which we have become so familiar in recent work on cathode rays and radioactive substances. Birkeland suggested that these electrons are discharged by the sun in all directions, but those which pass near to the earth get entangled in the earth's magnetic field and travel along the magnetic lines of force toward the magnetic poles where they produce the effects of the aurora when they strike the upper regions of the atmosphere. This theory was supported by remarkable laboratory experiments and by elaborate mathematical computations made by Störmer.[24]

It was realized throughout that both the experiments and computations left open the question of the sign of the charged particles, but the negative electrons were considered to be the most likely for many reasons, not the least being that glowing gases such as exist at the surface of the sun are known to emit a copious stream of negative electrons.

In 1912, however, Vegard [25] pointed out that, judging from the character of the aurora rays, it is more likely that the aurora is produced by the impact of the charged positive particles corresponding with the α rays of radioactive substances, and it must be admitted that he made out a very strong case.

During the last few years Prof. Carl Störmer has worked out with great patience and success a method of determining the exact height and position in space of the aurora rays. His method consists in photographing the aurora simultaneously from two stations at a considerable distance apart, which in practice is 27.5 kilometers. Then by comparing the apparent position of any marked feature of the aurora relative to the stars on the two plates he is able to calculate the coordinates of that part of the aurora. He has recently published a preliminary report [26] which is of surprising interest. He shows how the aurora rays end very suddenly between 90 and 100 kilometers above the earth's surface, but the result which is of the most interest is that in one marked case he has been able to determine the sign of the electricity in the rays. By calculating the exact position of the aurora ray at a certain time and comparing this with the simultaneous magnetic disturbance at the earth's surface he found that the ray must consist of positive electrons. It must be stated, however, that Störmer has so far only worked out one case, and he himself asks that the result should be taken as provisional until he has worked out further examples.

At the same time, as this observation fits in so well with the considerations advanced by Vegard, I think we are justified in considering the consequences of this remarkable result.

Vegard shows that the α rays which cause the aurora have the characteristics of the rays emitted by radioactive bodies, and his arguments point strongly to their origin being actually radioactive substances in the sun. It is a fascinating occupation to consider what may be the harvest of this discovery if future work should confirm it, and I can not refrain from mentioning some of the thoughts to which it already gives rise.

In the first place, if the sun contains radioactive matter to such a large extent as to give the copious radiation necessary to produce the aurora so far away as the earth, all theories as to the nature of the sun and the supply of his energy must be affected.

What must be the electrical field in the region surrounding the sun due to the constant loss of so much electricity? And what becomes of the matter and electricity distributed in this way to regions far beyond the earth's orbit?

Then, again, as the α radiation from different radioactive substances has different characteristics it may be possible to determine from the nature of the aurora what are the radioactive substances actually present in the sun.

If the α radiation from the sun produces the aurora, what becomes of the β and γ radiations which the same radioactive substances must emit? These may be the cause of the high ionization of the upper atmosphere which wireless telegraphy and Schuster's theory of the daily variation of the earth's magnetic field have led us to expect.

The depth to which the radiation penetrates into our atmosphere may give us information as to the density, and therefore temperature, of the upper atmosphere in regions far higher than we can possibly reach from the earth's surface.

These are only a few of the vistas opened up by this great discovery, and each one of you can doubtless suggest others. It is obvious in any case that another great field of cosmical discovery has opened up, but unfortunately it is one in which we in India are unable to participate. We can at least wish our confréres in polar regions all success in their work.

[22] Strutt, Bakerian Lecture *in* Proc. Roy. soc., 1911, 85A: 219, and in numerous subsequent papers in the Proceedings of the Royal Society.
[23] Birkeland *in* Expedition Norvegienne de 1899–1900.
[24] Störmer *in* Christiania Videnskabsselskods Skr., mat.-nat. Kl. N:o 3, 1904.
[25] Vegard *in* Phil. mag., London, 1912, 23: 211.
[26] Störmer *in* Terr. magnet. and atmosph. electricity, 1915, 20: 1.