

Terrestrial Magnetism *and* *Atmospheric Electricity*

VOLUME XVII

JUNE, 1912

NUMBER 2

THE PENETRATING RADIATION.

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Outline.

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- (4) The penetrating radiation at different altitudes above the ground.
- (5) The penetrating radiation over ocean and lake surfaces.
- (6) The γ radiation due to radioactive products in the ground.
- (7) The γ radiation due to radium products in the air.
- (8) The probable source of the penetrating radiation.
- (9) Some problems relating to the penetrating radiation.

ITS DISCOVERY.

The announcement of the discovery of the penetrating radiation was made simultaneously by Rutherford and Cooke¹ and McClellan and Burton² in 1902. Investigations on radioactive substances had shown that some of these emit a very penetrating radiation, the γ radiation, resembling hard X-rays. "Since the excited activity obtained from the atmosphere is very similar in character to the excited radiations from thorium and radium, Rutherford and Cooke thought it possible that some penetrating rays might be given off from the surface of the Earth and the walls of rooms on which excited activity from air is distributed." In order to test for the presence of this kind of a radiation, the ionization in a one liter electroscope was measured in lead screens of different thicknesses. A screen 2mm. thick had very little effect on the ionization while a lead screen 50 mm. thick or a

¹ RUTHERFORD and COOKE, *Phy. Rev.*, 16, p. 183, 1903; COOKE, *Phil. Mag.*, 5, p. 403, 1903.

² MCCLENNAN and BURTON, *Phy. Rev.*, 16, p. 184, 1903.



Fig. 1. The Absolute Building

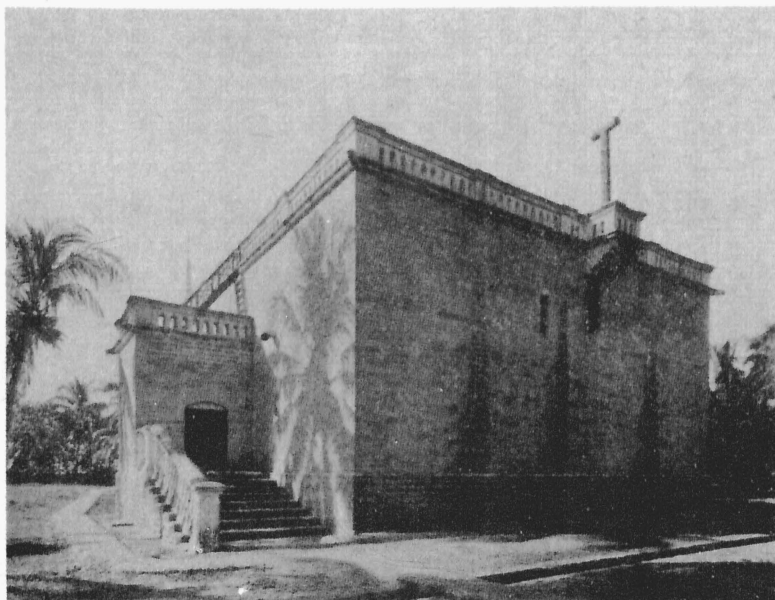


Fig. 2. The Variation Building

THE MAGNETIC OBSERVATORY AT ALIBAG, INDIA

water screen 70 cm. thick reduced the rate of discharge about 30 per cent. Increasing the amount of lead in the screens to a weight of 5 tons did not cause any further decrease in the rate of leak. The removal of the screen resulted in the ionization current returning to its previous value. The radiation seemed to come equally from all directions, and Rutherford and Cooke conclude that its source may be due to the excited radioactivity upon the surfaces of the room. Similar effects, produced on an electroscope placed on frozen ground, showed that there is a penetrating radiation in the open air. In a brass vessel they give the rate of discharge as corresponding to the production of 10 ions per cu. cm. per sec., this being reduced to about 6 ions when the penetrating radiation is screened off. [The potential gradient used in Cooke's work was about 20 volts per cm.] Cooke³ suggests that the penetrating radiation has its origin in the radioactive matter that is distributed throughout the earth and atmosphere.

McClennan and Burton used a cylinder 125 cm. long and 25 cm. in diameter with an electrode placed in the center charged to a potential of 165 volts. Filling the cylinder with air at a pressure of 400 cm. of mercury and surrounding it with a screen of 25 cm. of water reduced the ionization from 21.1 to 13.3, the units being arbitrary.

These and the investigations of other workers prove the universal existence of a penetrating radiation over all land surfaces. A small part of the ionization in the open air is produced by this radiation, which seems to possess properties that are the same as those of the γ rays from radium. Whether the penetrating radiation is the cause of any other terrestrial phenomena is not known.

DAILY AND ANNUAL VARIATIONS.

The earlier investigators discovered that the ionization in closed vessels was subject to various kinds of changes. The earliest to observe any periodic variation was G. Jaffé⁴. Jaffé found the natural ionization in nickel carbonyl to be about 5.1 times the ionization in air. The variations in the ionization in small vessels was much larger than the variations in large vessels, and amounted in certain instances to 40 per cent. [The electroscope used was of the Wilson type, *Proc. Roy. Soc.*, 68, p. 155; 69, p. 277, charged to about 80 volts.] Electroscopes placed near

³ *Phil. Mag.*, 5, p. 411, 1903.

⁴ *Phil. Mag.*, 8, p. 556, 1904.

together showed similar variations, whereas when placed in different rooms they showed very slight agreement, the deviations being sometimes in opposite directions. Large variations were common to both. A slight diurnal variation was noted, possessing a minimum between noon and 2 P. M. Large vessels of 3 liters capacity were found to show variations of about 10 per cent. Jaffé concluded that the variations depend upon the amount of surface of the ionization chamber rather than upon its volume. Borgmann⁶ found a minimum of ionization to occur at 3 P. M.

The first to discover the diurnal period of the ionization in closed vessels was A. Wood⁷ and N. R. Campbell. Vessels of 6 liters capacity were used with a central electrode charged to a high potential (potential not given). In most cases a gradual increase in the ionization was noted for the first ten or twelve days. McClennan and Burton, using smaller vessels, had observed a rapid increase at first, followed by a slow increase to a steady value. The increase was noticed for lead, no matter what the kind of gas used. In the case of a lead vessel in coal gas, the ionization current doubled in the course of seven days. Zinc vessels did not show this initial increase of the ionization current. Superimposed upon this permanent increase of the ionization current, Wood and Campbell discovered a periodic variation having two maxima and two minima daily. The most marked maximum appeared at about 11 P. M., and the most marked minimum, at 2 P. M.; the secondary maximum, at 8 A. M., and the secondary minimum, at about 4.30 A. M. The diurnal variation was found to take place independently of the kind of vessel and the nature of the gas. Curves are given showing that the range of the diurnal changes frequently amount to 15 or 20 per cent of the total ionization produced in the vessel. No relation was found between these variations and those of temperature. The atmospheric potential curves were shown to be somewhat similar and to possess two maxima and two minima at about the same time as those of the ionization curves. That temperature should not effect the ionization is to be expected since Clo⁷ has shown that the ionization due to γ rays from radium is independent of the temperature between 20° and 615° C.

The experiments of Wulf⁸ agree with those of Wood and Camp-

⁶ *Nature*, 70, p. 80, 1904.

⁷ Wood, *Nature*, 73, p. 583, Apr. 19, 1906; WOOD AND CAMPBELL, *Phil. Mag.*, 13, p. 265, 1907.

⁸ *Astrophys. Journ.*, 33, p. 115, 1911.

⁹ *L'Electrometre Bifilaire*, p. 62, Louvain, 1910.

bell in showing a close relationship between the variation of the penetrating radiation and the potential gradient.

The writer⁹ showed that the ionization in a closed vessel was subject to quite large variations. These variations were considered to be of three types: one due to meteorological changes, such as rain, snow, etc.; the second was of the same type as that discovered by Wood and Campbell, having a diurnal period; the third due probably to some effect on the apparatus such as would affect the nature of the ions formed, the radiometric effect on the gold leaf and possibly the leakage of the electric charge into the insulating supports. The electroscope had a capacity of about 2.6 liters and the active electrode was usually charged to a potential of from 1,500 to 2,000 volts. This was for the curved electrode¹⁰ type of electroscope. Small electroscopes showed variations of a different type.

(a) The ionization in a "curved electrode" instrument was found to be decreased about 25 per cent in value by a fall of snow. This effect appeared to be due to the products emitting the γ radiation in the air being swept down by the fall of snow. The recovery of the ionization shortly after the fall of snow was explained as being due to the γ ray products of the air returning to their equilibrium value. Unfortunately the writer has not been permitted the opportunity to repeat these experiments.

(b) The diurnal variation showed maxima at 9 A. M. and 10 P. M., and minima at 7 A. M. and 6 P. M.

(c) Screening the electroscope was found to make the ionization current¹¹ quite constant and from this result it was concluded that the variation of the ionization in closed vessels was therefore due to a variation in the intensity of the penetrating radiation.

(d) The maximum at 9 A. M. and the minimum at 6 P. M. seem to be somewhat peculiar in their nature. The 6 P. M. minimum was found to be very marked, and its appearance was so sudden that it was considered to be due in part to a condition in the ionization chamber.

(e) The writer¹² concluded that a considerable part of the penetrating radiation came from radioactive products in the air, and that variable meteorological conditions such as the existence of cyclones and anti-cyclones were responsible for some of the variations observed in the ionization currents in closed vessels.

⁹ *Science*, p. 52, July 12, 1907.

¹¹ STRONG, *Science*, 29, p. 470, 1909.

¹⁰ *Phy. Rev.*, 27, p. 41, 1908.

¹² *Terr. Mag.*, 12, p. 145, 1907.

(f) Small vessels were found to show a maximum rate of leak during the middle of the day, and this was shown to be due to the effect of illumination.¹³

McKeon¹⁴ has studied the leak between concentric cylinders by insulating the inner one and measuring the charge that it acquired and the variation of this charge after having reached the steady state. The outer cylinder was 120 cm. long and 24 cm. in diameter; the inner one, 110 cm. long and 19 cm. in diameter. On connecting the insulated inner cylinder to the electrometer, the quadrants gradually acquire a charge which reaches a maximum in a few hours and then falls off without dying away altogether or ever changing sign. After some twenty hours there appears a progressive change in the charge—which may be either an increase or a decrease—and a diurnal periodic change—principal maximum at 10.30 P. M.; secondary maximum 11 A. M.; principal minimum 6 P. M.; and secondary minimum 5 A. M.

Pacini¹⁵ found the maxima for the ionization in a closed vessel to appear at 2-3 A. M. and 9-10 A. M., the minima occurring at 7-8 A. M. and 1 P. M. The greatest production of ions per cu. cm. per sec. was found to be 30 and the minimum 6.3. The ionization as given by an Ebert instrument seemed to vary inversely as the ionization in a closed vessel. Mache¹⁶ concludes from observations made at Innsbruck that the portion of the penetrating radiation coming from radioactive products in the air or existing as an active deposit on the surface of the ground may be more than four times as great as the quantity coming from the ground itself. Mache and Rimmer¹⁷ consider that the active deposit on the surface of the ground is due largely to the Earth's being at a negative potential with reference to the air.

Mache¹⁸ has measured the rate of discharge of an electrode placed in a box made of thin sheet zinc 1.5 by 1 by 1m., the box being supported on posts 2 m. high. The electrode was connected to an electroscope, the rate of discharge being measured by the time for the potential to fall from 220 to 212 volts, the reciprocal of this being taken as proportional to the intensity of the penetrating radiation. Observations were made at 8 A. M., 2 P. M., and 8 P. M. The following are the results: (1) The intensity of

¹³ STRONG, *Phy. Rev.*, 27, June, 1908.

¹⁴ *Phy. Rev.*, Nov., 1907.

¹⁵ *Rend. Lincei*, 18, p. 123, 1909.

¹⁶ *Sitz d. K. Akad. d. Wis., Wien*, p. 119, 1910

¹⁷ *Phys. Zeit.*, 7, p. 617, 1906.

¹⁸ *Akad. Wiss. Wien, Sitz. Ber.*, 119, pp. 55-87, Jan. 1910.

the radiation shows a distinct annual period with a maximum in the autumn. The diurnal variation shows a maximum for the morning observation. For a whole year the figures are: 8 A. M., 81; 2 P. M., 67; 8 P. M., 68. (2) No conspicuous differences were noticed between radiation intensity and a rising, steady, or a falling barometer.

Gockel¹⁹, expressing the rate of leak in terms of volts per hour, gives the following values: average in the winter for snow-free ground, 10.7; for snow-covered ground, 10.9. No definite yearly period was detected although there seemed to be a maximum from January to March and in July and August.

Important and very interesting experiments have been made by Jaffé²⁰ on the ionization of liquids such as hexane, using a potential gradient of about 200 volts per cm. The ionization current is about 12 times that of air. About two-thirds of the conductivity was shown to be due to the penetrating radiation.

Diurnal Period.

OBSERVER	VARIABLE	MAXIMA	MINIMA
Wood and Campbell	Ionization current; electric field strong; value not given.	11 P. M. 8 A. M.	2 P. M. 4.30 A. M.
Strong	Ionization current; electric field very strong.	10 P. M. 9 A. M.	6 P. M. 7 A. M.
McKeon	Radiation current? No electric field.	10.30 P. M. 11 A. M.	6 P. M. 5 A. M.
Pacini	Ionization Current	2.30 A. M. 10 A. M.	1 P. M. 7.30 A. M.
Wulf	Ionization current in Wulf electrometer.	9 P. M. 9 A. M.	1 P. M. 1 A. M. about
Börnstein	Barometric pressure in the ground.	10 P. M. 10 A. M.	4 P. M. 4 A. M.

¹⁹ *Jahr. d. Rad. u. Elek.*, 9, p. 8, 1912.

²⁰ *Ann. d. Phys.*, 28, p. 326, 1909; 32, p. 148, 1910. *Phys. Zeit.*, 11, p. 571, 1910; *Le Radium*, 8, p. 293, 1911. *Compt. Rend.*, 151, p. 717, 1910.

The experimental work upon the variations of the ionization in closed vessels are of three types: temporary variations which disappear after the ionization chamber has been closed for some time; irregular variations whose cause is not known, one variation of this type, however, being sometimes attributed to the variation in the radioactive content of the air and the ground due to meteorological conditions; and periodic variations. The above description exemplifies how meagre is our knowledge of the exact nature of these variations and the experimental conditions existing in the ionization chamber during their measurement.

VARIATIONS CHARACTERISTIC OF THE LOCALITY.

If the penetrating radiation is due to radioactive matter, it follows that its intensity at any place will depend upon the amount of radioactive matter in the neighborhood. As the analyses of rocks have shown that their radium content is quite variable, it would be expected that the intensity of the penetrating radiation would depend upon the radioactive content of the surface soil and rocks and of the air. Indeed, the measurement of the intensity of the penetrating radiation might be made to serve as a test for the existence of radium and thorium existing in the surface rocks. A region containing rocks rich in uranium ought therefore be the source of an intense penetrating radiation.

At present little reliable data is at hand that gives any quantitative information of this kind, although there is considerable evidence of a qualitative nature. One reason for this is the fact that it is difficult to separate the effect of the ionization chamber upon the ionization currents measured. Among those who have made measurements of this kind have been Wulf²¹, Bergwitz²², Gockel²³, etc.

Gockel gives the following values of q , the number of ions produced per cu. cm. per sec. by the penetrating radiation, at different places: In a garden, 9.5; in a hole in the garden, 12.0; on a balcony, 13.5; in a room, 12.0; in a tunnel of granite, 33.5; in an ice chamber, 3.1.

According to Wulf²¹ the walls of houses are the source of penetrating γ rays. In the following table from Wulf, the effect of the

²¹ *Phys. Zeit.*, **10**, p. 152, 1909.

²² *Habilitationsschrift*, Braunschweig, 1910.

²³ *Jahr. d. Rad. u. Elek.* **9**, p. 4, 1912.

²⁴ *Le Radium*, t. 7, p. 173, 1910.

walls is the excess of the number of ions formed within them and the number formed in the open.

Place	Material of Construction	Age	Radiation in ions /cc. /sec.
Abbey of Maria-Laach, near Andernach-sur-Rhine.....	Volcanic tufa	50 yrs.	13.7
Fauquemont, College.....	Brick	15 "	5.7
Louvain, Collège.....	"	30 "	8.0
Namur, College.....	"	100 "	3.7
Wijnandsrade, Chateau.....	"	210 "	0.0

Wulf succeeded in obtaining the decay curves inside and outside of caves. Outside the decay curves indicated the presence of thorium, but inside only radium. The amount of deposit on an active wire was 150 times as great inside as outside the cave. It was found that the ionization in pools or small lakes in caves was much less than in the cave. The following table is due to Wulf:

	Matter	Meters below surface	Decrease of num- ber of ions /cc.
Fauquemont.....	Water	20	10.0
Maria-Laach.....	Water	12	7.3
Hau-sur-Lesse.....	Stone	100	9.5
Charleroi.....	Coal-mine	983	2.2
Auvelais.....	"	200	0.7
Fleurus.....	Baryte	20	5.1
Namur.....	Water	2	6.5

Wulf has found a decrease in the ionization on the lake Maria-Laach. When on the lake, plunging the apparatus to a depth of 12 m. had very little effect in further decreasing the ionization. On the other hand, he finds that placing the apparatus in a hole 20 cm. deep the ionization was increased from 23.9 to 30.1 ions per cc. On the surface of a small lake the daily variation was found to be as great as on land.

Wulf²² concludes from his observations that most of the penetrating radiation comes from radioactive matter in the surface of the ground not more than a meter deep. He thinks that the variation in the value of the penetrating radiation may be due to movements through the ground of air very rich in emanation.

In connection with the various problems of atmospheric ionization it is very important that observations be made of the active deposit, emanation content, intensity of ionization, intensity of the penetrating radiation, etc., at various altitudes in the atmosphere.

²² *Annal. Soc. Sci. de Bruxelles*, 34, p. 119, 1909-10.

THE PENETRATING RADIATION AT DIFFERENT ALTITUDES ABOVE THE GROUND.

A. Gockel²⁸ has measured the intensity of the penetrating radiation at altitudes of 4,000 m., using a Wulf electrometer. Large values of q are found even at these altitudes.

Wulf²⁷ has made a series of measurements of the number of ions produced by the penetrating radiation on the top of the Eiffel Tower (300 m.), and finds the value to be 3.5 ions per cu. cm. per sec., as compared with 6 ions at the foot of the tower and 10 at Valkenburg. If it is assumed that the γ rays are reduced to half their intensity in 80 m. of air, then the slow fall of the effect of the penetrating radiation can not be explained as coming entirely from the ground.

Gockel²⁸ gives the following values for the leak in a Wulf electrometer at different altitudes:

Starting.....	13.3	15.8
1,700 m.....	8.3	13.8
1,900 m.....	15.1
2,500 m.....	12.1
2,860 m.....	10.0
Landing.....	9.8

Hess²⁹ has obtained the following values of q , using a Wulf electrometer, with walls sufficiently thick to absorb all β rays. The value of the natural ionization when the instrument was placed in water was $q_0 = 25$. The coefficient of absorption of γ rays in air was found to be $0.45 (10)^{-4}$.

Height	Ionization
Surface.....	32.3 ions per cu. cm. per sec.
150-440 m.....	28.1 " " " " " "
440-800 m.....	34.7 " " " " " "
800-900 m.....	34.3 " " " " " "
900-1000 m.....	35.5 " " " " " "
Landing.....	34.9 " " " " " "

The above ascent was made before noon. An ascent made during the night of October 12, 1911, showed no decrease in the value of q .

The general results of the observations on the intensity of the penetrating radiation at different altitudes are those of Gockel and Hess, who have found practically no decrease in the intensity with altitude; and those of Wulf on the Eiffel Tower, Bergwitz³⁰

²⁸ *Phys. Zeit.*, 11, p. 280, 1910.

²⁷ *Phys. Zeit.*, 11, p. 811, 1910.

²⁹ *Phys. Zeit.*, 12, p. 595, 1911.

³⁰ *Phys. Zeit.*, 12, p. 1001, 1911; *Das Weltall*, 12, p. 85, 1911.

³¹ *Habilitationsschrift*, Braunschweig, 1910.

on a church tower, and McClennan and Macallum²¹ on a tower—these observers finding a marked decrease in the intensity of the radiation; Wulf a decrease of 40 per cent for an altitude of 300 m.; Bergwitz a decrease of 50 per cent in 85 m.; and McClennan and Macallum a decrease of 25 per cent in 64 m.

THE PENETRATING RADIATION OVER OCEAN AND LAKE SURFACES.

Quite a number of measurements have been made of the radium content of ocean and lake waters, and the amount present has always been found to be very small—of the order of about 1.0 (10)⁻¹⁵ grms. of radium per gram of sea water. From this poverty of the ocean and lake waters in radium it would follow that the emanation content of the air over mid-ocean should be very small. If, then, the penetrating radiation is due to radioactive products in the air and in the Earth's crust, its intensity far from land should be very small.

In general observers find much less active deposit far out at sea than is found over the land, although noted exceptions to this rule have been found. The exceptions may have been due to the wind currents being especially favorable for the carrying of radium emanation to sea, to the greater exposure of water surfaces to the winds or to the active deposit particles having a different mobility in ocean air from what they have in air over the land.

McClennan and Wright were among the first to take up measurements of the penetrating radiation above water surfaces. The following table gives the value of q as found by Wright:

	Lead	Zinc	Aluminium vessel
On Lake Ontario.....	6.4	4.4	4.8
On Land, Toronto.....	9.8	8.2	7.7
	<hr/> 3.4	<hr/> 3.8	<hr/> 2.9

The Canadian observers, such as Wright, Cline, Macallum, etc., have invariably found the evidence to indicate that the penetrating radiation, in the locality where they have experimented, is due to a γ radiation from the radioactive matter in the ground and that the value which they obtain on lake surfaces is the quantity q_0 , the "natural" ionization of the vessel. Their conclusions seem to be in accord with the theoretical results that one obtains from the values of the radium content of the rocks and of the air in this locality. Then again these observers have not obtained any evidence of any diurnal periodicity in the intensity of the ionization of closed vessels.

²¹ *Phil. Mag.*, 22, p. 639, 1911.

This is a condition that might be expected in the colder regions of the Earth's surface, although the work of Simpson in Norway does not support this view. One would expect that frozen ground covered with snow, would liberate much less emanation than ground in a warmer climate. The experiments of Pacini seem to support the view that in warmer climates a larger part of the penetrating radiation has its source in the radioactive products of the air.

Pacini³² has extended his study of the penetrating radiation to include observations on the water near Livourne, Italy. He used two Wulf electrometers and obtained the same results with each. The value of the ionization per c. c. in closed vessels was about two-thirds of the value obtained on the shore (about 15 ions). The observations were made about 300 m. from land where the water was 4 m. deep. The variations of the penetrating radiation under these conditions seemed to be due to variations of the amount of radioactive matter carried by the winds from the land and the amount of the variations was as great as on land.

The observations of Wulf and Gockel are in more or less agreement with those of the Canadian observers. In general the value of q on lake surfaces, as measured by them, is small, while in holes, caves, and tunnels q may have quite a high value. Submerging the ionization apparatus below the lake surfaces does not usually result in any very considerable decrease of the ionization.

Kleinschmidt³³ has made measurements of the penetrating radiation from 300 to 500 m. above the surface of the sea without obtaining any evidence that the intensity was any different at this altitude from what it was at the surface.

Simpson and Wright³⁴ have observed the ionization in a closed 26 liter zinc vessel on the ocean. The ionization was found to increase as the coast was approached, and the phenomena are explained by them as being due to an active deposit formed upon the ship.

In general it may be concluded that the evidence obtained from observations of the penetrating radiation on lakes and the ocean favor the view that the radiation comes from the ground and is very weak over water surfaces. Pacini's results, however, indicate that a large part of the penetrating radiation comes from the air

³² *Ann. dell' Uff. Centr. Meteor.*, 32, part I, 1910; *Le Radium*, 8, p. 307, 1911; *Nuovo Cimento*, 6, vol. 3, Feb. 1912.

³³ *Jahr. de Rad. u. Elek.*, 9, p. 7, 1912.

³⁴ *Proc. Roy. Soc.*, 85, p. 175, 1911.

and can be observed at distances sufficiently far from the coast that any radiation from the ground would be negligible.

THE γ RADIATION DUE TO RADIOACTIVE PRODUCTS IN THE GROUND.

The ionization due to the γ rays from radium and thorium in the ground can be calculated from the ordinary formula:

$$N = \int_0^{\infty} 2\pi r^2 \frac{N_0 Q}{r^2 e^{\lambda r}} dr = \frac{2\pi Q N_0}{\lambda}, \quad (1)$$

N being the number of ions produced per cu. cm. per sec., λ the coefficient of absorption of the ground, Q the amount of radioactive matter per cu. cm. of the ground; N_0 is a constant giving the value of N when $r = 1$ cm. If $Q = 1.4 (10)^{-12} \times 2.7$ and $\lambda = 0.34 (2.7)$, Eve finds that $N = 0.8$ ion. On the sea this value would be about 0.006.

In calculating the intensity of the penetrating radiation for different heights above the ground one may make use of the analogous problem in optics of calculating the intensity of radiation from a source of light having a given volume distribution and given coefficients of absorption for each medium. Consider a point P in air whose coefficient of absorption is λ at a distance r_1 from a radioactive substance whose coefficient of absorption is κ and whose far surface is at a distance r_2 from P . The intensity of ionization per unit volume at P due to a density of radium distribution Q is,

$$I = \int Q C e^{-\lambda r_1} \left[\int_{r_1}^{r_2} e^{-\kappa (r-r_1)} dr \right] d\omega, \quad (2)$$

C , being the intensity at unit distance, when there is no absorption, from the element of radioactive matter cut out by the solid angle $d\omega$. The integration is made to include the whole quantity of radioactive matter. If the radioactive matter is distributed uniformly throughout the region whose coefficient of absorption is κ , then,

$$I = \frac{QC}{\kappa} \int e^{-\lambda r_1} \left[1 - e^{-\kappa (r_1 - r_2)} \right] d\omega. \quad (3)$$

This value of I leads to the result that the ionization per unit volume due to a distribution of Q grams of radium per unit volume throughout a mass having the surface S is the same as the total ionization throughout the volume bounded by S , due to Q grams of radium concentrated at P .

The problem of calculating the γ radiation from an infinite slab of thickness h containing a homogeneous distribution of radioactive material has been made by King³⁵. Let z be the distance between P and the slab, ϕ the angle between PA and the normal from P to the slab, and ψ the azimuth angle which the plane

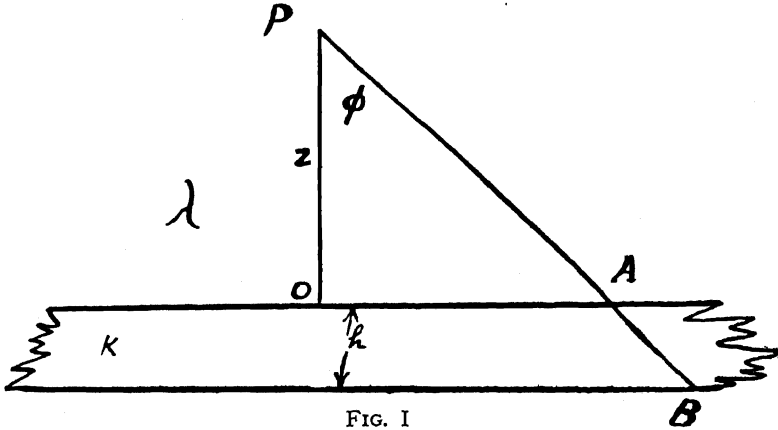


FIG. I

through PA and PO makes with a fixed direction in the plane of the slab. Then $AB = r_2 - r_1 = \frac{h}{\cos \phi}$. $PA = r_1 = \frac{z}{\cos \phi}$. $d\omega = \sin \phi \, d\phi \, d\psi$. The above equation on integrating with respect to ψ between 0 and 2π becomes:

$$I = \frac{2\pi QC}{\kappa} \int_0^{\frac{\pi}{2}} e^{-\lambda z \sec \phi} [1 - e^{-\kappa h \sec \phi}] \sin \phi \, d\phi \quad (4)$$

Letting $\cos \phi = \frac{x}{u}$, one has

$$\int_0^{\frac{\pi}{2}} e^{-x \sec \phi} \sin \phi \, d\phi = x \int_x^{\infty} \frac{e^{-u}}{u^2} du = e^{-x} - x \int_x^{\infty} \frac{e^{-u}}{u} du \quad (5)$$

and³⁶

$$\int_x^{\infty} \frac{e^{-u}}{u} du = - \int_{-\infty}^{-x} \frac{e^u}{u} du = Ei(-x) = -\frac{f(x)}{x} + \frac{e^{-x}}{x} \quad (6)$$

From tables $f(x)$ can be calculated and this is done by King. When x is small and γ is Euler's constant 0.5772,

$$Ei(-x) = \gamma + \log x - x + \frac{x^2}{2.2!} - \frac{x^3}{3.3!} + \dots \quad (7)$$

³⁵ *Phil. Mag.*, 23, p. 244, 1912.

³⁶ GLAISHER, *Phil. Trans.*, p. 367, 1870; MILLER and ROSEBERG, *Trans. Roy. Soc. of Canada*, 9, p. 73, 1903.

and

$$f(x) = 1 + x \log x - (1 - \gamma)x - \frac{x^2}{2} - \dots \quad (8)$$

When x is large the asymptotic expansion of $f(x)$ is obtained from (6) by successive partial integrations as

$$f(x) = \frac{e^{-x}}{x} \left[1 - \frac{2!}{x} + \frac{3!}{x^2} - \dots \right]. \quad (9)$$

The intensity of ionization at a distance z is then

$$I = \frac{2\pi Q C}{\kappa} \left[F(\lambda z) - f(\lambda z + \kappa h) \right]. \quad (10)$$

This is in different notation the formula worked out by Eve.³⁷

If n is the number of ions produced per sec. per unit volume of air by the γ radiation from the radium in the ground; Q is the amount of radium per unit volume in the ground (say $3.8 (10)^{-12}$ grms.); κ is $.034 \times 2.7 \text{ cm.}^{-1}$ say; n_0 is the number of ions produced per sec. per unit volume in air under normal conditions by the γ rays from a curve of radium supposed concentrated at a point at a distance of 1 cm. from the place of ionization; and λ is about $.44 (10)^{-4} \text{ cm.}^{-1}$, then

$$n = \frac{2\pi Q n_0}{\kappa} \int_1^\infty e^{-\lambda z/\nu} d\nu \quad (11)$$

Taking the surface intensity at $z = 0$ as unity, King has calculated values of λz , κh , z and h for various values of z .

The curves show that even in the case of distribution of radioactive matter throughout an infinite thickness, practically the whole effect on the gradient is due to a layer about 10 cm. thick.

In the chapter upon the variation of the penetrating radiation with increase of altitude it was shown that the observations of some observers indicated a considerable decrease. In general, however, observations have indicated a much smaller diminution than theory would account for, while the observations of Hess and Gockel indicate no decrease at all.

THE γ RADIATION DUE TO RADIUM PRODUCTS IN THE AIR.

Knowing the amount of radium emanation in the air and assuming that there exists an equilibrium amount of radium C present, one can calculate the ionization produced per cu. cm. per second by the γ radiation from radium C .

³⁷ *Phil. Mag.*, 21, p. 551, 1911.

In air at a distance r from a quantity of radium Q , the ionizing effect is $\frac{Q}{r^2 e^{\lambda r}}$, λ being the coefficient of absorption of the rays. Let N_0 be the number of ions produced per cu. cm. at a distance of 1 cm. from Q grms. of radium, then:

$$N = \frac{N_0 Q}{r^2 e^{\lambda r}} \quad (12)$$

Curves of the functions I. $y=e^{-x}$.

II. $y=f(x)=e^{-x}+x \operatorname{Ei}(-x)$.

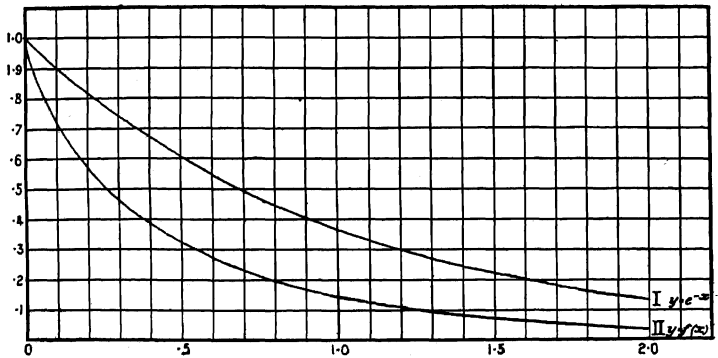


FIG. II

Decrease of intensity of penetrating radiation with height above the earth's surface. Intensity at surface is taken as unity. The various curves refer to intensities due to radioactive material in layers of different thickness.

Curve I. $h=.01$ cm.

Curve III. $h=1.1$ cm.

Curve II. $h=.11$ cm.

Curve IV. $h=11$ cm.

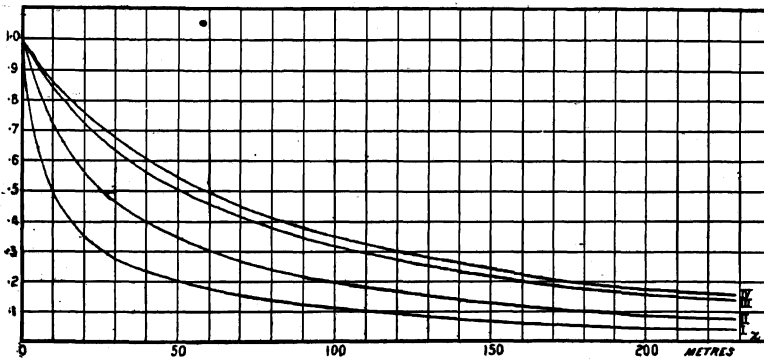


FIG. III

The ionization produced per cu. cm. due to a uniform distribution of radium is:

$$\int_0^{\infty} N_0 4\pi r^2 \frac{Q}{r^2 e^{\lambda r}} dr = \frac{4\pi Q N_0}{\lambda} \quad (13)$$

Eve³⁸ has measured the value of N [$3.1 (10)^{10}$], and calculates the ionization in the open air arising from the action of the α , β and γ rays from the radium products in the air to be as follows:

Rays	Radium	Thorium
α	1.63	1.00
β	0.033	0.025
γ	0.035	0.025

Among those that have supported the view that a considerable portion of the penetrating radiation (and especially that portion which shows seasonal, meteorological and diurnal variations) is due to radioactive products in the air have been the author³⁹, Pacini⁴⁰, Mache⁴¹, Gockel⁴² (from balloon observations) etc. According to this view a very considerable portion of the radium emanation is liberated from the upper layer of soil and carried about in the atmosphere by the winds. This emanation would probably be carried to very considerable heights—at least as high as the height of cumulus and nimbus clouds. This view of the origin of the penetrating radiation would explain the balloon observations of Hess and Gockel.

The explanation of the diurnal period of the penetrating radiation depends upon the assumption that the barometric pressure in the ground shows a diurnal period. Theoretically the former should lag several hours behind the latter—the lag being the time required for the formation of the γ product, radium C. Data on the diurnal period of the penetrating radiation are not sufficiently exact to corroborate this lag.

Observations have been made by Börnstein⁴³ on the diurnal period of the barometric pressure at a depth of 1 m. The diurnal variation was found to be the same as on the surface, maxima at 10 A. M. and 10 P. M., and minima at 4 A. M. and 4 P. M., occur a little later than on the surface. If this periodicity of the barometric pressure is the cause of the diurnal periodicity of the

³⁸ *Le Radium*, 8, p. 64, 1911.

³⁹ *Phy. Rev.*, 27, p. 39, 1908; *Terr. Mag.*, Dec., 1907.

⁴⁰ *Nuovo Cimento*, 6, vol. 3, Feb., 1912.

⁴¹ *Wiener Ber.*, 119, p. 55, 1910.

⁴² *Phys. Zeit.*, 11, p. 280, 1910; 12, p. 595, 1909.

⁴³ *Phys. Zeit.*, 12, p. 771, 1911.

penetrating radiation, this latter should have a phase lag of about 3 hours, due to the time required for radium emanation to come to an equilibrium value with radium C.

G. Wulf⁴⁴ explains the diurnal period of the barometric pressure (maxima in the evening and morning and minima at noon and midnight) as being due to an air tide and to the pressure of the sun's light.

THE PROBABLE SOURCE OF THE PENETRATING RADIATION.

As a result of the work of Cooke and the calculations of Eve, it was generally assumed at the time of Wood and Campbell's discovery of the diurnal period of the ionization in closed vessels, that the penetrating radiation came from radioactive products in the ground. No suggestion had been made as to the cause of the diurnal period of the ionization in closed vessels, although Wood and Campbell emphasize the similarity between these variations and those of the potential gradient of the air.

That the radiation does not come from an extraterrestrial source⁴⁵ seems to be thoroughly proved since the atmosphere (equivalent to 76 cm. of mercury) would completely absorb any such radiation. The experiments made to find the direction of the radiation have in general been inconclusive. The reason of this is probably due to the penetrating radiation being more or less diffuse and to its excitation of secondary radiation. It is quite probable that the constitution of the penetrating radiation is very complex. Recently it has been shown by Danysz⁴⁶ that the β radiation from various radioactive products is extremely complex. He finds at least 23 distinct types (depending upon their velocity) of β rays from the radium emanation. The general phenomena of vacuum tube discharges and radioactivity indicate that cathode and X rays and β and γ rays are very closely related. Cathode rays are the source of X rays whenever their acceleration is considerably changed. On the other hand, although a few cases have been noticed where β rays excite a γ radiation, yet in general it seems that the β and γ rays are both due to a common cause and if the β rays are very complex it is to be presumed that the γ rays are also.

The various elementary substances are known to possess characteristic fluorescent X radiations, the absorption coefficients

⁴⁴ *Journ. de la Soc. Physico-Chimique Russe*, p. 181, 1910.

⁴⁵ RICHARDSON, *Nature*, 73, p. 607, 1906; 74, p. 55, 1906.

⁴⁶ *Le Radium*, 9, p. 5, 1912.

of the radiations depending upon the nature of the secondary radiator. A substance only emits its characteristic X radiation when excited by a beam of X rays that is harder than its own radiation. Up to the present no corresponding types of fluorescent γ radiations have been found. If such existed, the penetrating radiation would consist of scattered primary γ rays and fluorescent γ radiations characteristic of the air, water, and the kind of soil and rock constituting the upper surface of the ground. Whether or not any effect of this kind takes place, it is probable that the penetrating radiation is composed of radiations of different coefficients of absorption and that the constitution of the radiation may be quite different in different localities.

The ionization in closed vessels is presumably due to external radiations, to secondary radiations from the walls of the vessel excited by these, to radioactive impurities in the gas itself or in the walls of the vessel and to any spontaneous ionization of the gas, if such exist. The smallest ionization that can be obtained in any way from vessels of given shape, size, and material, the enclosed gas being as pure as possible, will be called the "natural" ionization of the particular vessel and the intensity of this ionization will be called q_0 , being given in ions produced per cu. cm. per sec.

The natural ionization of a vessel, depending upon the existence of a possible spontaneous ionization of the gas of the electroscope, to radioactive impurities of the walls or to a radiation that is not absorbed by thick lead screens, is presumably constant in quantity. (The writer^a found the rate of leak of an electroscope surrounded by four feet of water in Sept., 1907, and in July, 1908. The value of the "natural" ionization was found to be the same in both cases.)

Variations in the ionization in closed vessels as usually measured by the ionization current may be due to several causes. (a) The gas or the walls may contain radioactive matter which slowly decays. For our purposes a variation of this type will not be considered. (b) The external penetrating radiation and the secondary radiation which it excites may undergo regular or irregular variations due to outside causes. As no method has as yet been devised for separating the effect of the direct and the secondary rays, these will be considered together. (c) The mobility or the rate of recombination of the ions may be modified by temperature,

^a *Science*, p. 470, March 19, 1909.

illumination, etc., changes. Unfortunately very little is known concerning changes of this kind. Knoll⁴⁸ has shown that moisture and temperature have a very pronounced effect, and Gockel⁴⁹ has concluded that many of the variations attributed to changes of the intensity of the penetrating radiation due to variable meteorological conditions may be due to a change in the character of the ions formed in the closed vessel. Pacini⁵⁰ has found at times differences in the rate of leak of two Wulf electrometers placed under the same conditions, thus showing that there are certain instrumental errors that probably enter into the determinations of the ionization current.

The γ radiations coming from the products in the ground will vary from place to place according to the richness of the surface soils and rocks in radioactive matter. At any one place the radiation may vary to some extent depending on rain, snow, and the porosity of the surface soils. In very rocky regions any variation of this kind should be small.

The variation of the penetrating radiation coming from radioactive products in the air would be expected to vary very greatly under different meteorological conditions, such as rain, winds, changes of temperature, barometer, etc., since these products originate either directly or indirectly from the gaseous emanations of radium and thorium contained in the ground. The total radioactive content of the air over any place at any time depends upon the history of that air for several days before and would therefore depend on the nature of the prevailing winds.

In order to explain some variations in the rate of leak of electric charges in closed vessels the writer⁵¹ considered that during cyclonic conditions the penetrating radiation was more intense than during anti-cyclonic conditions. During the former state of the winds part of the penetrating radiation comes from air that has been sweeping over the surface of the ground and that therefore ought to be rich in emanation. During anti-cyclonic conditions the air, coming from the higher strata of the atmosphere, would contain very little emanation and the penetrating radiation would then have a smaller value. Eve⁵² finds that cyclonic winds cause the emanation content of the air to increase while anti-cyclonic winds are accompanied by a small emanation content.

⁴⁸ *Wien Ber.*, 115, 2a, p. 164, 1906.

⁴⁹ *Jahr. d. Rad. u. Elektronik*, 9, p. 2, 1912.

⁵⁰ *Annali dell' Ufficio Centr. Meteor. e Geodin. Ital.*, 32, Parte I, 1910.

⁵¹ *Phy. Rev.*, 27, June, 1908.

⁵² *Phil. Mag.*, 16, p. 622, 1908.

The above are a few of the views that have been held as to the source of the penetrating variation. Experimental evidence seems to show that at places the penetrating radiation is nearly constant in value and probably comes almost entirely from the ground. At other places considerable variations are found in the intensity of the ionization currents in closed vessels, and the accepted explanation of these is that the penetrating radiation itself varies greatly in intensity. The simplest way of explaining these variations is that of assuming their source to be radioactive products in the air.

SOME PROBLEMS RELATING TO THE PENETRATING RADIATION

The problems concerned with the solution of the causes of the ionization in closed vessels include the problems of the intensity and the nature of the penetrating radiation and any secondary radiations which it may excite; the composition and the nature of radioactive matter distributed in ordinary substances; the question whether the common elements themselves are radioactive or not; the problem as to whether a gas is spontaneously ionized or not; and the nature of the phenomena of ionization itself. These are problems which the earliest workers upon the subject set out to answer, and as yet the results are more or less conflicting as to the nature of the penetrating radiation while the other problems have not been answered to any degree of certainty. One very good method of attack would be as follows:

(a) The study of the ionization in closed vessels under as simple conditions as possible. The work should be done in an underground laboratory as free from radioactive walls, emanations, etc., as possible, with all of the penetrating radiation cut off by screens. The temperature should be constant and the light used for illumination should be as constant and weak as possible, it being filtered of its heat rays. Variations of the following nature could be studied:

Effect of the nature of the walls of the ionization chamber at different (1) temperatures; for different (2) sizes of the chamber; for different kinds of (3) gases and liquids in the chamber; for the gases at different (4) pressures; for the gases and liquids subjected to (5) ionization agents that produce ions of known mobility and diffusion constants;

(b) Under the above simplified conditions a thorough study should be made of the effect of various kinds of nuclei, dust, etc., upon the ionization currents. The action of light, heat rays, and ionizing agents could be used to produce and modify these nuclei. One effect of this nature is the radiometer effect of the light used for illumination purposes.

(c) Under the above simplified conditions a thorough study should be made of the ionization currents for electric fields of

different and known intensities and as much knowledge should be gained concerning the nature of the "natural ions" of gases as possible.

(*d*) The manner by means of which electric charges leak into the well-known insulators, such as sulphur, and the effect of illumination and temperature on this leakage should be carefully studied.

(*e*) It is well known that slight impurities in some gases produce very great effects upon the nature of the ions formed. In the study of natural ionization little care of this kind has been taken by most observers. The effect of different degrees of humidity should be carefully studied.

(*f*) After a thorough study of the "natural" ionization in closed vessels, a similar study should be made of the ionization produced by the penetrating radiation and by the γ rays of radium, thorium, and uranium.

(*g*) The various ionization effects obtained in closed vessels could be applied to the explanation of observations made of dispersion, the measurements of the ionic content of the air, etc. It is well known that measurements of this kind at present have little value on account of the complexity of the ionization phenomena as they take place in the open air.

(*h*) Simultaneously with the study of the penetrating radiation, determinations of the emanation content of the air should be made; also the ionization, the potential gradient, the barometric pressure, the temperature of the air, etc., at the same place. Up to the present, few correlated measurements of this kind have been made. Theories to account for the penetrating radiation or the ionization at one place are made from a few data as to the radium emanation content of the air or the average radium and thorium content of the rocks from various parts of the world, and the results are applied to certain specific instances. At present this is the best that can be done, but one must not forget the paucity of data of this kind and the very great errors that may be introduced in our present calculations.

(*i*) A radium and thorium survey should be made of the soils and rocks in the vicinity of the "atmospheric ionization" laboratory in order to correlate the radioactive content of the various winds with the radioactive materials of the surface of the ground over which they pass.

(*j*) In obtaining continuous records of the intensity of the penetrating radiation, the value of the potential gradient, etc., it would be important to use two or more apparatus of this kind at the same place in order to find how much of the variation is due to the characteristic properties of the apparatus.